

Abstracts

POTENTIAL NEW IMPACT SITES IN PATAGONIA, ARGENTINA, SOUTH AMERICA

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Introduction: The southern part of Argentina has a total surface of 786,112 km². It is composed of five provinces: Neuquen, Rio Negro, Chubut, Santa Cruz, and Tierra del Fuego. So far, no impact sites have been reported in this region. As part of an ongoing project to discover meteorite impact sites, this area was investigated through examination of 76 color LANDSAT satellite images (1:250,000; resolution = 250 m) at the Instituto Geografico Militar (IGM) (Military Geographic Institute) of Buenos Aires. When a potential candidate was found, a more detailed study of images was done. LANDSAT color images at the scale of 1:100,000 and aerial photographs at the scale of 1:60,000 (IGM) were then consulted. Sites identified are described below. The coordinates given are those of the upper left and lower right corners of a rectangle enclosing the site. Further evaluation of the proposed sites is in progress.

Neuquen: 1) *Meseta de la Barda Negra;* 70°00′W, 39°00′S/69°45′W, 39°25′S; possible simple crater in black Miocene (14–10 Ma) basalt plateau. Diameter: 1.5 km. Raised rim. Fresh aspect. There are no visible lava flows coming from this crater. The crater has been described as a "salitral" (salty pan basin) containing blocks, conglomerates, and sands, on the geologic map of the province by SEGEMAR [1].

Santa Cruz: 1) *Meseta del Lago Buenos Aires;* 71°10'W, 47°00'S/ 71°30'W, 47°05'S; possible simple crater. Diameter: 1 km, similar to the Lonar Lake crater, India [2]. The area is composed of basalts of Pliocene age 7 to 3 Ma [3]. 3) *Estancia Los Mellizos, Ruta Provincial;* 39°N; 70°10'W, 47°15'S/69°50'W, 47°28'S; possible eroded and covered complex structure. At this site, there is a circular feature of ridges and low hills. Diameter: 15 km. The DLR's X-SAR images also show this circular structure. The geology of this entire area is not well known. Apparently, it is composed of degraded volcanic and pyroclastic rocks of the Chon Aike Formation of Jurassic age (170–140 Ma) [4]. 4) *Gran Altiplanicie Central;* 70°10'W, 48°23'S/70°05'W, 48°28'S; possible eroded simple crater in upper Miocene (about 11–12 Ma) basaltic plateau. Diameter: 1 km [5, 6].

Tierra del Fuego: 1) *Cerro Taarsh, Estancia San Justo;* 68°45′W, 54°00′S/68°30′W, 54°10′S; possible complex structure. Semi-circular area of concentric low ridges. Estimated diameter: 12 km. Probably very eroded. The ridges of the surrounding area run parallel NW to SE. The area is composed of marine sedimentary rocks (limestones) of lower Tertiary age.

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SPIN DYNAMICS OF TERRESTRIAL PLANETS FROM EARTH-BASED RSDI

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Introduction: Despite wide Earth-based observations and many spacecraft missions, much remains unknown in spin dynamics of terrestrial planets and related issues. Through accurate measurement of spin vectors and their variations with time, we may look deeply into planetary interiors. It has not been possible to do so with known Earth-based techniques and spacecraft missions have been the only way to obtain such data. The upcoming Messenger (USA) and BepiColombo (Europe, Japan) orbiting and orbiting/ landing missions should give obliquity and librations of Mercury closely related with its internal constitution [1]. In addition, we discuss new Earth-based opportunities for precision measurement of instantaneous spin components of planetary mantles offered by the Radar Speckle Displacement Interferometry (RSDI) technique [2–4].

RSDI and Today's Radar Facilities: RSDI technique was designed to measure as precisely as possible instantaneous spin components of distant bodies by laser or radar. Applied to terrestrial planets, the improvement in accuracy can be expected 3 to 4 orders of magnitude with respect to current Earth-based techniques [3]. The measuring time can be shortened by 5-7 orders of magnitude (from years to ~1 min). RSDI can measure regular and stochastic variations in spin axis orientation as precisely as in rotation velocity. The limiting accuracy for Mercury, Venus, Mars (better for the moon) is a few arcseconds or one part in 100,000 during observation within a few min (the round trip time is excluded) with existing radar facilities like the Goldstone 70 m radar and the Goldstone 70 m-Green Bank 100 m radio interferometer (USA) [2, 4]. This limiting, one-look accuracy roughly approaches the precision expected from spacecraft missions [1]. Computer simulation showed that RSDI limits in accuracy can be closely attained in reality. Repitition of one-look experiments on Mercury during ~20 days near a single inferior conjunction and the use of additional radio interferometers would improve uncertainty in obliquity and libration amplitude to less than 1 arcsec-better than expected from space missions. Unfortunately, the only fully steerable powerful transmitting facility in the world, at Goldstone, most probably cannot be widely used because it is exploited heavily in spacecraft navigation. Taking all of the above into account, we conclude that accuracy in spin dynamics of terrestrial planets provided by today's Earth-based radars approaches the precision of space missions.

RSDI Looks into the Future: The Goldstone transmitting facility was constructed several decades ago and is overwhelmed with proposals. A new, much more powerful and dedicated radar is needed to facilitate substantial progress in radar astronomy in the 21st century, e.g., an increase in transmitting power by 16 times to ~7 MW instead of today's 450 KW will improve accuracy by ~4 times, and a single measurement will replace 16 of today's measurements. Regular RSDI observations may result in detailed knowing of spin dynamics of terrestrial planets to tens of milliarcseconds. Reaching this accuracy through missions is not easy. A new radar may work for several decades, while its cost is comparable with a single spacecraft mission. Earth-based RSDI may be the best possible way to investigate detailed rotation dynamics of Mercury, Venus, and Mars in in the 21st Century.

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SEM-STUDY OF A MINERAL GRAIN SURFACE IN PALLASITES

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Scanning electron microscopy (SEM) study of chondrites [1, 2, 5] has shown that a surface of mineral grains is very sensitive to physicochemical conditions of their origin and evolution. The surface of mineral grains and chondrules exhibits sculptural features, which are classified according to their nature as primary and secondary. In contrast to chondrites, SEM data on the morphological features of minerals from differentiated meteorites are scanty.

Here, the results of SEM investigation of sculptural features of mineral grains from the pallasites Omolon, Brahin, and Kraçaoyarsk are originally presented. The studied objects include of 40–50 grains of olivine and 30–35 grains of metal from each pallasite and rare grains of chromite and shreibersite. The grains are characterized by a smooth, ribbed, or fine-grained surface.

The following primary sculptures are found on a surface of olivine and metal grains: 1) inclusions of chromite crystals and their imprints (chiefly on the metal) and a native copper (on the olivine); pores. Formation of these sculptures results from a self-rectification from Cr and Cu of the metal and olivine during a slow cooling of a pallasite parent body. The presence of small spherical pores on the surface of the minerals attests to some probable gas inclusions; 2) growth steps; rare polygonal faces and their embryos on the rounded grains of olivine.

Secondary sculptures, which were formed mainly as a result of shock metamorphism, are presented as the following features: voids, friable (fracturing, disruption, brecciation) and plastic (linear, ribbed, wedge-shaped, lamellar, bending) deformations, and sculptures of shock heating (recrystallization, sticked both sparks of melt and products of condensation). The surface of the minerals reveals the evidences of terrestrial weathering. Iron hydro-oxides are present both as open-worked films on the olivine and fibrous rosettes on the metal grains.

The presence of magnetite euhedral crystals and their globules, which precipitated on a surface of deformed olivine from Brahin is one of the most interesting sculptural features. The magnetite crystals and globules belong to condensates probably formed as a result of shock, which caused evaporation of the pallasite metal or troilite, and following precipitation. Similar magnetite crystals from carbonaceous chondrites [6] were considered as condensates of the solar nebula [3] or as products of aqueous alteration on the chondrite parent body [4].

A pollen, which has been found in the pallasite Omolon, testifies to the ease of contamination of meteorites by a terrestrial organic material. EDS study reveals that the pollen has selectively adsorbed only microcrystals of feldspar, orthoclase and albite, and may be classified as a biological separator of minerals.

Conclusion: A surface of mineral grains from the pallasites displays a lot of sculptures, which result, essentially, from a slow cooling of the pallasite parent body and a following shock metamorphism. The secondary sculptures are more widespread than the primary one's, corresponding to those in chondrites. A variety of primary sculptures is narrower in the pallasites than in unequilibrated chondrites.

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CARBONACEOUS XENOLITHS FROM THE KRYMKA CHONDRITE AS PROBABLE COMETARY MATERIAL

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Campins and Swindle [1], using results from the Halley missions [2], discussed the expected characteristics of cometary meteoritic material. They suggested that among any known type of meteoritic material, carbonaceous xenoliths from the Krymka LL3.1 chondrite [3–6] are the most probable candidates to be of cometary origin.

Here we present the results of mineralogical, chemical, and isotopic studies of two Krymka carbonaceous xenoliths. One of them (K1) is known from a previous investigation [5, 6], and the second one (K3) is new. Occurrences of organic material and graphite microcrystals within xenolith K1 allowed us to propose a metamorphic origin of graphite from organic compounds [6].

The xenoliths resemble each other and correspond chemically to C chondrites. They differ, however, from the Krymka host by low totals of the bulk composition, higher Fe content, higher FeO/(FeO + MgO) ratio, higher S and Ag contents, lower abundance of chondrules, and occurrence of carbon in three different forms: graphite, carbon-rich material, and organic compounds.

The structural order of graphite crystals is directly correlated to the grade of metamorphism of carbonaceous material [7]. TEM studies show that graphite from K1 is well-crystallized. These data strongly support the conclusion from the mineralogy on the metamorphic nature of graphite [6]. The presence of molten troilite, the moderately high dislocation density in olivine, the coexistence of ortho- and clinoenstatite lamellae, and the superstructure of FeS indicate shock metamorphism, which had promoted [7] the metamorphic processing of the carbonaceous material.

O-isotopic data attest that most of the xenolitic silicates have the same isotopic composition ($\delta^{18}O \ge 5.9\%$; $\delta^{17}O \ge 3.8\%$). Except a unique amoeboid olivine inclusion ($\delta^{18}O \le -19.4\%$; $\delta^{17}O \le -23.6\%$), the main textural components of K1 are genetically interrelated and represent different stages of transformation of isotopically identical silicate material. K1 is very similar to the Krymka graphite-containing fragments [8, 9] in the mineralogy, chemistry, and the C-isotopic composition of its graphite ($\delta^{13}C \approx 0\%$). Although, it differs by a lower grade of metamorphism.

Most features of the studied xenoliths are in a good agreement with expected characteristics of cometary material [1]. Some distinctions may be explained by low metamorphic processing probably due to lithification of the xenoliths or shock metamorphism of the Krymka parent body. We propose that carbonaceous materials of the xenoliths accreted in an environment which was rich in organic compounds, i.e., in highly volatile elements. These results testify that the precursors of the studied objects might be genetically related to cometary material.

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HIGHLY POROUS AGGREGATES WITHIN THE SARATOV (L4) AND GALKIV (H4) CHONDRITES

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Three highly porous (HP) silicate fragments were found in the chondrite Saratov [1, 2]. An additional search showed that HP aggregates are common in the unequilibrated chondrites Saratov and Galkiv [3].

Here we present mineralogical data for two HP aggregates from Galkiv and four from Saratov. They are arranged within a matrix of the chondrites and vary in size from 0.4×0.7 mm to 3.0×4.3 mm. One of them is surrounded by a fine-grained, dense silicate rim. The rest show diffusional boundaries with the matrix. Mineralogically, the aggregates resemble each other and differ from a host of the chondrites by unusually high porosity (up to 65 vol%), uniform fine-grained texture, and a very low content of metal and troilite. In contrast to the HP aggregates from Galkiv, those in Saratov contain rare porphyritic chondrules and their clasts.

A scanning electron microscopy study displays that HP material is composed of a friable aggregate of rounded and anhedral silicate grains and euhedral crystals of submicron and micron sizes.

The major mineral phases for HP aggregates from both Galkiv and Saratov are olivine (Fa17.1-18.2 and Fa22.2-26.3, respectively) and Ca-poor pyroxene (Fs_{14.5-17.6}En_{77.8-83.4}Wo_{0.4-7.7} and Fs_{6.8-22.8}En_{76.8-92.9}Wo_{0.2-2.8}, respectively). The minor are Ca-rich pyroxene (Fs4.9En47.9Wo47.2 and Fs4.3-17.6En53.0-73.2Wo9.3-40.7, respectively) and feldspar (Ab43.2An56.3Or0.5 from Saratov). Rare phases are Fe-Ni-metal (33.3-44.6 wt% Ni and 0.15-0.34 Co in taenite and 3.82-5.3 wt% Ni and 0.74-1.15 Co in kamacite from Saratov), troilite, merrilite (45.8-46.9 wt% CaO; 42.6-48.4 P2O5; 3.42-3.62 MgO; 2.49-2.81 Na₂O; 0.54-1.61 FeO and 45.9-47.0 wt% CaO; 42.5-45.4 P₂O₅; 3.22-4.39 MgO; 2.56-2.74 Na₂O; 1.21-1.4 FeO, respectively), and chromite (59.0-61.8 wt% Cr2O3; 27.7-28.4 FeO; 5.35-5.43 Al2O3; 2.55-2.76 MgO; 1.1-1.54 TiO₂; 0.85-0.89 V₂O₃ and 59.4-61.9 wt% Cr₂O₃; 29.1-30.3 FeO; 3.53-3.99 Al₂O₃; 1.36-1.6 MgO; 0.89-1.85 TiO₂; 0.5-0.66 V₂O₃, respectively). Single spinel grains and copper inclusions in taenite grain were found in the largest HP aggregate from Saratov. On the whole, a compositional variation of the minerals within HP aggregates is identical with those within the chondrites host.

The HP aggregates and the chondrites host are characterized by the same grade of metamorphic processing, which testifies to their metamorphism in situ during or after accretion of the chondrites parent body.

Conclusions: The porosity, structure, and mineralogical composition of the HP aggregates are similar to those of some particles of interplanetary dust [4] and, to a lesser extent, to the lunar breccias and agglutinates [5]. This allows us to suppose a similar accretional mechanism for friable aggregates from the chondrites and interplanetary dust. Some of the HP aggregates collected a fine-grained dust that resulted in formation of a dense silicate rim. The HP aggregates, as separate highly porous bodies or their fragments, were subsequently mixed together with typical unequilibrated ordinary chondrite material. All these constituents accreted to form the meteoritic parent body.

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REE GEOCHEMISTRY OF PALLASITE PHOSPHATES

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Introduction: Previous studies revealed that pallasite phosphates exhibit distinct REE patterns with highly variable abundances [1, 2]. Interpretations for this diversity include REE equilibrium partitioning between olivine and phosphates under subsolidus conditions, crystallization of phosphates from interstitial residue melts, and the late-stage products during crystallization [1]. Here, we report an ion probe study of REE distributions in phosphates from Albin, Eagle Station, Imilac, and Springwater with a goal to better understand the process(es) that led to the formation of pallasites.

Results: In Albin, we found four whitlockite grains, ranging from 100 to 500 μ m. One whitlockite grain and eight stanfieldite grains were found in Eagle Station; they are generally small (30 to 100 μ m) and in irregular shapes. Three whitlockite grains (200 to 500 μ m) found in Imilac are extensively fractured with numerous iron oxide veins. Springwater farringtonite is relatively large (up to 1.5 mm). The round boundary of farringtonite grains indicates that this mineral was initially present as molten droplets. Phosphates tend to occur interstitially between olivine and metal.

The four whitlockite grains in Albin have essentially the same REE pattern that is highly enriched in Sm, Eu, and HREEs (~50 × CI), but relatively depleted in La to Nd (~1 × CI). In Eagle Station, the whitlockite grain has a flat LREE with depleted abundances (~0.1 × CI), a large positive Eu anomaly, and a sharp increase from Gd (0.1 × CI) to Lu (70 × CI). The other five stanfieldite grains analyzed have a similar REE pattern to that of whitlockite in Imilac is enriched in HREEs (10 to 80 × CI) and relatively depleted in LREEs (0.1 to 1 × CI). Springwater farringtonite grains have relatively low REEs (0.001 to 1 × CI) with a highly fractionated HREE-enriched pattern (CI-normalized Lu/La ~100). Although the phosphates among the pallasites studied display distinct REE abundances and patterns, they tend to have the same REE pattern within a given meteorite. REEs are homogeneous in a given grain but vary significantly from grain to grain by a factor of up to 100.

Discussions: Pallasite olivine commonly displays minor element zoning (e.g., Ca, Ti) [3]. This indicates that minor elements such as Ca did not fully equilibrate between olivine and phosphates under subsolidus conditions. REEs are expected to have much lower diffusion rates than Ca in olivine. Thus, equilibrium partitioning of REEs between olivine and phosphates under these conditions may be ruled out to account for the HREEenriched pattern observed in pallasite phosphates. It is also hard to see any igneous processes which could have fractionated REEs in the phosphates.

The metallic phase of pallasites is chemically related to IIIAB irons. That pallasites might have formed through mixing of IIIAB-like molten metal with an olivine layer has even been suggested [4]. IIIAB irons usually contain small amounts of phosphates [5]. Therefore, it is possible that pallasite phosphates were incorporated into pallasites from IIIAB-like molten metal during mixing with an olivine layer. Once mixed, phosphate grains remained isolated from one another during the subsequent rapid cooling period. Each phosphate grain would have distinctive REE abundances and patterns which reflect characteristics of a previous history.

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GIS SUPPORTED INTERPRETATION OF HIGH RESOLUTION REMOTE SENSING DATA OF THE HAUGHTON IMPACT STRUCTURE, DEVON ISLAND, NUNAVUT, CANADA

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Since 1936 [1], remote sensing data were used to clear up impactstructures.

The Haughton impact structure is situated on Devon Island in the Canadian arctic archipelago, latitude 75°22'N, longitude 89°041'W (Fig. l). This is the northernmost impact structure of our planet. The Haughton dome was discovered in 1975 by geological mapping and lies in a cold arid environment, which is very similarity to the conditions on Mars (compare "Haughton Mars Project"). During the geological mapping, carried out between 1973–1978, nearly no remote sensing methods were used [2].

Since October 2002, a cloudless high resolution Landsat 7 ETM scene covering the Haughton dome was provided for scientific use [3]. In the context of processing these data, the following problem areas can be solved [4]:

- Verification/ascertainment of the assumed diameter of the impact structure,
- · Specification of the structural elements (Photo lineaments), and
- · Influence of the impact to regional morphology, dehydration net etc.



Fig. 1. The Haughton impact structure.

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COMPOSITION OF THE LATE INFLUX OF THE EARTH

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Introduction: Many authors explain the relative "high" abundances of HSE and their broadly chondritic proportions in the Earth's mantle (PUM) by the addition of a late chondritic veneer after core formation. Many recent studies have documented significant regional variations in absolute HSE abundances and interelement ratios in mantle samples. Such variations may have been caused by complex geochemical processes such as partial melting, melt percolation, and aqueous metasomatism in the subcontinental lithosphere [1]. For a better characterisation of the late veneer component(s) of the Earth, I review here selected neutron activation data from our own studies for orogenic spinel lherzolites [2, 3] that have suffered only slight melt depletion (Ca/Si >0.086) and compare this data with selected data from the literature [4–6].

Results: Abundances of HSE in PUM sampled by lherzolites from our studies [2, 3] are as follows: 0.16 ± 0.05 ng/g Re, 2.69 ± 0.38 ng/g Os, 2.80 ± 0.34 ng/g Ir, 5.60 ± 0.61 ng/g Ru, 1.20 ± 0.27 ng/g Rh, 7.33 ± 1.55 ng/g Pt, 5.68 ± 1.52 ng/g Pd, and 3.06 ± 1.60 ng/g Au [7].



In a large number of "fertile" samples [2–6], the abundance distribution of the HSE is remarkably uniform with slightly increasing abundances with decreasing refractory character of the elements from Re to Pd, except Pt (Fig. 1).



Fig. 2.

In Fig. 2, mantle HSE abundances (this work) are plotted normalized to Ir and chondrites. The HSE systematics show that the late veneer closely resembles E chondrites or LL chondrites [7, 8].

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PETROCHEMICAL COMPARISON OF THE ANCIENT AND RECENT (SNC) MARTIAN CRUST

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Introduction: The chemical composition of the martian crust, and even of Mars itself, has been inferred from SNC meteorites. However, with one exception, SNCs sample young volcanic centers that are not necessarily chemical proxies for the thick, ancient crust. Until Mars Odyssey GRS data are available, the only compositional information for the Noachian crust is Mars Pathfinder APXS analyses or chemical data calculated from deconvolutions of spectra from Mars Global Surveyor TES. In making this comparison, we will distinguish TES surface types 1 and 2 (ST1, ST2), previously interpreted as basalt and either andesite [1] or partly weathered basalt [2].

Method: By combining the compositions of spectral endmembers in proportion to their modes, we have estimated ST1 and ST2 chemical compositions from TES data [3]. The fitting was constrained to the 1301 to 233 cm⁻¹ region. Compositions were calculated on a water and CO_2 -free basis to facilitate comparisons.

Results: We have classified ST1 and ST2 using two widely used schemes for volcanic rocks. On a wt% alkalis versus silica diagram [4], ST1 plots as basaltic andesite and ST2 as andesite (near the Pathfinder rock). Using the molecular normative plagioclase composition versus color index classification [5], both ST1 and ST2 plot within the basalt field. However, oxidation of Fe can shift the ST2 composition closer to andesite. Both types of ancient crust are clearly resolvable from basaltic shergottites and nakhlites.

Both ST1 and ST2 plot within the calc-alkaline field on a FeO*/MgO versus silica diagram. The only geochemically similar terrestrial rocks form by hydrous melting and fractional crystallization in subduction zones. If these compositions represent igneous rocks, they imply a much wetter martian interior than previously envisioned. SNCs plot within the tholeiite field, as appropriate for dry magmas. The ST1 and ST2 compositions appear to have high Al contents (more like the Earth's crust than SNCs), although the uncertainties preclude a firm conclusion.

Alternatively, both ST1 and ST2 compositions could be partly weathered volcanic rocks, as suggested by their positions on dia-grams used to understand chemical weathering of basalts [6]. In this case, weathering must produce silica enrichment, as well as depletion in soluble elements. This scenario is more consistent with spectroscopic properties and the ~2 wt% water in alpha-mode APXS analyses [7] of Pathfinder rocks and could account for the high Al. Weathering is also consistent with the inferred sedimentary depositional history of the ST2 terrain in the northern plains.

If ST1 and ST2 are igneous, the chemical composition of the ancient martian crust is distinct from SNCs, which must represent remelting of a relatively dry mantle source that was previously depleted by formation of the early crust. If these compositions represent weathered materials, we do not know how their volcanic protoliths compare to SNCs.

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ANHYDROUS SILICATE EVOLUTION: HIERARCHICAL DUST ACCRETION AND PLANETESIMAL PROCESSING

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Introduction: The grain sizes and compositions of constituents in aggregate IDPs, including the pure-silicate principal components (PCs), and the dimensions and ablation chemistry of cometary meteoroids define a continuum of evolution of non-chondritic dusts during hierarchical dust accretion and recycling in planetesimals in the early solar system. I will assume that: 1) presolar ferromagnesiosilica PCs were the original dusts [1], and 2) Fe(Ni)-sulfides formed when Fe(Ni) oxides reacted with circumstellar H_2S gas.

Condensation and Initial Accretion: Constraints from vapor phase condensation experiments indicate that pure-silicate PCs in the matrix of aggregates IDPs are amorphous, non-stoichiometric, metastable silicates with well-defined compositions. First, the condensed solids, 'MgSiO;' 'FeSiO;' silica-bearing Fe- and Mg-oxides; and pure SiO₂, MgO, and Fe-oxides formed ~100 to 500 nm-sized Mg-rich, ferromagnesiosilica agglomerates, i.e., the Si-rich smectite dehydroxylate PCs. Next, these PCs and condensed silica-bearing Fe-oxides and pure Fe-oxides agglomerated into compact amorphous ferromagnesiosilica dust. These Fe-rich, Fe/Fe + Mg) >0.35, serpentine-dehydroxylate PCs required external energy to facilitate the assimilation of pure-Fe-oxide nanocrystals [1]. Speaking of only carbon-free dusts, both ferromagnesiosilica PCs were the materials from which all crystalline dusts in aggregate IDPs evolved in both chemical complexity and grain size.

Thermal Processing: Upon heat treatment, the amorphous PCs will initially yield crystalline olivine and pyroxene plus an amorphous phase [2]. The amorphous phase in Mg-rich PCs is silica with minor $Ca \pm Al \pm Na \pm K$. These nm-sized, crystalline or amorphous grains are unstable with a strong tendency towards thermodynamic equilibrium. Adjustments among identical silicates and oxides will be relatively easy, e.g., formation of a micron-sized olivine crystal from a cluster of nm-sized olivines. Similar growth of amorphous, minor element-bearing dusts would yield, for example, micronsized, crystalline or amorphous aluminosilicates. Thermal decomposition of such amorphous dusts produced the first mineral assemblages of plagioclase plus Mg, Fe-olivine and pyroxene and others depending on the original minor elements. At this stage of silicate evolution, the first "new" minerals were produced.

A Role of Planetesimals: Formation of larger, up to mm-sized "morecomplex" silicates, e.g., Ca, Al-bearing Mg, Fe-silicates (Ti-diopside), required thermal processing of increasingly crystalline precursors in an environment that facilitated diffusion-controlled processes. Such conditions existed in planetesimals that either became part of rubble piles or, in collisions, introduced their in situ evolved minerals among the other accreting solar nebula dusts.

Predictions: For example, comet nuclei will contain micron- to mmsized forsterite grains delineating hierarchical accretion as well as nm-sized forsterite annealed in amorphous dust during perihelion. Comet nuclei have a wide variety of anhydrous silicates, including those identified around young stellar objects [3], with a correlation between chemical complexity and increasing grain size.

Conclusions: The high "chemical energy" of the condensed dusts inherited by the pure-silicate PCs was the driving force behind the initial silicate dust evolution. The sizes and compositions of the anhydrous silicates in comet nuclei record the onset of mineralogical activity in the solar system that was lost in the meteorites.

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MODELLING OF CRYSTALS MODIFICATION AND CARBON DIFFUSION IN OLIVINES INDUCED BY ION BOMBARDMENT

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Summary: The radiation-enhanced diffusivity of carbon in olivine crystals and the data on desorption of atoms of major elements from the olivine at deuteron doses much lower than the amorphization threshold were obtained by in situ Ion Beam Analysis. The depth distributions of displaced O, Si, Mg, and Fe atoms in the olivine exposed to deuterons, as well as Ar and He ions, was numerically simulated. The effect of the alpha radiation of natural radionuclides on carbon migration in olivine of meteorites was examined in detail by means of numerical modeling as well. The direction of chemical fractionating of interplanetary dust particles (silicates) under solar wind is considered.

Analytical Methods: A Van de Graaf accelerator was applied to study olivine crystal modification under the 1.43 MeV deuteron beam. The RBS method was used to measure the major elements in the samples. Studies of radiation-enhanced diffusion were also carried out by the nuclear reaction ${}^{12}C(d,p){}^{13}C$ at cyclic irradiation by deuterons [1]. The TRIM-98 software package based on the Monte-Carlo method [2] was used for numerical modeling.

Results and Discussion: A partial destruction of olivine in the surface layer of 100–200 nm at a current density of 5–10 μ A/cm² and a dose of 3–8 $\times 10^{16}$ cm² (solar wind fluence) was discovered. This process, caused by high ionization and desorption of Mg (Fig. 1) and Fe atoms, includes the stages of Schottky defect generation, drift of metal ions to the surface, their neutralization by electrons, and evaporation from the surface. Simultaneously, a fraction of hydrogen from adsorbed hydrocarbons, and deuterium participating in the process, compensates the SiO_4^{4-} group charge. The loss of Mg has been observed earlier by [3] with 20 keV proton irradiation of olivine crystals of Allende meteorite. The main process responsible for accelerating the migration of elements in crystals is the generation of vacancies. Our results confirm the existence of charged space dust microcrystals (in the case of uncompensated charge) in the circumstellar space, as well as their high catalytic activity during the formation of molecules from volatile element atoms (H, C, N, O). The doses corresponding to the amorphization, as well as the desorption (sputtering) coefficients of atoms, were calculated depending on the energy. The desorption is not characterized by selectivity in the case of argon and helium ions and takes place at doses exceeding the amorphization threshold.



Fig. 1. Depth profiles of atomic ratio Mg/O in olivine before (1) and after (2) deuteron bombardment.

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LATE STAGE HIGH TEMPERATURE PROCESSING OF CA, FE-RICH RIMS AROUND ALLENDE DARK IN-CLUSIONS DI

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Introduction: Secondary Ca, Fe-rich minerals and aggregates (CFA) are widespread in the Allende meteorite. About 90 vol% of the total CaO content of the matrix is concentrated in CFA. The conditions and environment (solar nebula or asteroidal) of this alteration is still a matter of controversial scientific discussion [see summaries in 1, 2]. Here we present novel, compelling evidence of late-stage high temperature processes recorded in Ca, Fe-rich rims around Allende dark inclusions. A detailed scanning (SEM) and transmission electron microscopical (TEM) work on dark inclusions 3529 and IV-1 were performed.

Results: The rim shows a shell like structure divided in three different layers. The outermost rim layers are commonly intergrown with the matrix olivines and chondrule fragments of the Allende host, indicating formation in situ after consolidation as a rock. In the central portion of the rim around dark inclusion IV-1, we found several wollastonite polytypes (a polysynthetically-twinned polytype of pseudowollastonite, wollastonite-2M, and wollastonite-IT) and an intergrowth of hedenbergite-PM—augite. These findings require an unexpected high temperature above 1000°C and a cooling rate of >10°C/ hr during or after formation of the central part of the rim. The close relation, within a few micrometers, of three different polymorphs of wollastonite tends to a very localized process or incomplete retrograde transformation between the wollastonite polytypes. The innermost rim again shows the same intergrowth features like the outermost rim but with the dark inclusion matrix and to a lower extend. High temperature features are absent in the outer, the innermost rims, and the CFA of the inclusion.

Conclusion: We infer that the dark inclusions experienced a complex alteration history before and after incorporation into the host Allende. The early stage of the alteration took place in an asteroidal setting but not in the current location of the dark inclusions. During this stage, the first generation of Ca, Fe-rich minerals in veins, aggregates, and around nodules are formed. The next stage of alteration, which occurred during or after fragmentation of the DI parent material, resulted in mobilization of Ca and its redeposition as Ca-rich rims around the dark inclusions, forming the central part of the rim. The rim and probably also the CFA of the Allende matrix described by [2] were partially heated, most likely due to shear heating during several impact events, similar to a recent model on Mokoia DI [3]. We assume that shock heating was most effective at locations with high porosity contrast. During this short stage of heating and the subsequent cooling history, the outermost and the smaller, inner Ca, Fe-pyroxene layer of the rims grew in situ in its present position. Ca mobilization will also explain the low Ca contents of pyroxenes found in CFA of the Allende matrix. This model is in good agreement with recent data on REE pattern [4] and oxygen isotopic compositions [5].

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THE METEORITIC COMPONENT ON THE SURFACE OF MARS: IMPLICATIONS FOR ORGANIC AND INORGANIC GEOCHEMISTRY

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Introduction: The mixing relationships, the meteoritic contribution in particular, in the martian soil were determined by means of least squares analysis of chemical data from APXS aboard MarsPathfinder (MPF) [1] and XRF-Viking [2] measurements. The soil composition may be represented as a mixture of the MPF soil free rock (SFR), primitive cosmic material (CI-chondrite), and physical weathering products of MPF andesites (PWP). Based on the component analysis, the composition of the Global Dust Unit and constraints on trace element concentrations as well as the amount of putative organic matter are inferred.

Method and Results: In our least squares (LS) analysis, 13 major elements were taken into account. The SFR and CI-chondrite compositions were taken from [1] and [3], respectively. Prior to LS analysis, a CIPW normative calculation was done on the SFR chemistry. In analogy to Antarctic weathering scenarios, minerals with high susceptibility to physical disintegration were assigned to a fraction of detritus PWP according to their normative ratios in parent andesites. To account for the uncertainties inherent in analytical data from Mars, the individual element concentrations were weighted accordingly. The convergence of the regression lines to a single point indicate the existence and the composition of a Global Dust Unit (GDU). GDU material appears to be intimately admixed to MPF surface soils (~40 wt% CI) and also to Viking deep soil samples (~25 wt% CI). This is consistent with data in [4] and [5]. Some GDU material also appears to adhere to MPF rock samples.

Implications: Our analysis allows us to estimate soil formation rates and trace element as well as organic matter abundances on Mars. According to the inferred meteoritic contribution, 1.4 wt% C is missing in the martian soil. Similarly, 0.4 wt% Ni should be present in surface soils. This is more than APXS data would suggest. The discrepancy in Ni concentrations might be due to secondary fluorescence effects. Alternative in situ analytical techniques, such as Laser-induced Plasma Spectroscopy (LIPS), may help to resolve this problem.



Fig. 1.

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THE H4/5 THUATHE METEORITE FALL OF 21 JULY 2002, LESOTHO: HISTORY OF THE FALL, STREWN FIELD DETERMINATION, AND MINERALOGICAL AND GEOCHEMICAL CHARACTERIZATION

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Synopsis: We report on a new meteorite fall on 21 July 2002 over the Thuathe Plateau of northwestern Lesotho in southern Africa. The strewnfield has been mapped in great detail. Mineralogical and geochemical characterization of this meteorite is consistent with a classification of H4/5, S2/3. The name "Thuathe" has been accepted for this new fall.

The Thuathe meteorite: A meteorite traveling east to west exploded above Lesotho in southern Africa and produced an elliptical strewn field of 7.4×1.9 km over the western part of the Thuathe Plateau approximately 10 km east of Maseru, the capital of Lesotho. The oral history of this fall was researched in great detail. To date, more than 800 stones of masses between a few grams and 2.4 kg have been recorded, with several hundred others suspected. The total mass of this fall is estimated in excess of 35 kg. Our mineralogical analysis indicates that this meteorite is composed of, at the stone-size scale, chondritic material with either brecciated or unbrecciated texture. Sub-mm dark shock veining is abundantly observed and cuts across both phases-the massive leucocratic material and the slightly darker grey breccia matrix. On average, 20 vol% metal occurs, but in rare parts of the meteorite, this metal can reach >50 vol%. Fe/Ni metal occurs as kamacite with, on average, 6.03 wt% Ni (1σ standard deviation = 0.55 wt%) and 0.62 wt% Co (1σ standard deviation = 0.04 wt%, 11 analyses). This Co abundance in Thuathe kamacite is somewhat anomalous, as H group chondrites normally show 0.44-0.51wt% Co [1, 2]. Taenite has also been observed. Sulfide is characterized by negligible Ni contents and has an average composition of 62.2 wt% Fe, 36 wt% S, 0.52 wt% Pb, and 0.11 wt% Co (1σ standard deviation are 0.28, 0.23, 0.39, and 0.01 wt%, respectively). Electron microprobe analyses of olivine indicate an average forsterite content of 82.6 mole% (1 σ standard deviation = 0.79 mole%) and of orthopyroxene, an average composition of Wo_{1.04}En_{83.8}Fs_{15.7} (1 σ standard deviation are 0.32, 1.0, and 0.9 mole%, respectively). This high degree of mineral equilibration, together with the observation that chondrules are distinct, but not abundant, suggests that this new meteorite should be classified as H4/5. Along with undulatory extinction in both olivine and pyroxene, irregular fracturing is strongly developed in many mineral fragments, and many fragments are internally brecciated. These features, together with the relative abundance of shock veins, places the Thuathe meteorite into the S2/3 shock classification of [3]. Chemical analysis (XRF and INAA) is in progress and results will be presented at the conference.

Thuathe is, to our knowledge, the first meteorite fall recorded and evaluated in Lesotho. The diligent and comprehensive study of its fall and distribution in a reasonably densely populated rural area, involving numerous villagers and particularly school children, has resulted in a phenomenal growth of knowledge about meteorites and awareness of the meteorite fall phenomenon in the wider region of Lesotho and parts of South Africa.

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FIELD AND LABORATORY STUDIES ON SHATTER CONES IN THE VREDEFORT DOME, SOUTH AFRICA, AND THEIR GENESIS F. Wieland and W. U. Reimold. Impact Cratering Research Group, School of Geosciences, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa. E-mail: wielanf@scinece.pg.wits.ac.za; reimoldw@geosciences.wits.ac.za

The orientation of shatter cones has played an important role in the debate about the formation of this impact-related deformation phenomenon. New orientation data derived from samples collected from sites throughout the collar of the Vredefort dome and in situ measurements of striations on shatter cone surfaces have been obtained. The orientation of shatter cone apeces in the Vredefort dome was described in detail by [1] as consistently outward or downward (with respect to the center of the dome). Considering, that the collar strata have been dramatically rotated, restoration of the bedding to their position prior to the impact would change the orientation of apeces to an upward and inward direction, respectively, i.e., toward the crater center. Although this study confirms that the most prominent oriention of shatter cone apeces is indeed normal to the strike to the bedding (and therefore parallel to the dip direction of the bedding plane), two other trends have been observed. One set is parallel to the strike of the bedding (and normal to the dip direction of the bedding plane), not changing the apex orientation when rotating the bedding back to the presumed pre-impact position, and a third trend is at angles between 30 and 60° to the strike of the bedding and the bedding surface. Note that shatter cone apeces may point in opposite directions (i.e., up and down) within each set of orientation. Observation on striation geometries confirm their radial to subparallel character, as discussed by [2]. Sagy et al. [3] defined striations to form distinctive ridges with a certain angle between their flanks or margins. They suggested a relationship between increasing angles and the distance of the sample location from the crater center. We wish to demonstrate that contrary to Sagy et al.'s thinking, these ridge-like structures are formed not by a single striation, but by a whole bunch of striations, lending themselves a "small shatter cone-like"" appearance. In situ measurements on striations, following the concept of [3], from samples from the collar of the Vredefort dome do not confirm their relationship between angle and distance from crater center. The average width of these angles varies from cone to cone, not providing consistent results for a single cone specimen, and certainly not for a number of samples from a given location (angles measured on the same sample may vary between 15 and 47°.

Conclusion: The orientation of shatter cones is more diverse than described in previous studies. A rotation of the strata back to their pre-impact position does not satisfy the variety of shatter cone orientations. On the premise that the cone apeces should always point into the direction of the energy (shock wave) source, our observations imply a scattering or reflection of the shock wave on discontinuities. These could include inhomogeneities in the rock (such as textural or structural heterogeneities), change in lithological character (e.g., degree of recrystallization), and mineral content. The hypothesis of a relationship between the width of angles of striation ridges with distance of the sample location from the center of the impact structure is not supported by this study.

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REVISITING THE BRAZILIAN HEXAHEDRITES: ANGRA DOS REIS (IRON), PIRAPORA, AND PATOS DE MINAS

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The three meteorites Angra dos Reis (iron), Pirapora, and Patos de Minas show a typical hexahedrite (IIA) structure with Neumann bands.

The history of Angra dos Reis (iron) remains obscure. It is known that a mass of 6175 g was shipped out of Brazil in 1888 as a donation to Pope Leo XIII to form part of an exposition in the Vatican. The fall date of 1869 was incorrectly added to the label "Angra dos Reis, Brasile-Siderite." This is the date of fall of the well-known achondrite, Angra dos Reis [1–3]. The Pirapora meteorite was described by [4, 5] and little information is known about the circumstances of discovery. It was apparently found in the vicinity of the town of Pirapora at an unknown date. According to [3], the Patos de Minas meteorite was an old fall which was probably discovered in 1925 [6].

There are several uncertainties about the origin of these three meteorites. Angra dos Reis is a normal hexahedrite with shock-melted troilite aggregates. While it seems to be different from Patos de Minas and other South American hexahedrites, there are certain close similarities to Pirapora. A detailed analysis of these hexahedrites is in progress. Angra dos Reis should be compared to Pirapora to establish whether or not the two small irons are a paired fall, and Patos de Minas should also be compared to Pirapora to exclude this possibility.

The purpose of this communication is to review these uncertainties by making use of the improvements in instrumentation and data treatments. Different techniques are being used to analyse the samples: electron microprobe, optical and scanning electron microscopy, Mössbauer spectroscopy, and magnetization measurements.

Acknowledgments: We want to express our gratitude to Guy Consolmagno for the Angra dos Reis (iron) sample.

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COSMIC-RAY PRODUCTION RATES OF KR ISOTOPES BASED ON CHLORINE-36/ARGON-36 AGES

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Introduction: The ⁸¹Kr-Kr method of cosmic-ray exposure dating [1] allows the determination of shielding-corrected cosmic-ray exposure ages based on a single Kr analysis. The basic equations, which correlate the ⁸¹Kr/⁸³Kr ratio to measured ⁷⁸Kr-⁸⁰Kr-⁸³Kr concentrations, were deduced from Apollo 12 lunar samples. They are also widely used to date meteorites, which may have widely different concentrations of the major target elements Rb, Sr, Y, Zr, and Nb. However, so far, the reliability of these equations has been tested on two meteorites only [2]. We therefore analysed He, Ne, Ar, Kr, and Xe in 9 H chondrites which were recently investigated for their ³⁶Cl-³⁶Ar exposure ages and light noble gas production rates. We also analysed 7 samples from the very large L4 chondrite Gold Basin. An analysis of the well studied L/LL5 chondrite Knyahinya proved the reliability of our method.

Results: Two aliquots of the Gold Basin meteorite yield ⁸¹Kr-Kr ages in good agreement. In addition, the ⁸¹Kr-Kr age of Knya-hinya of 41 ± 4 Myrs is in very good agreement with literature data. This confirms that the method used here produces reliable and reproducible ⁸¹Kr-Kr cosmic-ray exposure ages. A comparison of the exposure ages deduced via ³⁶Cl-³⁶Ar [3], with the ⁸¹Kr-Kr ages determined here, is shown in Fig. 1.



Fig. 1. Comparison of cosmic-ray exposure ages determined using ${}^{36}\text{Cl}{}^{-36}\text{Ar}$ with those obtained by the ${}^{81}\text{Kr}{}$ -Kr method.

The ⁸¹Kr-Kr exposure age for one meteorite (Uberaba) is about 4 times higher than its ³⁶Cl-³⁶Ar age. At present, we cannot give an explanation for this discrepancy. For the remaining 8 H chondrites, five show ⁸¹Kr-Kr and ³⁶Cl-³⁶Ar ages that are in agreement with each other. The ⁸¹Kr-Kr ages are higher by 3 for two meteorites and by 5 for one meteorite (Cereseto). Considering the data, we believe that the fact that 8 of the 9 ⁸¹Kr-Kr ages are higher than their ³⁶Cl-³⁶Ar ages is significant. We will therefore measure the concentrations of Rb, Sr, y, Zr, and Nb in aliquots of the samples and search for correlations of the Kr isotopic ratios with the relative target element abundances, e.g., Rb/Sr.

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PHASE FUNCTIONS OF PRE-FRACTAL CLASTERS MODELING REGOLITH AND COMETARY DUST PARTICLES

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Introduction: We develop an approach to calculate, in geometric optics approximation, phase functions of fractally arranged particles. The approach is based on the scale invariance principle of classical photometry [1]. The function depends on 3 parameters: the number of the hierarchical levels of the pre-fractal μ , the characteristic distance between particles on the highest hierarchical level, and the albedo ω of the cluster monomers.

Photometric Function of Hierarchically Arranged Objects: Let us consider a three-dimensional object, whose physical extent, on average, is equivalent to a sphere of radius R. This object consists of a succession of self-similar objects of smaller sizes, with the mean distance between particles equal to L (see Fig. 1).





We calculate the phase function of such an object, or pre-fractal cluster of monomers, as it is suggested in [1], extending the approach to double scattering. Results are presented in Fig. 2, where $\tau = R/L$, ω is albedo of the monomer, and $\tau = \mu\tau$. Solid and dashed curves correspond to single and double scattering.



Fig. 2.

Conclusion: Thus, we resolve the problem of finding the phase function of a pre-fractal object in double-scattering geometric optics approximation. The function can be applied to analysis of observational data for particulate objects, including planetary regolith and cometary dust aggregates.

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A MODEL FOR BIMODAL NEGATIVE POLARIZATION OF THE REGOLITHS OF JUPITER'S SATELLITES

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Introduction: Atmosphereless celestial bodies exhibit negative branches of polarization (NPBs) of light scattered at small phase angles. Usually, an NPB has a parabolic shape, but for some cases, e.g., Jupiter's moon Europa, it is bimodal (pluses in Fig. 1) [1]. This feature has also been found with laboratory measurements in [2]. The bimodal shape of NPB has been shown to be caused by albedo spottiness of the light scattering surface. We consider here another mechanism. The NPB of regoliths is believed to be due to superposition of single and multiple light scattering [3, 4]. So, if NPBs of single and multiple scattering have different widths, then one can anticipate the total NPB to be bimodal. Here, we verify this idea with our computer model of light scattering by particulate media.

Model: We simulate regolith-like surfaces with semi-infinite random particulate media having the macroscopically flat boundary. To simulate single scattering, we use the data for irregular particles of the Locon volcanic ash [5]. The size parameter of the particles is $x \approx 90$ ($x = 2\pi t/\lambda$, where r is the radius of the particles and λ is the wavelength). The model uses a ray-tracing method accounting for electromagnetic phases of direct and time-reversal trajectories [3, 4]. The packing density of the model medium studied is 0.1. Our method takes into account both the shadow-hiding effect and coherent enhancement of backscattering.

Results and Discussion: Dark points in Fig. 1 present NPB of the "average" particle of the Locon volcanic ash [5]. Note that here we smoothed





experimental data [5]. The solid line in Fig. 1 presents results of our simulation for the model medium composed of irregular particles of the Locon volcanic ash. As one can see, our calculations qualitatively reproduce bimodality of Europa's NPB. Thus, we can conclude that if single particles of a medium possess an NPB and multiple scattering in the medium is strong, then the shape of the resulting NPB can be bimodal. An additional possibility is if the single particles have no NPB of their own, but NPBs of low and high orders of scattering are of strongly different widths, then the resulting NPB shape can be bimodal, too.

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THE LARGEST SPLASH FROM GEORGIA TEKTITE

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The first Georgia tektite was found by Dewey Horne near DuBois, Georgia in 1938. The specimen was identified by the Smithsonian as a "probable tektite." Until 1959, about 12 tektites had been found near Dodge County, Georgia [1].

In the 1960s, William Hambrick of Eastman, Georgia found a beautiful 36 g tektite that was shaped like a silver dollar. It was the largest tektite found, and was donated to the Smithsonian Institution where it is on display today.

In October 1975, I was informed that a very large tektite had been found near Plainfield, Georgia. I immediately made a trip to Dodge County to authenticate this new specimen. It was a thrill to view this new world record tektite. It was shaped like the typical "Apollo Module," blunt front ablative end and with the back somewhat resembling a sombrero. It has the dimensions of $63 \times 48 \times 31$ mm and its weight is approximately 70.5 g. The color is the typical drab olive green, and there are no visible inclusions or bubbles. Usually, there are small chips caused by farm implements, but with one tiny exception, the deep ridges are in pristine condition. The soil that the tektite was found in was the typical gray-tan Hawthorn gravel outwash that covers the area. No other specimens were found nearby.

In about 1980, a large textite was brought in, and I purchased it. It was found in the Cochran area in Bleckley County. It is shaped like a half disk and has a weight of approximately 57.0 g. The dimensions are $71 \times 45 \times 11$ mm.

In October 2002, J. Dykes found a large tektite in northern Dodge County. It was not recognized as a tektite for several months. This elongated disk measures approximately $74.0 \times 47.5 \times 19.0$ mm. It weighs approximately 86.37 g and shows no obvious bubbles or inclusions. It is the typical drab-olive green and shows no chips from the plow. The find site was on a hilltop west of Chester, Georgia. The soil appeared to be the typical Altamaha yellow-tan gravel with many plinthite pebbles.

The largest tektite found in the Georgia strewn field was the 130.06 g Muong Nong-type, or layered specimen, found by Robert Strange on July 31, 1993. This unique specimen was found near Riddleville in Washington County. This specimen has been thoroughly studied and has been the Rosetta Stone for our understanding of the North American strewn field [2].

Today, there about 2000 Georgia tektites known. They are found in approximately 17 counties. The average weight of a specimen is approximately 9 g. Georgia tektites larger than 50 g are exceeding rare. There are always rumors of large tektites being found, but these are the only ones that are well documented.

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THE MOON—VOLCANICALLY ACTIVE?

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For a body to be volcanic, there must be heat. Here we list three major sources of heat. First, we know that the moon has a molten core of iron. The diameter of this molten core is approximately 800 km. We know the size and that it is molten because the ALSEP seismometers from the Apollo era showed that secondary seismic waves do not penetrate this area. This shows that the center is in a liquid state. The temperature of this core must be approximately 1000 °K. If the iron core was solid, there would be a much stronger magnetic field. The fact that the lunar magnetic field is slight is an indication that the core is molten.

The second source of heat is the radioactive decay of uranium, thorium, and potassium. Since the mantle and regolith of the moon are excellent insulators, the heat generated in the interior will not readily escape.

The third source of heat is tidal stresses from the Earth. It is commonly known that the moon causes the tides on the Earth. What seems less commonly known is that the Earth exerts tidal stresses on the moon that are approximately 50 times stronger. Every impact crater on the moon has cracks, fractures and faults underneath it. These are stressed continually due to tidal forces from the Earth.

From the surface features, we have about 50 clear examples of large lunar shield-type volcanic structures. Some of these are 60 km in diameter. The returned Apollo samples show that the moon is totally igneous or volcanic in its structure. This shows that the moon was volcanically active in recent geologic times.

There have been approximately 2200 lunar transient phenomena events documented. Some of these are likely impact events. However, a very large quantity of these events appear to be centered on about 10 lunar disturbed features. Among the most prominent of these include Aristarchus, Alphonsus, Gassendi, Plato, Kepler, Ptolemaeus, Arzachel, Schroter's Valley, the western part of Mare Crisium, and the Cobra Head region of Herodotus Valley. For these, a volcanic event appears to be the best answer. Three of these events are extremely well documented by Ph.D. astronomers who were specialists in their field using state of the art equipment and corroborated with photographs, spectra, and multiple highly experienced witnesses.

The spectra obtained by N. A. Kozyrev on November 4, 1958 showed gas emissions which were essentially identical to terrestrial volcanic gas emissions.

The missions of Apollos 15 and 16 had alpha particle spectrometers on them. Both missions recorded radon gas over the Aristarchus crater. Whether or not this was from a seismic or volcanic event is not known. The fact that Aristarchus has been a source of many suspected pyroclastic and volcanic Lunar Transient Events cannot be ignored.

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THE DISTRIBUTION OF THE GEORGIA TEKTITES

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Since 1970, one hundred and ninety two field expeditions have been made to east central Georgia in an effort to determine the parent formation and distribution of the Georgia tektites by locating new specimens. These have been given the name "georgiaites." About 100 new specimens have been recovered. They represent about five percent of the known Georgia tektites. The primary area is a fan shaped region approximately 30×72 km. The total area of distribution appears to extend to the ENE towards Augusta. It is likely that the tektites have been transported by water from the parent formation [1]. The parent formation has been identified as the Tobacco Road Sand [2]. No correlation has been found between size, shape, soil type, elevation, and tektite location.

The first Georgia tektite was found by Dewey Horne in 1938 near Dubois in Dodge County. By 2003, approximately 2000 Georgia tektites have been found covering an area of 6934 sq. miles and 17 counties as shown in Fig. 1.

The greatest concentration has been found within the rough triangle formed by the towns of Empire, Chester, and Plainfield in northern Dodge County. Approximately 90 percent of all georgiates have been found in Dodge and Bleckley counties [3].

Several georgiaites found outside of the 90 percent area should be mentioned, because some of them are unique specimens. To the south, one large 17.8 g thin, disk shaped georgiaite was found in Irwin County near Osierfield. To the west, a large disk shaped tektite was found 3 km southwest of Hawkinsville in Pulaski County. In June, 1994, a 10 g georgiaite was found near the southwest border of Pulaski County, suggesting that the neighboring counties of Dooly, Crisp, and Wilcox should also contatin tektites. To the northeast, 32 georgiaites have been found in Washington County. including the first Muong Nong-type georgiaite [4]. In 1984, the first tektite was found in Montgomery County. Six georgiaites have been found in Johnson County and two specimens have been found in the western part of Jefferson County. Four tektites have been found in Wheeler County and three from Treuten County. In 1992, four tektites were found in western Emanuel County along the Ohoopee River. One tektite has been found in Jenkins County, and more recently, one tektite has been found in Richmond County in the Savannah River. From this trend, it is very likely that tektites will be found in South Carolina

Much more field work needs to be done, especially in the northeast. This is important with the announcement of the 90 km crater found under Chesapeake Bay [5]. If this were the source of the North American tektites, then tektites should be found near the source crater.

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NITROGEN IN INDIVIDUAL CHONDRULES OF DHAJALA

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Chondrules, a major constituent of chondrites, are still not completely understood. Oxygen isotopic studies of individual chondrules have revealed that chondrules from carbonaceous, enstatite, and ordinary chondrites have oxygen isotopic compositions that are different from their respective host chondrites [1]. Also, the oxygen isotopic composition of chondrules from Dhajala has revealed a dependance on the chondrule size, most probably due to exchange with nebular oxygen reservoir [1, 2]. Similar to oxygen, the $\delta^{15}N$ of each class of chondritic meteorites is very distinct [3]. We have initiated a program of measuring the N systematics of individual chondrules from chondritic meteorites with the objective of understanding the nature of the precursors of chondrules in each class of chondrites and exploring the possibility of deciphering the nebular $\delta^{15}N$ signature by looking at size dependant effects. Here, we report our results on chondrules from the Dhajala (H3.8) chondrite.

Nine individual chondrules separated from a single piece, ranging in mass from 0.172 to 0.985 mg (and in size from 220 to 400 μ m) have been analysed by a laser microprobe [4] for N and noble gases [4, 5]. The N contents range from 1.3 to 15.6 ppm, a factor of ~12 variation, while the δ^{15} N values lie in the range of -74 to +171‰. These data suggest that the δ^{15} N of Dhajala chondrules have a large spread as compared to the bulk meteorite (having 2 to 4 ppm N with δ^{15} N[‰] of 3 to 5) [5]. In Fig.1, both N contents and δ^{15} N (corrected for cosmogenic contribution) values have been plotted against the chondrule mass. There is a trend of increasing N content as well as a decreasing δ^{15} N, with decreasing chondrule mass (size). The δ^{15} N trend with chondrule size suggests an exchange with nebular N that is lighter than -75‰.



Fig. 1. Plot of N (•) and δ^{15} N (o) versus mass for Dhajala chondrules.

Trapped ³⁶Ar among these chondrules is the same within a factor of two. Compared to the bulk meteorite [7], chondrules are depleted in trapped ³⁶Ar by about an order of magnitude. The ratio $(^{14}N)^{36}Ar)$ for trapped components for the bulk samples of Dhajala lies in the range of $(2-4) \times 10^4$. For seven of the nine chondrules in the present study, the ratio is an order of magnitude higher, while in the remaining two chondrules, it is two orders of magnitude higher, due mainly to higher N contents in these two chondrules. This could be due to mineralogical differences, as shown in an earlier study that found that troilite in chondrules might contain relatively more N [8].

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EVIDENCE FOR DISCONTINUOUS EVOLUTION OF THE MAR-TIAN METEORITES NAKHLA AND Y-000593

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Introduction: The Nakhlites are clinopyroxenites with minor FeO-rich olivine and crystallized intercumulus melt (mesostasis). Nakhla and Y-000593 clinopyroxenes consist of large, rather homogeneous augite cores with FeO-rich rims. Fe/Mg zoning of olivines and the Fe-rich rims of augites are commonly explained by diffusive re-equilibration with an FeO-rich late stage melt [1, 2, 3]. Recent discussions on the thermal evolution of the cumulus minerals focus on a more or less continuous evolution in respect to cooling and fO₂ [4]. Our detailed, combined SEM and TEM investigation of clinopyroxene microstructures and the application of pyroxene thermometry for Nakhla and Y-000593 provide compelling evidence for a discontinuous history of the studied Nakhlites.

Clinopyroxene Thermometry: We estimate a minimum temperature of 1150°C required to form the core clinopyroxenes ($En_{44-46}Wo_{34-35}Fs_{20-22}$ for both Nakhlites) based on the phase diagram of [5]. The widespread homogeneous chemical composition of the large pyroxenes requires a longer equilibration under these conditions. The minimum temperature required for the FeO-rich rims range from 1050 to 1150°C for Nakhla and 1000–1150°C for Y-000593, and for clinopyroxenes in the mesostasis, 850 to 1150° (Nakhla: $En_{22-35}Wo_{30-34}Fs_{30-47}$; Y-000593: $En_{14-35}Wo_{30-34}Fs_{30-55}$). The irregularity of the FeO-rich rims indicate that they were not simply formed by continuous growth or diffusive re-equilibration with an evolving melt.

TEM-Microstructure: Our TEM study revealed that the FeO-poor cores of the clinopyroxenes are free of lamellar low-Ca pyroxene exsolutions. In contrast, the FeO-rich rims and the late stage clinopyroxenes in the mesostasis show extensive exsolutions parallel to (001) and (100). With increasing FeO-content, the width of the exsolution lamellae increase, which is opposite to the trend expected from experimental data [6].

Discussion and Conclusions: If we simply apply the calibration of time-temperature versus microstructure by [7], the absence of exsolution in the clinopyroxene cores will indicate fast cooling rates, more than several degrees per hour [7]. In contrast, the type and size of exsolution lamellae in rims and mesostasis pyroxenes would require cooling rates lower than 0.005° /hr. Obviously, it is not possible during a single cooling process to cool rims and matrix pyroxenes slower than FeO-poor cores. Thus, in this case, we had to assume local reheating of rims and mesostasis, which seems difficult to explain. Another possibility would be that the controlling parameter of microstructure evolution in clinopyroxene is composition and fO₂ rather than cooling rate. Probably, changing fO₂ will trigger the exsolution mechanism, as a higher point defect concentration will enhance diffusion.

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STRUCTURAL EVOLUTION OF THE CENTRAL UPLIFT OF THE VREDEFORT IMPACT STRUCTURE, SOUTH AFRICA

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A structural investigation of the collar rocks of the 80 km wide Vredefort dome provides evidence of the geometries and chronology of impact-related deformation features in the deep levels of the central uplift of the giant, 2.02 Ga, Vredefort impact structure. The dome exposes a 40 km wide core of crystalline basement gneisses and a 15–20 km wide collar of predominantly siliciclastic supracrustal strata. Recent petrographic work by [1] has established that the rocks experienced strongly variable shock pressures across the dome, from ~2 GPa in the outer parts to >30 GPa in the center. Outcrops across the dome are marked by an intense fracture network with cm to meter spacing, which contains pods and veins of pseudotachylite and which ranges from planar to curviplanar in the collar rocks to anastomosing in the crystalline core rocks. The pseudotachylites are attributed to shock \pm friction melting along the fractures, triggered by local heterogeneities in the impact shock wave.

Segments of shatter cones are present throughout the collar rocks up to at least 65 km from the crater center. Contrary to previous studies, the orientation of shatter cone apices does not point consistently towards the crater center after backrotation of the bedding, and up to three different orientations have been observed in individual outcrops. Formation of the central uplift involved strong inward and upward displacements. The collar strata were uplifted by at least 15 km and were rotated to subvertical orientations. This rotation extends into the crystalline core, but the inner ~15 km radius shows no evidence of substantial rotation, suggesting a plug-like geometry for the central uplift. On a smaller scale, the dome is polygonal rather than circular. Individual segments are up to several km long and display relative rotations of ~30-45°. They are separated by radial obliqueslip faults with estimated slips of several hundreds of meters up to a few km, which are flanked by km-scale drag folds with intense jointing. These features reflect tangential shortening during the initial formation of the central uplift. The preponderance of sinistral offsets along the major faults may reflect asymmetric stress distribution during central uplift formation caused by inclined target strata. This is supported by the NW-SE asymmetry of dips of the strata in the dome.

Multiple joint sets are intensely developed on a cm to dm scale in all rock types. Most of these appear to be extensional and are attributed to radial and tangential collapse of the central uplift. They may contain pseudotachylite, but may also cut across thin pseudotachylite veins, suggesting that the latter crystallized before jointing was complete.

In summary, the Vredefort dome displays a chronological sequence of structures formed during the shock compression phase of impact, the initial phase of central uplift formation, and the final collapse of the central uplift. While the large-scale features are consistent with the tangential shortening associated with the initial formation of the central uplift, most of the smallscale joints appear to be related to radial extension, which most likely occurred during the collapse of the central uplift.

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EARTH-CROSSING ASTEROIDS AS INITIAL PARENT BODIES OF METEORITES WITH CRE AGE <100,000 YEARS

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Introduction: Within about 20 years, two H5 chondrites fell near the city of Zhuanghe, Liaoning province in China. The first one was named Zhuanghe. It was 2.90 kg stone that fell on August 18, 1976 into muddy soil in the village Shishan. The second one was named Guangmingshan. It was a 2.91 kg stone that fell on December 30, 1996 into frozen ground in the village of Guangmingshan. We obtained samples of these meteorites for characterizing the mineralogy, chemical composition, and noble gases. Preliminary mineralogical studies were published by [1]. In this work, we also report on our investigations of two chondrites collected by the 15th Chinese Antarctic Research Expedition. Grove Mountain (GRV) 98002 (L5) and GRV 98004 (H5) were found in 1999 on blue ice near the Grove Mountains in East Antarctica.

Results: We determined the mineralogical and chemical characteristics and the He, Ne, and Ar isotopic abundances of these meteorites. Guangmingshan (H5), Zhuanghe (H5), and Grove Mountain (GRV) 98002 (L5) yield cosmic-ray exposure (CRE) ages of 68.7 + 10.0 Ma, 3.8 + 0.6 Ma, and 17.0 + 2.5 Ma, respectively. These ages are within the range typically observed for the respective meteorite types. GRV 98004 (H5) had an extremely short parent body-Earth transfer time of 0.052 + 0.008 Ma.

Discussion: Among the >1600 meteorites for which a CRE age was determined, there are only four with an age <0.1 Ma: Farmington (L5, 0.032 Ma) [2, 3, 4], Galim (LL6, 0.033 Ma) [4], GRV 98004 (H5, 0.052 Ma), and ALH 82100 (CM2, 0.04 Ma) [5]. These low ages are not caused by noble gas diffusion loss after parent body break-up as they are concordant with the CRE ages from radionuclides (Farmington [6] and ALH 82100 [5]), or the ²¹Ne CRE ages can be shown to be reliable. Either these meteorites were broken off an asteroid in the main belt and were rapidly ejected through a resonance such as the 3:1, the 5:2, or the v₆ resonance [7], or their immediate precursor body was an Earth-crossing Apollo object [8, 9]. Possible parent bodies of the ordinary chondrites are the Q-type and G(IV)-type asteroids, and of the CM chondrites, those of C-type and G-type. Numerous spectral matches with ordinary chondrites and CM chondrites, respectively, have been identified in the near-Earth asteroid population and among the main belt asteroids with orbits close to the ejection resonances.

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WINONAITE PETROGENESIS: FIRST RESULTS FROM TRACE ELEMENT DISTRIBUTIONS

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Introduction: Winonaites are primitive achondrites related by oxygen isotopes to silicate inclusions in IAB iron meteorites [e.g., 1–3]. One detailed model of their origin [2, 3] suggests they underwent limited partial melting, followed by impact breakup and reassembly of the parent body. Mixing of unmelted to partially melted silicate material and molten metal was followed by extended metamorphism during slow cooling of the re-accreted body.

To constrain the origins of winonaites and IAB silicate inclusions and their relationships to one another, we are using the ion probe to study trace element distributions in individual minerals from these meteorites. In particular, we will evaluate the roles silicate partial melting and metamorphism may have played on their parent body. Here, we report on three winonaites, Winona, Tierra Blanca, and Hammadah al Hamra (HaH) 193.

Results: Tierra Blanca is coarse-grained (~200 μ m) with large poikilitic calcic pyroxenes [2, 4] that enclose smaller olivine, orthopyroxene, and plagioclase grains. Winona is finer-grained (~100 μ m) with equigranular textures, but contains regions dominated by coarse-grained (300–500 μ m) olivine, interpreted as partial melt residues by [2]. HaH 193 has not been studied and we report on its petrology and mineralogy in a companion abstract [5]. Our section contains large poikilitic orthopyroxenes enclosing olivine, plagioclase, and clinopyroxene. It also contains large grains of the amphibole edenite that seem to be of preterrestrial origin [5].

REE compositions in plagioclase show some variability, but have similar ranges in all three meteorites. However, REE and other incompatible trace element (e.g., Ti, Y, Zr) abundances in orthopyroxene and clinopyroxene show distinct ranges with little or no overlap. There are no consistent trends among the three meteorites, but abundances of incompatible trace elements (including the REE) are highest in the clinopyroxene and orthopyroxene of Winona. Apatites in HaH 193 have flat to somewhat LREErich patterns with negative Eu anomalies, as typically observed for this mineral, but in Winona they show a continuum of patterns from LREE-rich with negative Eu anomalies to HREE-rich with slight positive Eu anomalies, similar to those seen in some lodranite phosphates [6].

Discussion: The trace element data so far provide only limited support for silicate partial melting. Most compelling are the variable REE patterns in apatite from Winona combined with elevated trace element abundances in pyroxenes, which suggest some melting and redistribution. However, the pyroxene data from the other winonaites may be more consistent with equilibration of initially heterogeneous minerals in compositionally distinct regions of the winonaite parent body. Furthermore, trace element compositions of coarse olivines in Winona do not differ from those of finergrained olivines, although depleted abundances are expected if the former are indeed partial melt residues, as suggested by [2]. A complicating factor is that the winonaites seem to have experienced complex histories, including impact brecciation and metamorphism, which may have obscured or modified trends due to partial melting.

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HAMMADAH AL HAMRA 193: AN AMPHIBOLE-BEARING WINONAITE

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Introduction: Winonaites are reduced meteorites with oxygen isotopic compositions distinct from those of other primitive achondrites, except for silicate inclusions from IAB irons [1, 2]. They have equigranular textures and chondritic mineralogies, but can contain mm- to cm-sized regions with different textures and/or mineralogies. These include plagioclase-diopside-rich regions, coarse-grained olivine-rich areas, and/or large poikilitic calcic pyroxenes [2]. Here, we report on a texturally and mineralogically unusual winonaite, Hammadah al Hamra (HaH) 193.

Results: HaH 193 was found in 1996 in the Libyan desert as a single stone of 259 g. Its identification as a winonaite [3] was confirmed by oxygen isotopic analysis ($\delta_{18}O = +4.79$, $\delta^{17}O = +1.90$; R. Clayton, personal communication). We obtained a thin section of HaH 193 for a trace element study of winonaites [4] and discuss here its mineralogy and petrology.

Our section of HaH 193 is dominated by very large (up to 5 mm) optically continuous orthopyroxenes that poikilitically enclose smaller grains of olivine, plagioclase, and occasionally clinopyroxene. Two distinct lithologies occur interstitial to the poikilitic orthopyroxenes. One consists of clumps of equigranular 200–300 μ m olivine grains, similar to areas described in Winona and other winonaites [2]. The other lithology contains abundant amphibole and clinopyroxene. The amphiboles are large (up to 2 mm) and poikilitically enclose smaller grains of primarily olivine, but also plagioclase, clinopyroxene and orthopyroxene.

Major element mineral compositions are similar to those seen in other winonaites (orthopyroxene: $Fs_{4,9-5.1}Wo_{1.7-2.0}$; clinopyroxene: $Fs_{1.3-2.2}Wo_{43.2-44.2}$; olivine: $Fa_{4,3-4.6}$; plagioclase: $An_{20.9-21.4}$). The amphibole in HaH 193 is nearly stoichiometric fluoro-edenite, $K_{0.1}Na_{1.1}Ca_{1.7}Mg_{4.8}$, $Fe_{0.1}$, $Ti_{0.1}Si_{7.0}Al_{1.0}O_{22}(F)_{1.8}$. Raman spectroscopy confirms the amphibole structure and shows no OH peak. Edenite is rare and endmember fluoro-edenite has only recently been identified terrestrially [5]. This is the first reported meteoritic occurrence.

Discussion: Textures suggest that fluoro-edenite is replacing clinopyroxene in HaH 193, probably in a reaction between clinopyroxene and plagioclase. This is supported by trace element evidence. Clinopyroxene and edenite have similar bow-shaped REE patterns with negative Eu anomalies. However, relative to clinopyroxene, the edenite has lower trivalent REE abundances (\sim 2 \times), and higher abundances of Eu (\sim 3 \times), Ba (\sim 15 \times), Na (\sim 10 \times) and K (\sim 100 \times), all elements that are typically enriched in plagioclase. The source of the F is probably apatite. Apatite is rare in HaH 193, but several grains associated with edenite have F contents ranging from 3.9 to 4.2 wt%, in contrast to the chlorapatite commonly found in other winonaites.

Although HaH 193 is fairly weathered, and our section contains several alteration-filled veins, the edenite appears to be of preterrestrial origin. Evidence for this includes textural relationships and its OH-free composition, as well as the fact that HaH 193 minerals show little evidence of the terrestrial alteration commonly observed in other hot desert meteorites [e.g., 6].

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NORTH FLORIDA FIREBALL OF APRIL 20, 1974

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On Friday evening, April 19, 1974 the skies were clear over north central Florida. The Lyrid meteor shower was active, so there were many experienced meteor observers out. At 9:43 EDT (1:43 UT, April 20), a bright sporadic fireball occurred over north Florida.

While there were a large number of high quality reports, they were not in the best of locations and the results were not as good as hoped for. The atmospheric path was fairly well computed. Due to the high beginning and endpoints and lack of sonic phenomena, no meteorites are likely to be found. At the time of the fireball, the radiant was approximately 18.3° altitude.

In central Florida, many experienced observers estimated the magnitude at about -8 or -9. In north Florida, under the fireball's path, the magnitude was likely at least -10. The fireball started at magnitude -5, flared to -10 or brighter, and faded to magnitude -5 at burnout. From central Florida, the beginning color was a sky blue, and it lit up the entire northern sky. This color quickly changed to orange-red with sparks at the termination. The diameter was smaller than the moon, probably about 15'. The nucleus was tear dropped shaped. There was some terminal burst, and the brightness varied during the short flight.

A long duration train was observed and accurately recorded by two very experienced observers, Karl Simmons and Michael Reynolds. They gave naked eye durations of 130 and 160 seconds and binocular durations of 10 minutes and 6 minutes and 50 seconds. Both plotted and recorded the train drift. The drift azimuth was 160° and the observed drift rate was approximately 1° per minute. This would correspond to about 160 km per hour at a height of 105 km. Apparently, the observers in central Florida did not observe the long duration train.

Date: April 20, 1974 Time: 1:43 UT (8:43 EST on April 19) Sideral time at endpoint: 153°14' Began over: 81°26', 29°26' at 120° 19 km Ended over: 81°01', 29°44' at 92° 25 km Projected path: 52 km Path: 59 km

The corrected radiant was in Canis Major five degrees south of Sirius. This location was checked for matching known major meteor showers and none were found. The corrected radiant: $(2000.0) \text{ RA} = 100^{\circ}57' \text{ Dec.} = -21^{\circ}37'$.

It was suspected that the observed duration of 2.5 seconds was too short.

The elliptical orbital elements based on 16 km/sec are: a = 2.328; e = 0.5752; q = 0.9888 AU; q' = 2.67 AU; ω = 343°.07; Ω = 209.°98401; and i = 14.°97

This is a quite common asteroidal orbit and must certainly be very close to correct.

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CRATER EVIDENCE ABOUT EROSION HISTORIES OF MARS AND EARTH

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Because impact craters of relatively uniform shape are created on planets at fairly well-known rates, the degradation of such craters offers a measurement that characterizes net erosion/deposition regimes on plantes. Older regions on Mars, and all regions on Earth, show marked losses of small craters relative to larger craters, offering specific clues about erosion/ deposition histories. The shape of this size distribution in older martian areas suggests higher crater loss rates before about 2.5 to 3 Gyr ago and lower loss rates since that time.

Additional data on the same phenomena can be obtained from independent estimates of the resurfacing history of Mars by [1]. These workers tabulated the total area resurfaced by processes such as volcanic, fluvial, periglacial, and aeolian activity, including areas of units visible in some areas but partly covered by later units, in various stratigraphic time epochs such as Late Noachian, Early Hesperian, etc. Without absolute dates, these statistics do not give information on rates of change of these resurfacing processes. However, Hartmann and Neukum [2] have prepared a synthesized cratering chronology assigning absolute dates to the martian geologic periods, and this system is highly consistent with martian meteorite data.

Combining the resurfaced areas from Tanaka et al. with the durations of the epochs from [2], we derive estimated rates of resurfacing in the different epochs. The direct tabulations affirm higher resurfacing rates by all processes before about 2.5–3 Gyr ago and, in particular, 1–2 orders of magnitude higher resurfacing rates by fluvial and periglacial processes at that time.

The direct tabulations suggest a mild upturn in cratering and fluvial resurfacing in the last 1 Gyr. This could be attributed to better visibility and tabulation of the most recent geologic units. However, one can artificially adjust the estimated durations of the epochs so as to force a more realistic cratering curve as a function of time with constant recent cratering. If this is done, the resulting curves still show an order of magnitude higher resurfacing rates by fluvial, periglacial, and other processes before about 2.5–3 Gyr ago.

Thus, current data, both from craters alone and from geologic mapping, give fairly strong evidence that Mars had much higher rates of geologic activity, including water and ice-related resurfacing, in the first third of martian history.

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EFFECT OF FLASH HEATING ON MELILITE SOLID SOLUTION

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Introduction: We have reported kinetics of partial melting of a melilite solid solution (ss) system when heated at a constant temperature within the range between solidus and liquidus [1]. Rapid heating and cooling of melilite ss produces a mosaic structure composed of gehlenite (Ge)-rich crystals and åkermanit (Åk)-rich glasses or crystals. The mosaic structure once produced can be retained under a prolonged heating under subsolidus temperatures, since interdiffusion of Al + Al versus Mg + Si or Ge and Åk components is very slow in the solid state [2].

The mosaic structure, if found in a meteoritic melilite, may provide a marker for the thermal history of the sample. In principle, the composition and the average size of the crystals indicate maximum temperature and the time of heating interval, respectively [1].

For the purpose of possible implication for meteoritic melilite samples, we examined the possibility of determining the mosaic structure in the natural samples by combination of X-ray diffraction and SEM/optical microscopy in addition to the previously used SEM/EDX. We used artificially prepared analogues for this purpose. We also examined the possible effects of flash heating on the meteoritic melilite crystals.

X-ray Diffraction: To determine end-member compositions, we used the shift of major peaks in the powder X-ray diffraction spectra. The observed d versus composition relation showed that the shift of (211)-peak (d = 2.8446 Å) is about 0.01 Å, which is large enough to resolve the difference between Ge-rich and Åk-rich crystals. For the observation of peak-shift in small samples, a micro-focus X-ray diffracto-meter (beam radius = 50 μ m) was used.

Discussion: Using SEM/EDX, maximum temperature attained and the time interval of heating can be estimated, if the size of the grains were large enough for EDX measurement, e.g., a few μ m or heating time interval of longer than 10 min at 1415°C. The mosaic structure produced by shorter heating time interval, i.e., 2–10 min, can be determined by X-ray diffraction/ optical microscopy.

Retention of the Mosaic Structure. Under a subsolidus temperature, homogenization of Ge- and Åk-composition occurs through interdiffusion of Al+Al versus Mg+Si. The time necessary to erase the structure is calculated based on the simplified 1-dimensional alternate Ge/Åk-slab model [3], using a constant diffusion coefficient value of 1×10^{13} cm² sec⁻¹ [2]. The annealing time, which decreases the compositional difference of Ge-rich and Åk-rich crystals to a half of the original difference, is calculated to be about 140 days to 8.6 years for the structure composed of crystals of 10 to 50 µm in size or produced by 1–100 hr of heating at 1415°C.

Enhancement of O Isotope Exchange. Since the self-diffusion coefficient of O in Ca, Al-rich silicate melt $(1.66 \times 10^{-6} \text{ cm}^2 \text{ sec}^{-1} [4])$ is larger than that in melilite single crystal $(1.74 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1} [5])$ by ~4 orders of magnitude, exchange of the O isotope with the environmental gas phase is enhanced considerably by partial melting, provided partial pressure of O in the gas phase and a reasonably high exchange rate of O at the surface. A simplified isotropic sphere (r = 1 mm) model indicates the time necessary to decrease the difference between O isotope ratios in and out of the sphere to 1/10 to be about 20 min at 1415°C.

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SOME PROPERTIES OF AN UNUSUAL GLASS AND CARBONATE IN THE D'ORBIGNY ANGRITE

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Introduction: The angrite D'Orbigny is unusually rich in glass when compared to other members of the angrite group [1, 2]. The most common glass fills open spaces in druses and hollow shells. Carbonate fills in part of the abundant open spaces. Inside hollow shells, in the center of the rocks, it forms crystal bushels and is white. In contrast, near the surface of the meteorite, it forms crusts and has an ochre color.

Analytical Methods and Results: Glass in some of the abundant open spaces in D'Orbigny, druses and hollow shells, is black (brown in thin section), is rich in schlieren, and contains variable amounts of bubbles, mineral fragments, and sulfide beads [1, 2]. Its chemical composition is similar to that of the bulk rock for major, minor, and trace elements [1-3]. The major element contents of the glass in the D'Orbigny angrite were determined by electron microprobe analysis [2]: SiO₂ (38.4 wt%), TiO₂ (2.54 wt%), Al₂O₃ (8.1 wt%), Cr₂O₃ (0.09 wt%), FeO (25.8 wt%), MnO (0.32 wt%), MgO (4.20 wt%), CaO (20.4 wt%). The glass easily dissolves, in part, in aqua regia producing a clear yellow solution, a white porous residue, and relict minerals. The white and porous leach residue preserved the shape of the original glass sample and consists mainly of SiO₂ (93 wt%) with low contents of TiO₂ (~1 wt%), Al₂O₃ (3-4 wt%), and FeO (0.5-1.5 wt%), as determined by electron microprobe analysis. The determination of the ion concentrations of the solution also shows that all major elements, except Si and Ti, were dissolved. The relict minerals olivine and spinel which are embedded in the white porous residue could be observed by Micro-Raman spectroscopy. In contrast to the reaction of the D'Orbigny glass with aqua regia giving a residue, treating with 25% aqueous HCl produces a yellow solution which forms a yellow gel within some days.

The Micro-Raman spectrum of the D'Orbigny glass shows the typical spectral features of an aluminosilicate glass with broad bands which can be attributed to stretching modes of oxygen atoms (930 cm⁻¹, s br), intertetrahedral deformation modes (714 cm⁻¹, w br), and bending modes of oxygen atoms (573 cm⁻¹, w br). The glass appears to consist primarily of the coexisting anionic species SiO_4^{4-} , SiO_3^{2-} , and $Si_2O_5^{2-}$. The D'Orbigny glass occasionally contains rounded minerals of which iron sulfides, and obviously diamonds, could be identified by Micro-Raman spectroscopy. A contamination with diamonds is very unlikely but cannot be excluded entirely yet.

The Micro-Raman spectrum of the white leach residue of the glass shows bands which can be attributed to the amorphous silica structure of four-membered siloxane rings of SiO_4 tetrahedra.

The structure of the carbonate could be determined by Micro-Raman spectroscopy. The white bushels show the spectral features of pure calcite while the ochre crust exhibits Raman bands of disturbed calcite which are almost completely hidden by the highly fluorescent background.

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Introduction: Particles in a protoplanetary disk frequently collide with other particles. Planetesimal formation by this process takes place if the collisions result in the net growth of a larger (more massive) body. Collision velocities range from fractions of a mm/s up to 100 m/s. While the low velocities result in sticking, the question is if growth at the larger velocities can occur, i.e., at speeds above several tens of m/s. It looks like no collision of two bodies alone can do this. Erosion or fragmentation of the larger body is always the result. However, the collisions take place in a gaseous disk. In the collision of a large body with a smaller one, the large body experiences a head wind in which the small body is entrained. Fragments of the collision can get entrained again and be returned to the large body, this time at a reduced velocity. Sticking and reaccretion of fragments would occur. This eventually leads to a net growth instead of erosion.

The mechanism has experimentally been proven to work with small dust aggregates for velocities above 10 m/s [1, 2, 3]. Thus, growth of bodies much larger than 10 cm in protoplanetary disks can be explained quite naturally without any special assumption. This is one step further in the growth sequence. However, this is probably not yet enough, e.g., to explain the formation of meter-sized or larger bodies.

With respect to our previous experiments, there is still room to change parameters, by which we expect to get net growth at higher speeds. This essentially concerns the morphology of the dusty particle assemblies and the sizes involved. We will present a follow-up experiment which will verify if this mechanism (termed by us as aerodynamical sticking) also works at higher velocities for larger bodies. In the experiment we call WHALE (Wind Hatched Planetesimals in Laboratory Experiments), collisions of dusty bodies are studied in a low pressure, high speed wind channel designed for this purpose.

Our recent first measurements look promising but this qualitative statement still has to and will be substantiated by more experiments and a more detailed analysis

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IN THE BEGINNING THERE WAS DUST ... THE WHALE EXPERIMENT—GROWTH OF METER-SIZED BODIES IN PROTOPLANETARY DISKS

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How did our planetary system form? This question is still far from being fully understood. In the standard model of planetary accretion, planetesimals originate from micron-sized dust grains embedded in a protoplanetary gaseous disk. The dust grains collide with each other, stick together, and grow to kilometer-sized objects, at which stage mutual gravitational interaction will cause them to grow into planets. Most collisions of meter-sized bodies happen at tens of m/s up to 100 m/s. Such high-speed collisions normally result in erosion of the larger body and, sometimes, in destruction of both. This, however, is a problem. How, then, do they grow ?

If a large body collides with a smaller one in a dust-gas disk, then the larger one will experience a head wind. The collision will initially lead to erosion of the larger body. The particles ejected during this process are slow and small enough to couple to the gas flow. Then, the head wind returns them to the large body and sticking can occur. With our collision experiment (The Whale), we will verify the mechanism. We developed a low pressure wind channel with gas velocities up to 100 m/s at pressures as low as 0,1 mbar. Within this wind, we carry out impact experiments at collision velocities up to 100 m/s. Our projectile and target consist of dust. We try to answer to the fundamental question, "Is a net-growth at high impact velocities possible?" We report on the status and first result of the experiments.

COSMIC RAY EXPOSURE HISTORY OF THE NEW OMANI LUNAR METEORITE SAYH AL UHAYMIR 169

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Introduction: Sayh al Uhaymir lunar meteorite consists of extremely KREEP-rich polymict, anorthosite-free impact-melt breccia and an adherent polymict regolith material. We studied the cosmic ray exposure (CRE) history of the impact-melt breccia by analyzing the light noble gases He, Ne, and Ar and the transfer time from the radionuclide ¹⁰Be.

Results:

Table 1. Light noble gases in Sayh al Uhaymir lunar meteorite [10 ⁻⁸ cm ³ STP/g].						
⁴ He	²⁰ Ne	⁴⁰ Ar	²⁰ Ne/ ²² Ne	²² Ne/ ²¹ Ne		
42000	23.4	7449	0.802	1.197		

Transfer Time Moon-Earth T_{trans}: The ¹⁰Be activity in Sayh al Uhaymir lunar meteorite is 8.05 dpm/kg. In a scenario with no pre-exposure to cosmic rays on the moon immediately before ejection and assuming a saturation activity of 25 dpm/kg at 4π irradiation geometry, we optain T_{trans} = 0.85 Ma. In an alternative scenario with pre-exposure in the upper layer of the lunar regolith, some ¹⁰Be activity was present at ejection, hence T_{trans} is <0.85 Ma.

Regolith Residence Time: We calculated the cosmogenic components of ²¹Ne and ³⁸Ar using the method given by [1]. Adopting production rates according to [1] and $T_{trans} = 0.85$ Ma, we calculated the cosmogenic noble gases produced during the transfer. We find that 99% of the cosmogenic noble gases were produced at the lunar surface. With production rates for the lunar surface [2], assuming a shielding depth of 40 g/cm³, we get $T_{reg} = 200 \pm 40$ Ma.

Discussion: the moon-Earth transfer time of Sayh al Uhaymir lunar meteorite lies in the range of 0.02–8 Ma [3] for other lunar meteorites. The exposure of Sayh al Uhaymir lunar meteorite to cosmic rays during T_{trans} is short compared to T_{reg} . Since solar gases are absent in the impact-melt breccia, this material was never exposed at the very top surface in the regolith. The T_{reg} of Sayh al Uhaymir lunar meteorite is comparable with the T_{reg} of other lunar meteorites [5].

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DID ORGANIC COMPOUNDS IN THE TAGISH LAKE METEORITE FORM VIA CATALYTIC PROCESSES IN THE SOLAR NEBULA AND WITHIN PARENT BODIES?

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Introduction: Dust-catalyzed reactions of the Fischer-Tropsch-type (FTT) and Haber-Bosch-type (HBT) almost certainly contributed to the production of gaseous organic and N-containing compounds in the warm, inner solar nebula [1, 2]. In addition, the surfaces of these nebular dust grains (amorphous silicates, oxides, etc.) were probably rich in high molecular weight organics [2, 3]. However, the link between such catalytic processes and the organic content of chondrites is poorly understood [1, 2]. Here, we compare the organic composition of the Tagish Lake meteorite with likely FTT and HBT catalysis products in the solar nebula and in parent bodies in an attempt to ascertain whether the apparently restricted distribution of organic compounds in Tagish Lake is consistent with catalytic synthesis.

Analytical Methods and Results: The samples studied were silicate smokes ("synthetic nebular dust") following catalytic experiments [1–3] and fragments of the Tagish Lake meteorite. The organic analyses were performed using pyrolysis-gas chromatography mass spectrometry (Py-GCMS), and the methods have been summarized elsewhere [3, 4]. The predominant compounds observed in the catalysis products were homologous series of aliphatic hydrocarbons, aromatic hydrocarbons and nitrile-aromatic hydrocarbons [3]. Tagish Lake macromolecular material is highly aromatic in character—the dominant pyrolysis products are parental PAHs, alkylsubstituted PAHs being scarce by comparison. Pyrolysis also revealed the presence of several heteroatom species such as O-containing phenols, Scontaining thiopphenes and benzonthiophenes, and N-containing species such as benzonitrile [4].

Implications: Meteoritic organic matter in CM2 chondrites such as Murchison is characterized by structural diversity and a general decrease in abundance with increasing molecular weight. The more restricted distribution observed in the free aromatic inventory of Tagish Lake has led to the suggestion [5] that it may reflect a contribution from processes involving catalytic synthesis, since these tend to be more selective in the classes of compounds they produce than other synthetic pathways. FTT synthesis typically produces relatively aliphatic-rich products. However reprocessing of these products leads to progressive aromatization and the production of more complex molecules, as we noted in the course of our catalytic experiments [2]. Tagish Lake macromolecular organic matter is extremely aromatic in nature, although the free organic inventory does contain aliphatic material in the form of carboxylic and dicarboxylic acids [5]. It would appear, therefore, that FTT/HBT products formed in the inner solar nebula could have contributed to the Tagish Lake meteorite's parent body. However, if so, they were likely subjected to extensive secondary processing in this environment

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⁴⁰AR-³⁹AR AGES OF MINERAL SEPARATES OF EUCRITES DHO 300 AND DHO 007

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Introduction: We report new ⁴⁰Ar-³⁹Ar measurements on two brecciated eucrites recently discovered in the Oman desert: Dho 007 and Dho 300. Dho 007 was classified as cumulate eucrite [1], though it has very high bulk Ni and Co contents in comparison to other eucrites [2]. Dho 300 belongs to the noncumulate type of eucrites [3]. To better separate and quantify the various Ar components, high-resolution ⁴⁰Ar-³⁹Ar stepwise heating analyses were carried out on whole rock samples, as well as handpicked mineral separates (plagioclase, pyroxene, and vein glass).

Results and Discussion: All samples display distinct release peaks of trapped argon at 400°C and 700°C. This trapped component is of atmospheric composition, as revealed by three isotope correlation diagrams. Correction of the low temperature extractions results in less complex age spectra, as shown in Fig. 1 for Dho 300. ⁴⁰Ar-³⁹Ar age spectra of Dho 300 and Dho 007 are similar to other typical eucrite age spectra and are characterized by stepwise increasing apparent ages. Judging from the release temperature of K-derived ³⁹Ar and the K/Ca spectra, the main K carrier in all samples is plagioclase, but of presumably differing grain size. While for the plagioclase separate, preferably large grains were picked, in the pyroxene separates, there remained some percentage of small plagioclase grains that could not be successfully removed. However, these dominate the K budget and, hence, the age and release spectrum. Release of K-derived ³⁹Ar that correlates with Caderived ³⁷Ar release from the pyroxene lattice at high temperatures of >1200°C was hardly observed. The Dho 300 age spectra (Fig. 1) can be explained by a recent thermal event that induced varying degrees of secondary ⁴⁰Ar loss (weakest for large plagioclase grains). Apparent ages in the high temperature extractions indicate that the last total reset occurred ~3.9 Ga ago (Fig.1), coeval with the intense cratering period on the moon [4].



Fig. 1.

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⁴⁰AR-³⁹AR AND ²⁴⁴PU FISSION TRACK COOLING AGES REVEAL ²⁶AL HEATING OF THE H CHONDRITE PARENT ASTEROID

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Synopsis: ⁴⁰Ar-³⁹Ar and ²⁴⁴Pu fission track thermochronometry was applied to several unshocked H chondrites of different petrologic types. Cooling ages indicate significantly longer cooling for higher metamorphosed types in deep parent body layers, fast cooling for low petrologic types in surface sited regions [1]. Our results highly favor ²⁶Al as the heating source for planetesimals in the early solar system and imply fast accretion within a few Ma, within currently considered lifetimes of protoplanetary disks of <6 Ma [2].

Accretion and Planetesimal Heating: Fast (within a few Ma) accretion, heating, and differentiation of asteroidal-sized planetesimals in the early solar system is constrained by Pb-Pb ages of Allende CAIs and basaltic achondrites [3, 4]. Studies demonstrating in situ decay of short-lived ²⁶Al [5, 6] advanced this nuclide as a candidate heat source for planetesimal differentiation and heating of chondritic parent bodies. Model calculations of a chondritic parent body [1] heated by ²⁶Al predict slower cooling for higher metamorphosed petrologic types in deeper parent body layers.

Thermochronological Results: Using the different closure temperatures of radiogenic ⁴⁰Ar and ²⁴⁴Pu fission tracks, we determined cooling curves for variably metamorphosed H chondrites that were not disturbed by collisional events. Our results, together with available Pb-Pb data [7], strikingly agree with the ²⁶Al heating model (Fig. 1), if accretion of the ~100 km sized body is completed 3 Ma after Allende CAIs [1].





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AQUEOUS ALTERATION AND HEATING EVENTS OF ANOMALOUS CM CHONDRITES

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Introduction: Unusual carbonaceous chondrites from the desert of Oman, Dhofar 225 (Dho 225) and Dhofar 735 (Dho 735), have similarities to the Antarctic metamorphosed carbonaceous chondrites (MCC) B-7904 (CM), Y-82162 (CI), and Y-86720 (CM). Dho 225 and Dho 735's very different post-accretional histories, including aqueous alteration and heating events, have not affected their oxygen isotopic systematics.

Results: Texturally, Dho 225 [1] and Dho 735 are similar to CMchondrites, but Dho 735 is a highly brecciated chondrite. They contain irregular olivine aggregates, chondrule-like objects, and refractory inclusions embedded in a fine-grained phyllosilicate matrix. The rounded objects are mantled with a dark, fine-grained, accretional-dust patina. Minor phases include FeNi metal, troilite, pentlandite, pyrrhotite, chromite, schreibersite, and Ca-carbonates. Among accessories, Dho 225 contains eskolaite Crbarringerite, Dho 735 possesses Mg-ilmenite and rutile and contains abundant sulfides.

Olivines from Dho 735 are not zoned, and the meteorite lacks enstatite, isolated grains of olivine and pyroxene in the matrix, tochilinite and Ca, Feoxysulfides [1]. In contrast, Dho 225 contains all of these components. Cacarbonates in Dho 735 are abundant, associated with phyllosilicates, and occur often in veins.

Dho 225 and Dho 735 have similar oxygen isotopic compositions (Fig. 1), close to the MCCs [2]. Similar to the MCCs, the matrices of these stones show high EPMA totals, depletion in Fe and S, and the presence of small grains of troilite, taenite, and tetrataenite. The matrix of Dho 735 is more depleted in Fe than Dho 225 and the MCCs. The bulk composition of Dho 225 also has both a low H_2O -content (1.76 wt%) and low Fe.

Oxygen isotopic compositions



Fig. 1.

Discussion: Dho 225 and Dho 735 supplement the MCC group, being its first non-Antarctic members. Similar to the MCCs, they have experienced heating events after aqueous alteration in CM parent asteroids. However, the presence of tochilinite, zoned olivine grains, and Ca, Fe-oxysulfides in Dho 225 contradict this interpretation. That might indicate a possible episode of aqueous alteration followed by a heating event. The low thermal stability of tochilinite, which decomposes at 245°C to troilite, indicates that it could have formed after the heating event [3]. This difference in post-accretional histories of Dho 225 and Dho 735 has not affected their oxygen isotopic systematics. They may represent a group of carbonaceous chondrites from a different oxygen reservoir.

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TIDAL DISRUPTION OF PRIMORDIAL ASTEROIDS: A NEW PATHWAY FOR METEORITE PETROGENESIS

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Introduction: We evaluate the tidal disruption of planetesimals by planetary embryos from dynamical, geophysical, and meteoritical perspectives. It is widely believed that the present population of asteroids (and thus most meteorites) derive from material that survived intense (99.9%) mass depletion in the protoplanetary disk between Earth and Jupiter. According to this scenario, about one in a thousand bodies survived scattering, close encounters, and mergers to become the ancestors of the present main belt and the precursors of meteorites. Close tidal encounters with embryos were inevitable.

Process and Implications: This "long march" took its toll on the survivors, which begat the present asteroids. The rate at which planetesimals accrete onto planets is comparable to the rate at which planetesimals come inside the Roche limit of a dominant embryo [1]. Specifically, for very weak bodies (rubble piles, or those with half their mass in regolith) and for gravity-dominated bodies of fairly low viscosity ($v_{lim} < \sqrt{G}\rho^{3/2}R^2 \sim 10^{11}$ poise for 100 km radius), periapsis <~ 0.5 R_{roche} results in catastrophic disruption as defined by removal of half the original mass. Note that even partially molten silicate bodies have sufficiently low viscosity to undergo disruptive tidal deformation, especially if water was abundant at this phase of planetary accumulation.

Our dynamical calculations show that a few percent of the surviving primordial asteroids underwent catastrophic tidal disruption during encounters with the transitory main-belt embryos [cf. 2], if a majority were either partially molten or rubble piles during the first ~3 Ma. Melting and differentiation of asteroid parent bodies is known to have occurred during this time [3], so planetary mantles may have been ripped from cores in several instances, a process which could even have been relatively common.

Tidal disruption produces a symmetric chain of fragments; comet Shoemaker-Levy 9 was an example. In models of tidal disruption [1], differentiated bodies pull apart into one or more central cores almost devoid of mantle rock, flanked by core-free bodies of diminishing size away from the center. The process need only occur a few times to resolve several dilemmas associated with iron and stony iron meteorites and their parent bodies.

Thermodynamics: Tidal disruption induces pressure-release melting and brings core and mantle material into sudden close association across a wide surface area. Silicate and iron mix as the core and deep mantle are brought abruptly (in the course of hours) to low pressure. Melts degas abruptly and generate turbulence. The shock-free disruption and mixing of parent materials can explain highly varying cooling rates within a single taxonomic type, and mantle-removal of classic M-type asteroids such as Psyche and Kleopatra without invoking intense impact bombardment of a sort that would have easily removed Vesta's crust.

Results: We shall present dynamical models showing that this process is likely to have occurred for a significant fraction of the asteroid precursor population, together with detailed hydrodynamical calculations of the process, using SPH with the revised ANEOS equation of state tracking the thermodynamics.

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THE LATTICE STRAIN OF OLIVINE IN EXPERIMENTALLY SHOCKED CHONDRITES

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Introduction: Shock metamorphism is pervasively recognized in meteorites, and it is an important subject to estimate the degree of shock experienced by each meteorite. Chondrites were qualitatively classified based on shock textures mainly on olivine by [1]. In this study, we determined apparent strains of olivine crystals in experimentally shocked chondrites by an X-ray diffraction method using a Gandolfi camera. This approach will provide a basis to construct a new measure of the shock degree experienced by chondrites.

Experiments: Great Bend (H6, S1) chondrite was used for the shock experiments, which were performed by using a 30 mm bore propellant gun. Three samples, being shock-compressed at 15.3, 32.7 and 43.8 GPa respectively, were recovered. Polished thin sections of recovered samples were prepared and chemical compositions of olivines were analyzed by EPMA. Olivine grains of about 50 μ m in size, being confirmed to be homogeneous in their compositions, were taken out of the polished thin sections for the X-ray analysis by using a Gandolfi camera. The position and the integral breadth of each reflection in X-ray powder diffraction patterns were precisely determined by applying a profile-fitting technique with a pseudo-Voigt type shape function. Apparent strains of olivine crystals were determined by the method shown in [2].

Results: Apparent strains of olivine crystals were plotted against the peak shock-pressures loaded on each sample (Fig. 1). Fig. 1 shows that the values of apparent strains of olivines for each pressure vary in the range of about 0.05% and proportionally increase with shock pressures. Shock experiments using an olivine single crystal [2] show a constant apparent strain at each shock pressure. The 0.05% variation of apparent strains at each shock pressure found in this study may be due to petrographic textures of chondrite, being composed of chondrules and a matrix. The results of this study strongly suggest that the apparent strain of olivine determined by the X-ray method can be used as a measure with which shock degrees of chondrites will be quantitatively estimated.



Fig. 1.

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EVIDENCE AGAINST THE NEBULAR SHOCK MODEL OF CHONDRULE FORMATION

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The shock wave heating model is thought of as one of the most probable models for chondrule formation [1]. The advantage of the model is that the thermal history of the chondrule obtained from calculations of numerical models of shock wave heating agrees well with results of chondrule texture reproduction experiments [e.g., 2].

We examined the validity of the shock wave model from the viewpoint of iron sphere inclusions of chondrules. Recently, Uesugi et al. [3] have shown that strong apparent gravitational force (~40 G, G = gravitational acceleration on the earth's surface) acts on the molten chondrule precursor due to the drag deceleration of the shocked nebular gas. They have also shown that high speed internal rotational flow (~10 cm s⁻¹) is driven by the tangential component of momentum flux of the shocked nebular gas flow after total melting of the chondrule precursor (Fig. 1a). Based on these results, we calculated the trajectories of molten iron spheres in the chondrule precursor. The results show that the molten iron spheres are quickly (<3 s) ejected from the inside to the surface of the chondrule precursor due to the apparent gravitational force and centrifugal force of the rotational flow. Fig. 1b shows cross section of the dust particle sphere and trajectories of the molten iron spheres whose radii are 0.1 times that of the chondrule precursor. The iron sphere which was initially located far from the center of the circular flow is directly ejected to the surface of the chondrule precursor. The time scale of ejection is <0.1 s. On the other hand, the sphere that is located near the center of the rotational flow gradually migrates toward the outer rotational orbit and reaches the surface within 3 s. These time scales are quite short compared to the duration of chondrule precursor melting in the shock wave (~20 s) [e.g., 2].



Fig. 1. Flow and trajectories of iron spheres in the chondrule precursor.

We also performed observations on 41 chondrules, from meteorites Y790448 (LL3) and Y791558 (LL3.1), having spherical shapes that might have experienced the high degree of melting during the heating event. Large (>0.1 parent chondrule radius) iron spheres are found within 14 chondrules, but their distribution is quite random and we could not find any tendency. Though our observation is performed on thin sections, some tendency of the distribution of the iron spheres must appear if they are formed by the shock wave heating. These results strongly indicate that the shock wave heating could not be responsible for the chondrule formation.

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A NEW PRIMITIVE UNGROUPED ACHONDRITE, DHOFAR 500: LINKS TO WINONAITES AND SILICATE INCLUSIONS FROM IAB-IIICD IRONS

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Introduction: Dhofar 500 (Dho 500) is an unusual ungrouped achondrite from Oman. We report our preliminary results on the petrography, mineralogy, chemistry, and oxygen isotopic compositions of the meteorite, which appears not to fit in any groups of primitive achondrites. Dho 500 may have some links to winonaites and silicate inclusions of the IAB-IIICD irons.

Results: Dho 500 (116 g) is a weathered (W4), recrystallized, shocked (S4) polymict achondritic breccia, consisting of several different lithologies: 1) fine-grained Px-Ol-Pl of equigranular texture with triple junctions, 2) coarse-grained Ol-rich, and 3) coarse-grained poikiloblastic Px-Pl. The lithic fragments are embedded in a poikiloblastic Px-Pl matrix. The Ol-rich lithology is enriched in Cr-troilite (20 vol%), while the Px-Pl rock contains chromite. Olivine and pyroxene are of the same composition in all lithologies, and appear to be in equilibrium. Olvine (Fa_{4.8}) is similar in composition to that of winonaites (Win), silicate inclusions (SI) from IAB-IIICD irons, and ureilites (Ur). Orthopyroxene (En₉₅Wo₂) is close in chemistry to that of Win and SI. Pyroxene is higher in Mg# relative to acapulcoite-lodranites (Ac-Lod) (En84-88), Ur (En79-91), and brachinites (En_{70}) [1, 2]. The Fe/Mn ratio (6 at.) of pyroxenes is close to that of pyroxene in OCs and less than that of Ac-Lod and Ur pyroxenes. Pyroxene is richer in TiO₂ (0.24 wt%) in comparison with Ac-Lod and Ur. The significant contents of Cr2O3 and CaO in the Dho 500 olivine are not typical for Ac-Lod olivines and similar to those in Ur olivines. The feldspar (An13-14) composition of Dho 500 is close to that of Win and SI in IAB, but feldspar of SI in IIICD is more albitic (An1-6). Minor phases are Ca-rich augite (En52Wo44), Cr-bearing troilite, chromite, iron hydroxides, and rare Fe-Ni metal. Troilite is enriched in Cr (up to 3.11 wt%) in comparison to Win, Ac-Lod, and SI [3, 4] and close in Cr content to Ur [1]. No daubreelite was found. The total Tr/Met ratio and the modal content of Tr + Met (0.3%) are very low in comparison with Win, Ac-Lod. and SI.

In bulk composition, Dho 500 is higher in Mg# than Win and Ac-Lod. The Px-Pl lithologies are similar in bulk composition to SI in Landes (IAB) [1]. Unlike polymict Ur, Dho 500 has a narrow range of silicate compositions and is enriched in feldspar. The oxygen isotopic composition of Dho 500 is $\delta^{18}O + 9.21\%$, $\delta^{17}O + 4.29\%$, $\Delta^{17}O - 0.49\%$, out of any known meteorite composition fields, but close to Win, the SI of IAB-IIICD irons, and Ur [1, 5].

Discussion: Dho 500 is a primitive achondrite that experienced intensive thermal and impact metamorphism. In texture and mineral chemistry, Dho 500 is close to winonaites and the silicate inclusions in IAB and IIICD irons. However, the oxygen isotopic composition indicates that Dho 500 was formed in a distinct oxygen reservoir. The Cr-enrichment of troilite could indicate that Dho 500 was formed under more reducing conditions than other primitive achondrites, because partitioning of Cr in sulfide is dependent on fO_2 .

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LUNAR METEORITE DHOFAR 310: A POLYMICT BRECCIA WITH DEEP-SEATED LUNAR CRUSTAL MATERIAL

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Introduction: Dhofar 310 is a new lunar highland meteorite found in the desert of Oman nearby Dho 302, 303, 305, 306, and 307. This is the first lunar meteorite that contains material derived from a deep location of the lunar crust.

Results: Dhofar 310 is a small stone weighing 10.8 g. The meteorite is a clast-rich impact melt breccia containing numerous mineral fragments and clasts of feldspathic rocks embedded in a devitrified glassy matrix. Clasts of granulites and possible igneous rocks are abundant and have mainly anorthositic, troctolitic, and gabbronoritic compositions. The minor lithologies are impact melt breccias, pyroxenites, and dunites. Rare glass veins and fragments are present. One of the glass fragments is of a KREEPy composition (TiO₂ 2.63, Na₂O 0.76, K₂O 0.16, and P₂O₅ 0.27 [wt%]). The major minerals show a huge compositional range: feldspar An₉₃₋₉₈Or_{0-0.2}; olivine Fo34-88; orthopyroxene En54-89Wo1-5; clinopyroxene En25-77Wo5-46. The accessory minerals are Ti-rich chromite, ulvöspinel, pleonaste, ilmenite (2-7 wt% MgO), armalcolite, silica, troilite, and FeNi metal (2-32 wt% Ni; 0.4–3.0 wt% Co). The composition of the impact melt matrix is: SiO_2 43.6, TiO₂ 0.12, Al₂O₃ 29.2, Cr₂O3 0.06, FeO 2.84, MnO 0.05, MgO 5.79, CaO 17.8, Na₂O 0.39, and K₂O 0.01 (wt%). There is one unique fragment in Dho 310. This is a fragment of spinel pyroxenite. The clast, about 150 µm in size, consists of Al-rich orthopyroxene, En₈₉Wo1 (~7 wt% Al₂O₃), minor Mg, Al-spinel (Mg# 80, Cr/(Cr + Al) = 0.04 at.), and a single plagioclase grain (An₉₇). The mineral chemistry is similar to that of rare spinel cataclasites described from Apollo 15 and 17 highland breccias [1]. However, in contrast to the cataclasites, the Dho 310 pyroxenite does not contain any olivine.

Discussion: Dho 310 was found nearby to Dho 302, 303, 305, 306, and 307, which are possibly paired but, nevertheless, appear to be distinct [2-4]. In clast population and trace element contents, Dho 310 is most similar to Dho 305 and 307 which also contain abundant troctolite lithologies and rare dunitic and pyroxenitic clasts. However, Dho 310 appears to have a more polymict composition than the others and contains the main lunar non-mare lithologies, including KREEP. The presence of spinel pyroxenite indicates that the rock contains lithologies excavated from deep units of the lunar crust. The Al-rich orthopyroxene-spinel association points to high-pressure conditions [1]. Depth estimates, based on the mineral chemistry, show that the pyroxenite must have been derived from a depth of >20 km in the lunar crust or the uppermost lunar mantle. Thus, lunar meteorites can contain material of deep origin and should be searched for other high-pressure phase associations related to the lunar interior.

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THE NEWLY DISCOVERED JIDDAT AL HARASIS STREWNFIELD IN OMAN

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Introduction: The newly discovered strewnfield [1] is so far the largest found in the Sultanate of Oman. The nearly 3000 single stones collected range in weight from >54 kg down to <1 g (Fig. 1). The field shows a NW-SE orientation and covers an area of $\sim 20 \times 4$ km. The meteorite belongs to the H6 chondrites (Fa₂₃₋₂₅, Fs₂₀₋₂₂Wo_{1.4-1.7}, An_{9.9-11.8}). The material is only moderately shocked (S4). The meteorites contain frequently macroscopically visible, several mm-sized, ochre-weathering chondrules. Increased salt weathering of the stones is observed in sandy depressions. The weathering grade hence is strongly variable and ranges from 2 to 4. Within sandy areas, smaller stones show a higher weathering grade in general.



Fig. 1.

Isotopic results: Neon isotopic analyses of two samples yielded an average cosmic-ray exposure age of 30.6 ± 4.0 Ma. Cosmogenic ³⁸Ar was partly lost due to weathering of Fe, which is a major target element for ³⁸Ar production. Five ¹⁴C measurements on stones with variable weathering grade yielded ¹⁴C from 3.8 to 49.9 dpm/kg. Since these stones are all from the same fall, the range is only consistent with a meteoroid with a pre-atmospheric radius of >1.2m. Due to the size of the object, precise terrestrial ages can only be determined from ¹⁴C/¹⁰Be determinations [2]. However, the high values observed in one fragment suggests the shower may be due to a relatively recent fall.

Interpretation: The strong rounding by ablation and the good sorting of the stones within the strewnfield suggest disruption far from the ground. The varible weathering grade as a function of ground/soil composition indicates that the weathering grade is not a suitable criteria for defining pairings in areas where the underground geology is strongly variable.

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GERMANIUM ISOTOPE SYSTEMATICS IN METEORITES

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Introduction: Germanium is a moderately siderophile element which strongly partitions into core during metal-silicate differentiation of planetesimals. Its partition coefficient is strongly dependent on fO_2 conditions, which also control the volatility of Ge [1]. Ge is the most volatile siderophile element, suggesting potential isotopic fractionation during HT and specific fO_2 processes. In order to constrain the thermodymanic conditions of core-mantle differentiation, Ge isotopes have been measured in the IIAB magmatic and IAB non-magmatic Fe-meteorites, the latter being formed during the HT impact-melt model [2].

Methods: Ge isotopes are analyzed using an Isoprobe Multi-Collector ICP-MS with a precision better than 0.088‰ per amu (2σ total external reproducibility on replicate samples) (‰ δ^x Ge = [(*Ge/⁷⁰Ge)_{sa}/(*Ge/⁷⁰Ge)_{JMC} _{Std} - 1]*1000). Germanium was perfectly isolated from the matrix by liquid-liquid chromatography [3, 4].

Results and Discussion: The results for magmatic group (IIAB), nonmagmatic group (IAB), and UNGrouped samples are shown in Table 1 and Fig. 1.

Table 1. Average Ge isotopic compositions in Fe-meteorites.

0	1 1		
‰	$\delta^{72}Ge/^{70}Ge$	$\delta^{73}Ge/^{70}Ge$	$\delta^{74}Ge/^{70}Ge$
IAB	0.857 ± 0.168	0.609 ± 0.112	1.210 ± 0.236
IIAB	0.969 ± 0.274	0.785 ± 0.102	1.574 ± 0.21
UNGrouped	0.967 ± 0.216	0.663 ± 0.183	1.341 ± 0.273



Fig.1. Comparison of Fe-meteorites with terrestrial sphalerite (ZnS) and the Aldrich Ge standard.

All Fe-meteorites fall on a single mass fractionation line similar to the TMFL, with no isotopic anomalies, indicating a common isotopic source [5]. The Fe-meteorites are slightly enriched in heavy isotopes (δ^{74} Ge = 1.21 to 1.57‰) in contrast with the strong depletion of terrestrial samples (δ^{74} Ge = -4 to -1.76 ‰). This would indicate Ge isotopic fractionation during core-mantle differentiation and metal segregation related to density, under specific fO₂ or fS₂ conditions.

While UNGrouped samples cover the whole spectrum of Ge isotopic composition (in agreement with their large range in Ge contents), IAB and IIAB samples are distinct. The magmatic group has high δ^{74} Ge, which is positively correlated with Ge contents, while the non-magmatic group has lower δ^{74} Ge, which is negatively correlated with Ge contents, probably induced by liquid-liquid Ge partitioning and high temperature/pressure conditions during the impact process.

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A STUDY OF THE FRAGMENT DISPERSAL AND TRAJECTORY OF THE SAYH AL UHAYMIR 001 METEORITE SHOWER

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Sayh al Uhaymir 001 (SAUH 001) is one of Oman's largest known meteorite showers. We obtained hundreds of GPS find locations, analyzed the fragment distribution, and developed a model of the meteorites trajectory.

SAUH 001 is a stony meteorite shower (L4/5) found March 16, 2000. More than 2670 samples weighing more than 450 kg have been collected. The collected samples may be a large portion of the total mass of the meteorite body, because the surface in this region is hard and it is likely that only a small portion of the fragments penetrated the surface. GPS locations were obtained for 748 found samples to within 0,001 min (~2 m) (Fig. 1). We assume that the fragments were not moved after falling.





The ground track of the meteorite was modeled as follows: 1) determined center of mass (CM) of the fragment distribution; 2) fitted a line, weighted for fragment mass, through the CM along the long axis of the distribution in both directions. Increasing fragment mass along track indicated a flight direction of 233°.

The fragments' mass distribution was used to model the meteorite trajectory. In the model, the distribution depends on the speed of entry into the atmosphere (v), angle to the surface (α), and breakup height (H). We developed a computer program to calculate trajectories based on the distribution. For seven mass classes, we calculated the average mass and position along the ground track. We then varied v, a, and H to find solutions closest to the observed locations of the mass classes. To limit the solutions, we used the relationship between v and H at the destruction air flux A = $(\rho v^2)_{max}$:H = -h•ln(A/v• ρ_0), where ρ_0 is the sea-level air density and h is the scale height. A was taken as 6.5×10^6 , the average of several measurements for L chondrites [1]. The model yielded trajectory angle of 70-75° and breakup heights of 40 km with a meteorite velocity of 27 km/s, 30 km altitude with v = 15 km/s, and 25 km with v = 11 km/s. The meteorite may have broken up in several stages. For example, Pribram broke up gradually from 44 km down to 23 km altitude [2]. SAUH 001 samples show evidence of multi-stage fusion crust formation, suggesting multi-stage breakup.

Conclusion: Our model indicated the SAUH001 bolide travelled northeast to southwest, bearing 233° . The trajectory angle was $\sim 70^{\circ}$, with a probable velocity of 27 km/s. Our model gave a range of breakup altitudes similar to observations of Pribram. Breakup appears to have occurred in several stages.

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FURTHER EXAMINATION OF "PLANET-POLLUTION" AS A SOURCE FOR THE PARENTLESS RADIOGENIC NOBLE GASES IN LUNAR SOILS

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Surface-correlated noble gases implanted in lunar soils are known to contain parentless radiogenic components such as 40Ar, 129Xe, and fission Xe [1-3] that are not thought to be attributable to the solar wind (SW). These components have been assigned a lunar origin: radiogenic components produced in the lunar interior were degassed to the transient lunar atmosphere, and some of these degassed noble gasses were re-implanted to the lunar surface together with SW [4, 5]. However, this degassing hypothesis requires an untenably high degassing efficiency of radiogenic noble gases from the lunar interior. We, therefore, inferred that the parentless radiogenic noble gases may have been imported from an extra-lunar source(s), and suggested that "pollution of the sun by planetesimals/planets," inspired by recent studies on the extra-solar planetary system, could be responsible for these parentless radiogenic noble gases [6]. Since planets are likely to be volatile-deficient, the pollution effect will increase the star's metallicity. Radiogenic noble gas isotopes such as 40Ar, 129Xe, and 244Pu-fission Xe will be relatively enriched in a volatile-depleted planet because they were initially trapped in solid planetary bodies as "metallic" parent elements 40K, 129I, and ²⁴⁴Pu. For these isotopes, absorption of a planet can lead to changes in relative isotopic abundance.

To evaluate the effect of planet pollution on the SW, we compare noble gas flux in SW with the rate of noble gas pollution into the sun. In the case of Xe, we estimate the present 132 Xe in the SW to be 1.65×10^{31} atoms/a with the present SW ⁴He flux (6.3×10^6 atoms/cm² s at 1 AU) and the solar abundance ratio of 132 Xe/⁴He (4.57 × 10⁻¹⁰). If the sun was polluted by planetary materials of about two Earth masses, as suggested by [7], the total amount of the polluting radiogenic 129 Xe will be 2.4 × 10³⁹ atoms with chondritic values of I content (0.4 ppm) and ¹²⁹I/¹²⁷I (10⁻⁴). From the lack of crustal records in the Earth and abundant lunar craters before 4 Ga, we assume that planet pollution into the sun was limited to the first 500 Ma in solar history. Therefore, we infer that the polluting radiogenic ¹²⁹Xe flux will be 5×10^{30} atoms/a, i.e., about 30% of the total ¹²⁹Xe flux in the present SW. If a substantial fraction of the polluted radiogenic ¹²⁹Xe were re-ejected with SW and implanted in lunar soils, we would be able to observe excess radiogenic ¹²⁹Xe in lunar soils. From the criteria for tidal disruption [e.g., 8] and for atmospheric impact break up [e.g., 9] of impacting solid bodies, we infer that solid bodies are very likely to break up in the outer envelope of the sun, thereby allowing substantial re-ejection of the polluted ¹²⁹Xe with SW. In contrast to Xe, however, excess ⁴⁰Ar in lunar soils appears to be too large to be attributable to planet pollution alone.

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Introduction: It is well known that the chemical compositions of spinel group minerals and Fe-Ni metal can be used to distinguish chemical groups and petrologic types in ordinary chondrites. Here, we report the results of our systematic study of the oxides and Fe-Ni metal in eight LL3 (3.0–3.9), and LL4, 5, and 6 chondrites. We suggest that such mineral chemistry is not only useful for distinguishing secondary metamorphic processes (petrologic types), but also indicates primordial chemical features acquired prior to accretion to the LL parent body.

Spinel and Ti-Oxides: Kimura [1] and Tomiyama et al. [2] showed that chemical composition of spinel group minerals in type 3.0 chondrites varies widely in comparison with those in higher petrologic subtypes. Our new data are consistent with this observation, and we found that the atomic Mg/(Mg + Fe) ratios of spinel range from 0.01 to 1.00 in types 3.0-3.3, 0.04-0.61 in types 3.5-3.9, and 0.07-0.18 in types 4-6. In type 3.0-3.3, nearly pure chromite (<0.5% Al₂O₃ and <0.5 MgO) is encountered, typically as isolated minerals within the matrix. The chemistry of spinel group minerals is a good indicator of petrologic subtypes in ordinary chondrites.

We found three kinds of Ti-oxides: ilmenite, rutile, and perovskite in LL chondrites. Although perovskite is encountered only in a barred olivine chondrule in an LL3.2 chondrite (Y790448), this is the first discovery of perovskite in ordinary chondrites, except in refractory inclusions [e.g., 3]. Ilmenite is encountered in all LL3–6 chondrites studied here, although only a few grains are present in each section. The chemical composition of ilmenite depends on petrologic type; the MnO contents of ilmenite in types 3.0–3.3 are 0.2–0.5 wt%, while those in type 3.5–6 contain 0.7–2.6%. Rutile typically occurs in close association with ilmenite in LL3.0–3.3 chondrites.

Fe-Ni Metal: The metal data in LL3.1–6 chondrites are consistent with previous results [e.g., 4]. Kamacite grains have higher Co contents than taenite. On the other hand, Fe-Ni metal in LL3.0 chondrites (Y74660 and Semarkona) is different in chemistry from that in higher petrologic type LL chondrites. Although rare high-Co taenite was previously reported in LL3 chondrites [e.g., 5], we found that taenite, occurring as isolated grains and on the surface of chondrules, is enriched in Co (0.3-2.2%) in the LL3.0 chondrites. Taenite within the chondrules is depleted in Co (0.03-0.2%) and is typically associated with kamacite. Fe-Ni metal in the LL3.0 chondrites shows a weak positive correlation between Ni and Co. The metal in LL3.0 chondrites that in the CR clan chondrites [6]. Metal composition is a good indicator of the lowest petrologic subtype (most primitive) chondrites.

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Synopsis: The Widmanstatten pattern for the low P meteorites can nucleate if the martensite start temperature is crossed during cooling and before P saturation occurs. The Widmanstatten pattern in meteorites can be formed either by this mechanism for the low P meteorites or the by transformation $\gamma \rightarrow \gamma + Ph$. $\rightarrow \alpha + \gamma + Ph$ for P saturated meteorites.

Introduction: Several phase transformation mechanisms for the formation of the Widmanstatten pattern have been proposed. The reaction path $\gamma \rightarrow \gamma + Ph$. $\rightarrow \alpha + \gamma + Ph$. (type I) occurs at high P content [1]. Other reaction paths $\gamma \rightarrow \alpha + \gamma$ (type II), $\gamma \rightarrow \alpha + \gamma \rightarrow \alpha + \gamma + Ph$. (type III), and $\gamma \rightarrow \alpha 2 \rightarrow \alpha + \gamma$ (type IV) have been suggested for low P iron meteorites [1–3]. Type II–IV mechanisms are not entirely satisfactory to explain the Widmanstatten pattern in low P meteorites.

Phase Transformation Mechanism in Low P Meteoritic Fe-Ni Metals: We propose a new phase transformation mechanism (type V): $\gamma \rightarrow \alpha 2 + \gamma \rightarrow \alpha 2 + \alpha + \gamma \rightarrow \alpha + \gamma$. The nucleation temperature of the Widmanstatten pattern is given by Ms, the martensite start temperature [4]. This mechanism is supported by experimental data on a formation from γ in synthetic alloys [1, 5], by the measurement of Ni profiles and central Ni contents in plessite [6, 7], and by the simulation of the Widmanstatten pattern using the metallographic cooling rate method [3, 8]. The type V mechanism takes place for iron meteorites that are not P saturated at Ms. Fig. 1 shows the critical P content which separates the type I from the type V reaction path. It also shows that the Widmanstatten pattern in IVA and most of the IIIA iron meteorites (Fig.1, [9]) can be formed by the new phase transformation mechanism for the low P meteorites.



Fig.1. Type I versus type V reaction paths.

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SEDIMENT-DISPERSED EXTRATERRESTRIAL CHROMITE TRACES MAJOR ASTEROID DISRUPTION EVENT 480 MA

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More than forty fossil meteorites (1-20 cm in diameter) were recently recovered in mid-Ordovician (480 Ma) marine limestone in the Thorsberg quarry at Kinnekulle, southern Sweden [1]. The high abundance of meteorites deposited in ancient sea floor sediments indicates that the meteorite paleoflux was enhanced by up to two orders of magnitude compared to the recent flux [1, 2]. Here, we searched for sediment-dispersed extraterrestrial chromite grains [3-6] from sea floor weathered fossil meteorites in Ordovician limestones from five sites over a transect of 500 km in southern Sweden. Large samples, 7-45 kg, of lower to middle Ordovician orthoceratite limestone were searched for sand-sized chromite grains, which were analyzed for their chemical composition using EDAX-SEM equipment [1]. The results show that abundant extraterrestrial chromite grains (up to about 3000 m⁻² per bed) occur in middle Ordovician marine limestone over a >250,000 km² area in southern Sweden. At the five sites studied, beds of the same age as the meteorite-rich beds in the Thorsberg quarry typically yield about 20 extraterrestrial chromite grains per 10 kg of limestone. Orthoceratite limestone in the stratigraphic interval 2 to 9 m below the meteorite-yielding beds did not yield any extraterrestrial chromite grains, although as much as 195 kg of limestone was searched. The chromite anomaly in the meteoriterich beds gives support for a two orders of magnitude increase in the influx of meteorites to Earth during the mid-Ordovician. The increase in meteorite flux most likely reflects the disruption of the L chondrite parent body at about 480 Ma [7, 8]. Extraterrestrial chromite grains in mid-Ordovician limestone can be used to constrain, in detail, the temporal variations in flux of extraterrestrial matter to Earth following probably the largest asteroid disruption event in the asteroid belt in late solar system history.

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REE MICRODISTRIBUTIONS IN THE LHERZOLITIC SHERGOTTITE GRV99027

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Grove Mountains (GRV) 99027 has recently been identified as a lherzolitic shergottite, closely related to ALHA77005, LEW 88516, and Yamato-793605 [1, 2]. Hydrogen isotopic analysis of phosphates in GRV 99027 further indicated its martian origin [3]. Here, we report an ion probe study of REE microdistributions in individual mineral phases from this new martian meteorite and compare the results with previous data obtained for other lherzolitic shergottites.

Olivine in poikilitic areas occurs as round or euhedral crystals (0.1-0.5 mm) enclosed by large (up to several mm) oikocrysts of pigeonite. REEs are depleted (La ~0.3 CI and Lu ~0.2 CI) and display a V-shaped pattern in olivine. Pigeonite is quite abundant and has low REEs (Lu ~0.5-1 CI) with an HREE-enriched pattern. It commonly displays an upturn at La and a negative Ce anomaly. Augite is present in a lesser amount and usually occurs as irregular grains surrounding pigeonite crystals. It is relatively enriched in REEs (1-10 CI) and has an HREE-enriched pattern with a small negative Ce anomaly. Maskelynite is generally depleted in REEs (0.1-1 CI) with a large positive Eu (~15 CI) anomaly. The melt glass is enriched in REEs (7-20 CI) with a pattern parallel to the whole rock REE patterns of other martian lherzolites [4]. The accessory phase whitlockite is highly enriched in REEs (200-1000 CI) with an HREE-enriched pattern and a negative Eu anomaly. In general, REEs are essentially homogeneous within an individual mineral grain, but show small inter-grain variations. In particular, pyroxene in nonpoikilitic regions has higher REEs than in poikilitic areas.

The REE data confirm that GRV 99027 is indeed related to lherzolitic shergottites. The estimated whole rock REE abundances (La ~2 CI and Lu ~7 CI) of GRV 99027 are similar to those of other lherzolitic shergottites [4]. It is evident that GRV 99027, along with other lherzolitic shergottites, may have originated from the same lithologic unit on Mars. Their parent magmas were likely derived by partial melting of an already depleted source. However, GRV 99027 also exhibits some characteristics that distinguish it from other martian lherzolites. For example, pyroxenes in GRV 99027 have homogeneous REEs, while those in others display major, minor, and REE zoning [5]. This indicates that GRV 99027 may have experienced a higher degree of thermal metamorphism. In addition, olivine and pyroxenes in GRV 99027 commonly display LREE enrichments and a negative Ce anomaly, suggesting a longer residence time in the Antarctic environment and the addition of LREEs from terrestrial weathering.

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A MULTIPLE IMPACT EVENT AT THE END OF THE CARBONIFEROUS

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Synopsis: Multiple impact structures have been discovered in the Midland Valley of Scotland. These elliptical structures appear to have been produced by fragments of a large asteroid following a low-angle oblique impact event. Field evidence points to a date at the end of the Carboniferous period for this impact, similar to that of several known North American craters and suggesting that this was a global event which may have been implicated in the disappearance of the forests of Laurentia and Laurussia.

Introduction: The sudden disappearance of the forests of Laurentia and Laurussia at the end of the Carboniferous has been attributed to climate change. However, coal-producing forests thrived throughout the Permian in China and Siberia, which were separated from the main Pangean continent at the time [1], suggesting that some other agent was involved.

Two lines of evidence suggest that a multiple impact event was responsible for the deforestation. Analysis of known impact structures [2] shows that three small North American craters of approximately end-Carboniferous date lie (within 1.3 km) on a great circle, suggesting a common provenance. These craters are Decaturville (6 km diam, 300 Ma), Des Plaines (8 km, 280 Ma,) and Ile Rouleau (4 km, 300 Ma). Another 8 North American craters have similar ages. These could be secondary impact craters produced by fragments of a larger asteroid which broke up on impact following a low-angle oblique impact event. Statistically, this type of event should have happened at least once in Earth's history [3].

Field Observations: A previously unknown impact structure has been found in the Midland Valley of Scotland and is believed to be the site of the primary impact event. It has an elongated elliptical form $(18 \times 8 \text{ km})$ and is in the Loch Leven basin of east-central Scotland. It is surrounded on three sides by quartz-dolerite intrusions which were emplaced around the edges of the crater infill and have thus preserved its shape. Vestigial outcrops of impactites are preserved close to the quartz-dolerite, and field relationships demonstrate closely similar ages. These constrain the date of the structure to that of the intrusion (290 Ma). Lithologies include suevites, lithic breccias, friction-melt rocks, and impact melts. The structure has topographic features in common with lunar low-angle oblique impact structures [4], including lateral terraces and a central ridge which hosts the most highly-altered rocks. Sandstones of the structure contain planar deformation features (PDFs) in quartz, and a highly vesicular rock from the central uplift contains both unaltered quartz grains with PDFs and vesiculated quartz grains.

Downrange Structures: Two more probable impact structures have been identified in Central Scotland downrange of the Loch Leven structure. Both are elliptical in form and were probably produced by spalled fragments of the initial impactor. Identification is based on field evidence and petrologic data (PDFs). One of these structures is partly composed of basalts previously assigned to a widespread "volcanic" suite of the Scottish Midland Valley. If these rocks also prove to be impactites there may well be several more impact structures in central Scotland.

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LIMITING RSDI ACCURACY OF SPIN STATES ESTIMATION OF NEAR EARTH OBJECTS

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Introduction: Spin states of near-Earth asteroids (NEAs) can be estimated from optical light curves and by radar remotely from Earth. Since a cometary coma is nearly transparent at radio wavelengths [1], radar should be capable of detection and estimation of physical properties of a cometary nucleus. We analyze below the limiting accuracy of a new Earth-based radar technique, radar speckle displacement interferometry (RSDI) [2–4], to measure spin vectors of near-Earth objects (NEOs) independently and with better accuracy.

RSDI Accuracy: The limiting RSDI accuracy of spin components joint estimation by a two-element receiving interferometer with baselength b can be written analytically as [5]

$$= l m / qbn$$
 (1)

where $l = \lambda R/a$ is the correlation radius of the scattered radar field, R is the Earth-NEO distance, λ is the transmitted wavelength, a is the effective size of scattering area on NEO (e.g., for an NEO of ~100 m in diameter, we accept a = 20 m), m = v/v_Ω v is the velocity of speckle pattern displacement [6], v_Ω is the part of v caused by rotation, n depends on asymmetry and orientation of the NEO (for a spherical object, n = 1, for asymmetric objects, n = 1) [5], and q is the signal-to-noise ratio [2]. As applied to NEOs, the limiting accuracy, Equation 1, is about an order of magnitude better than that of the delay-Doppler radar. Computer simulation for several particular cases [7] showed that, in practice, the accuracy close to Equation 1 should be attainable. As applied to Doppler imaging, RSDI may give improved unambiguous orientation of the Doppler axis in space (to determine the orientation of the NEO from its image) and resolve the NEO's size ambiguity along this axis through transformation of the scale from Hz to meters in the first delay-Doppler image obtained.

NEAs: The spin state of asteroid 4179 Toutatis (size ~2–4 km) was determined by the delay-Doppler radar during the 1992 apparition (R ~0.026 AU) to uncertainty within a few percent [8]. The calculation of Equation 1 for those conditions gives ~10⁻³, i.e., the relative accuracy of ~0.001 in absolute value and ~3 arcmin in the direction of the NEO's aspect angle vector derivative. For a typical NEA of ~1 km in diameter at R ~0.07 AU, the RSDI limiting accuracy is ~10⁻². Also, from Equation 1, it follows that the spin states of smaller NEAs of ~100 m in diameter should be measured by today's radar and radio facilities to an accuracy of a few percent at R ~0.02 AU. In the last two cases, it seems to be hardly possible to obtain Earth-based estimates by a radar technique different from RSDI.

Cometary Nuclei: We hope that the RSDI technique can be especially helpful in the determination of spin states of cometary nuclei to the above accuracies. The detection of any rotating substance inside a comet would give valuable information about the physics of its nucleus. RSDI can be combined with the Doppler continuous mode radar observations, and we hope that RSDI experiments about NEOs will be prepared in near future.

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A PRELIMINARY REPORT ON THE MN-CR CHRONOLOGY OF FE-RICH OLIVINE IN THE KAINSAZ CO3 CHONDRITE MEASURED BY SIMS

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Introduction: The age of chondrule formation (relative to the ages of formation of CAI or some other meteorites) has been estimated based on Al-Mg chronology [1]. But, it is not yet established whether the differences in the inferred initial ²⁶Al/²⁷Al ratios are due to time difference or due to isotopic heterogeneity in the solar system. Mn-Cr chronology due to decay of ⁵³Mn (half-life of 3.7 Ma) is potentially useful for providing additional information on the age of chondrule formation. Previously, Mn-Cr chronology of bulk chondrules was studied by [2]. The initial ⁵³Mn/⁵⁵Mn ratios (~9.5E-6) for bulk chondrules were suggested to date the condensation of chondrule precursors. SIMS analyses of Cr isotopic compositions of constituent minerals in chondrules could reveal chondrule formation ages.

Description of Olivine: Fe-rich olivine is a major carrier of Mn and is depleted in Cr and, hence, is the main target for Mn-Cr dating. There are three possible types of Fe-rich olivine in the Kainsaz CO3 chondrite. First, there are Fe-rich olivine grains in type II chondrules which were formed by igneous fractionation form the chondrule melt. Fe and Mn concentration gradients in such olivine suggest that they may remember chondrule formation events. Such olivine grains in three chondrules with Fa >50% were analyzed. Second, there are small (typically 50 µm), irregular-shaped olivine fragments that are homogeneously Fe-rich. These grains often contain tiny speckles of chromite. Presumably, such olivine was formed from chondrule olivine by aqueous alteration and subsequent thermal metamorphism. Four such olivine grains with Fa >60% were analyzed. Third, there are olivine grains similar to the second variety but larger in size (typically 100 µm) and/or more idiomorphic in shape. Such olivine may have been formed by aqueous alteration and subsequent metamorphism of isolated forsteritic olivine. Alternatively, this third variety is could simply be a less altered version of the second variety. Two such grains were analyzed. Note that the first variety contains higher amounts of Ca than the second and third varieties and, hence, the latter grains were not fragments of the first variety. Note also that the Kainsaz is a breccia and may contain grains with various metamorphic histories

Results: Mn/⁵²Cr ratios in the olivine ranged from 30 to 210. The metamorphosed olivine grains tend to have higher ratios than the chondrule olivine (first variety with Mn/⁵²Cr ratios less than 80) because Cr is lost from olivine during metamorphism. Cr isotopic compositions ranged from normal to δ^{53} Cr = 11.8 ± 6.8 (2 σ) per mil. Olivine grains of the second variety tend to have smaller anomalies (normal within 2 σ errors). The first variety shows positive δ^{53} Cr = 9.1 ± 3.9 [2 σ] per mil). The third variety shows well resolved Cr isotope anomalies (δ^{53} Cr = 6.3 ± 2.5 [2 σ] per mil and δ^{53} Cr = 11.8 ± 6.8 [2 σ] per mil). The inferred Mn initial ratios for the three olivine grains with significant Cr isotope anomalies are not inconsistent with those (53 Mn/ 55 Mn ~9.5E-6) reported by [2], though errors attached to our data are quite large. More data will be presented at the meeting.

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SUPERNOVA II MODELS AND THE SI ISOTOPIC COMPOSITION OF MAINSTREAM SIC GRAINS

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Introduction: Mainstream presolar SiC grains are believed to have formed around carbon-rich asymptotic giant branch stars of metallicity similar to solar and initial masses in the range of 1.5 to 3 solar masses (e.g., see [1]). The initial silicon isotopic composition of these stars is affected by neutron capture nucleosynthesis that produces higher than solar ²⁹Si/²⁸Si and ³⁰Si/²⁸Si ratios. However, this effect is too small (up to 4%) to account for the anomalies observed in mainstream SiC grains (up to 20%). These anomalies have been attributed to variations in the initial composition of the stars due to the Galactic chemical evolution. In this scenario, a possible effect comes from incomplete mixing of stellar ejecta and subsequent inhomogeneities in the interstellar medium. Calculations by [1] showed that when this effect is taken into account, the silicon composition in SiC can be reproduced. These calculations used the yields from supernovae of type II (SNII) of solar metallicity computed by [2]. We repeated the calculations using updated SNII yields by [3], [4], and [5].

Results and Discussion: It turned out that the data measured in SiC can be matched in any case provided that: 1) the SNII yields are normalized to obtain the solar silicon isotopic ratios, and 2) the dilution factor of the supernova ejecta is varied within a factor of ten. To compute the solar composition, we considered the average of the SNII yields weighed with a salpeter initial mass function and we added a 20% contribution from supernovae of type Ia [6]. This is the same mixture that we considered when calculating the effect of inhomogeneities in the interstellar medium. To obtain the solar composition, we have to multiply the SNII yields of ²⁹Si and ³⁰Si by some factors depending on the SNII model used. These factors vary from 1.30 when using [2] to 2.05 when using [4] for 29 Si, and from 0.87 when using [2] to 1.25 when using [4] for ³⁰Si. The fact that ²⁹Si is underproduced with respect to solar was already noted and discussed in detail by [7], who computed the galactic chemical evolution of the silicon isotopes using the SNII yields of [2]. Future supernova models will have to address this problem. Once this normalization is done, we obtain very similar results by varying the dilution factor of the ejecta from 0.00003 when using [2] to 0.0002 in all the other cases. The Ti and Fe anomalies observed in SiC also have to be analyzed in this framework.

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NOBLE GASES IN 55 STONE METEORITES: A COMPARISON OF "OLD" AND "NEW" DATA AND IMPLICATIONS FOR EXPOSURE AGE DISTRIBUTIONS

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Introduction: Between 1963 and 1965, noble gas concentration and isotopic composition of about 170 stony meteorites were measured in Mainz using methods developed by F. A. Paneth and his students. Samples of about 5 to 10 g were degassed at 1500°C. After purification, the He was separated from Ne by adsorption and desorption on activated charcoal. The concentrations of He and Ne were measured separately with a Pirani gauge. The gas samples were then sealed in glass tubes and their isotopic composition later determined in a mass spectrometer. The data are not published but calculated exposure ages are discussed (e.g., [1]). The data are, however, incorporated into Noble Gas Compilations [2]. During recent years, we have remeasured 55 of these samples with our present procedures [3] and compare here the old and new data, including the calculated exposure ages.

Results: Concentrations of ³He in old and new analyses generally agree within a few percent, but the ²¹Ne concentrations are about 20 to 30% lower in the old measurements, possibly due to incomplete degassing of the old samples. The old Ne isotopic data are systematically biased because they are normalized to values [4] that were revised in 1965 [5]. This effect—about 2.5% per mass unit favoring the lighter masses—is not corrected in the compilation but is done in this comparison. But, even with this correction, the old cosmogenic ²²Ne/²¹Ne ratios tend to be too low by a few percent. The reason for this discrepancy is not known.

Discussion: ²¹Ne is preferred for the calculation of exposure ages because ³He can be affected by diffusive loss due to even moderate solar heating. Cosmogenic ²²Ne/²¹Ne is used as a shielding parameter for production rates (see [6]). Low ²²Ne/²¹Ne ratios will result in high production rates. This effect, together with low ²¹Ne concentrations results in old analyses displaying a lower exposure age when compared to modern ones. This comparison is shown in Fig. 1.



Fig. 1. Comparison of exposure ages calculated from old and new analyses.

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NUCLEOBASES IN CARBONACEOUS CHONDRITES

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Carbonaceous chondrites contain up to 3% organic matter, most of which is locked into an insoluble component. The bulk nitrogen content of the insoluble organic matter (IOM) is low (~2 wt%), resulting in a C/N ~55. However, some of the soluble components have very low C/N. Glycine, the simplest amino acid, has a C/N of 2. In addition, nucleobases have even lower C/N. The purines adenine and guanine have a C/N of 1, while the value for the purines hypoxanthine and xanthine is 1.25. The pyrimidine uracil has a C/N of 2 (Fig.1).



Fig. 1. Chemical structures of nucleobases.

Our research aims to determine the origin of purines and pyrimidines in carbonaceous chondrites. These compounds, which are one- or two-ring aromatic compounds containing several nitrogen atoms in their rings, play a major role in terrestrial biochemistry. They are central components of DNA and RNA, molecules that are used in the storage, transcription, and translation of genetic information in all terrestrial organisms.

We report on the abundances of these compounds in carbonaceous chondrites [1, 2]. In addition, we will determine the stable isotope ratios for carbon and nitrogen in individual compounds, which will help us to trace the synthetic pathway of these compounds.

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THE NOBLE GAS RECORD OF CENTRAL EUROPE'S STONE METEORITES

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Introduction: Central Europe is defined as the region between 46– 57°N and 3–21°E. We report here on noble gases of all meteorites recorded in this sector, which includes Austria, Belgium, Czech Republic, Denmark, Germany, Netherlands, Republic of Slovakia, Switzerland, and parts of Croatia, France, Hungary, Poland, and Sweden. The total number of stony meteorites known from this area is 90. Noble gas analyses of 57 specimens have been previously published (see [1]). We present here 31 new meteorite analyses and calculated exposure ages.

Results: Table 1 shows the results of the 31 new analyses. Rumanova, Wernigerode, and possibly Nagy-Borovè contain solar gases and are thus regolith breccias. The sample of St. Denis Westrem exhibits a very high cosmogenic ²²Ne/²¹Ne ratio and must come from a rather unshielded position. Additionally, with its low exposure age, St. Denis Westrem might be a good candidate for studying the influence of solar cosmic rays on meteoritic matter.

Table 1. Concentrations of ⁴He, ²⁰Ne, and ⁴⁰Ar (in 10^{-8} cm³ STP/g) and the ²¹Ne-exposure age (T21 in Ma) calculated according to [2] with cosmogenic ²²Ne/²¹Ne as a shielding parameter.

C	Class	⁴ He	²⁰ Ne	⁴⁰ Ar	²² Ne/ ²¹ Ne	T21
Aachen	L5	680	5.35	5265	1.152	20.0
Aarhus	H6	1326	2.11	6576	1.179	9.2
Barntrup	LL4	830	8.84	3914	1.127	30.3
Chervettaz	L5	1677	10.68	7052	1.118	36.2
Gross-Divina	H5	1522	3.90	3608	1.193	17.7
Grzempach	H5	308	2.08	2760	1.164	8.6
Hedeskoga	H5	265	1.65	2130	1.204	7.5
Les Ormes	L6	1080	15.23	5691	1.089	45.5
Lesves	L6	1238	7.07	5722	1.251	33.9
Lillaverke	H5	1650	1.68	5769	1.246	8.8
Linum	L6	860	6.57	6520	1.208	29.4
Lundsgard	L6	489	4.97	3283	1.108	15.8
Menziswyl	L5	1228	13.87	2917	1.089	41.7
Mern	L6	1568	6.77	6295	1.154	25.7
Meuselbach	L6	754	15.00	3335	1.087	44.1
Minnichhof	?	983	6.64	6526	1.120	22.5
Morávka	H5-6	388	1.88	3173	1.071	5.5
Mühlau	?	1377	1.77	5920	1.073	4.8
Neuschwanstein	EL6	1410	15.92	6068	1.137	51.4
Nagy-Borovè	L5	1017	9.96	3799	1.110	9.3
Ploschkovitz	L5	843	3.67	4679	1.076	10.3
Prambachkirchen	L6	330	5.94	772	1.230	27.4
Rumanova	H5	4930	17.00	4540	1.110	9.2
Sazovice	L5	163.2	1.84	544	1.208	7.8
Schönenberg	L6	1015	16.42	7033	1.087	48.5
St. Denis Westrem	L6	876	0.35	6350	1.319	1.6
Ulmiz	L	690	2.57	4859	1.107	8.1
Usti nad Orlici	L6	1170	5.52	6084	1.231	25.7
Villedieu	H4	1331	2.35	3731	1.094	7.7
Wernigerode	H5	7217	15.96	5252	1.110	7.2
Wessely	H5	1385	2.55	6100	1.105	8.7

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SAYH AL UHAYMIR 150 - A FURTHER FRAGMENT OF THE SAU-SHERGOTTITE SHOWER

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Introduction: On October 8, 2002 a suspected stone meteorite of 107.7 g was found on a gravel plateau of Miocene fresh-water limestone [1] 43.3 km south of Ghaba, Oman. It was discovered by R.Bartoschewitz and his son.

Petrography and Mineralogy: The angular stone exhibits macroscopically dark brownish-gray crystals in an olive-gray matrix with one small area of black-brown fusion crust about 1 cm^2 . Additionally, the cut surface shows vesicles up to 2 mm. Some of these are filled with white alteration products (calcite, gypsum).

Thin sections show a micro-gabbroic texture of brownish porphyric olivine up to 3 mm embedded in a matrix of prismatic clinopyroxene crystals up to 2 mm and interstitial maskelynite, accompanied by several opaque minerals. Mostly brown, feathery recrystallized melt pockets and veinlets are present. The olivine shows small, dark melt inclusions and strong mosaicism. Twin lamellae of clinopyroxene are parallel to (001) and sometimes slightly curved. Point counting of two thin sections of 40 mm² each yielded: olivine = 23 vol%, clinopyroxene = 56 vol%, maskelynite = 17 vol%, opaque minerals = 1 vol%, and melt and holes = 3 vol%.

Microprobe measurements were performed with a JEOL JXA 8900 R microprobe at the University of Kiel. The minerals are in the following compositional range: Olivine Fo_{64–67}, FeO/MnO_{50–57}; Pigeonite En_{62–69}Wo_{7–11}; and Maskelynite An_{53–66}Or <1.

Rare pyroxene with $En_{65-66}Fs_{34-35}$ is interpreted as orthopyroxene based on Wo <5 [2].

The texture and mineralogy reflect a basaltic shergottite with relations to the lherzolitic (wehrlitic) shergottites. According to [3], SaU 150 should be classified as olivine-phyric shergottite. O-Isotopes $\delta O^{17} + 2.78$ and $\delta O^{18} + 4.74$ plot in the SNC field and confirm the petrological classification.

Pairing: Petrological data and mineral-chemistry of SaU 150 meet those of the well described SaU 094 [4] and the further five published olivine-phyric shergottites SaU 005/008/051/060/090 discovered within an area of approximately 3.3 km² between 1998 and 2002 [5–7]. Thus, SaU 150 is most probably paired with them.

A pairing of SaU shergottites with the very similar Dar al Gani 476/489/ 670/735/876 shergottites from Libya was also under discussion [8, 9]. Nishiizumi et al. presented a 14 C- 10 Be terrestrial age of about 60 kyr for DaGshergottites [9], while for SaU 005, they reported about 13 kyr [10], confirming two distinct terrestrial events.

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PETROGRAPHIC CRITERIONS OF THE IMPACT ROCKS SUBDIVISION

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Uniform and internationally accepted systematic petrology, subdivision, and terms for impact lithologies originate during impact cratering do not exist so far [1, 2, 3, 4, 5]. All these conceptions should be based on the general principles adopted for classification and nomenclature of igneous, metamorphic, and sedimentary rocks [6, 7]. The proposed classification is grounded on several petrographic criterions: 1) aggregate state and mineral composition; 2) modal composition; and 3) textural and structural features. This approach allows us to compile discriminating tables for distinguishing rock species; non-descriptive proper names have been used for them. For a systematic classification, mode of occurrence and mode of origin may be taken into account.

Impact rocks are produced by the transformation of target rocks (shock metamorphism, fusion, displacement). This taxon (i.e., rock type) is equivalent to the terms sedimentary, magmatic, and metamorphic rocks. Impact rocks are also named coptogenic rocks (from the Greek "copto": to destroy by shock [3, 8]). Impact rocks are further divided into three groups. Shock metamorphosed rocks are target rocks displaying shock features and occasionally initial melting. The primary texture of the precursor rocks may be still discernible. Impact lithic breccias consist of fragments of unshocked and shocked target rocks. Impact lithic breccias are subdivided according to clast: 1) content, 2) composition, and 3) size. The glass-bearing varieties may contain <10 vol% of the impact glass. Impactites are regarded as rocks consisting completely or to a considerable extent (conventionally >10 vol%) of chilled or crystallized impact melt with various amounts of lithic and mineral clasts. This restricted use of the term is in keeping with its primary meaning [3, 8, 9, 10]. This rock group includes two rock species: tagamite and suevite. Tagamite is a massive impactite, the matrix of which consists of impact glass and/or minerals and commonly encloses various amount of lithic or mineral clasts. The subdivision of tagamites into several varieties is based on crystallinity, texture, and clast content. The holocrystalline coarsegrained varieties may be classified and named using the criterions applied to igneous rocks. In this case, the letter "c" (crater-related) may be added (e.g., c-norite, c-monzonite, etc.). Suevite is a breccia with a clastic matrix composed of glass, lithic, and mineral fragments. Suevites are further divided according to the abundance and size of the clasts (ash, lapilli, bomb) and their composition (vitro-, litho-, crystalloclasts).

Aside from the impact rocks, some other minor rock groups occur at craters produced by dislocation and thermal metamorphism.

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THERMAL EFFECTS ASSOCIATED WITH THE FORMATION OF CUMULATE EUCRITES, INCLUDING YAMATO-980318

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Introduction: Cumulate eucrites include a broad compositional spectrum of igneous rocks, ranging from magnesian feldspar cumulates (e.g., Serra de Magé with a bulk Mg# of 58.4 [1]) to ferroan heteradcumulates that are composed of plagioclase enclosed in poikilitic Fe-rich augite with an Mg# of 20.7 [2]. These medium- to coarse-grained eucrites display variable degrees of enrichment in pyroxene or plagioclase. Compositional and mineralogical variations among these igneous rocks suggest fractional crystallization with associated cumulus processes in magma chamber(s) intruded into the crust of the HED parent body (4 Vesta).

Data: Yamato-980318 (Y-980318) was recovered by the Japanese Antarctic Research Expedition in 1998. The medium-grained meteorite (166.81 g) has a weathering classification of B/C [3] and is composed of blocky white feldspars and anhedral brown pyroxenes with rare grains of chromite, ilmenite, and a silica mineral. Mild to moderate shock caused undulating extinction and the mosaic texture of feldspars. Pyroxenes have relatively sharp extinction, but rare faults offset exsolution lamellae.

Feldspar has a range of composition, Ab_{6.5-12.8}An_{93.1-86.8}, and is slightly reverse zoned. Similar reverse zoning of feldspar was described in the cumulate eucrites Medanitos and Moama (e.g., [4]). Commonly, pyroxene host is Wo_{2.0}En_{50.9}. An inverted pigeonite composed of Wo_{1.8}En_{51.6} occurs in the center of some grains. Exsolution lamellae include a thick set (up to 30 μ m wide) with a composition of Wo_{45.0}En_{36.7}. A thinner set (up to 5 μ m wide) has a composition of Wo_{44.7}En_{37.2}. Finer sets, some of them blebby, also occur. These pyroxene compositions and exsolution textures are similar to those described in the cumulate eucrite Moore County [5].

Modal analysis of a thin section and of areas of the surface that are not covered by fusion crust (total $>7 \text{ cm}^2$) suggest 34–38% feldspar. The meteorite has a bulk Mg# of 53.6, which is similar to that of Moore County (Mg# 52.1) [1]. Hence, composition, mineralogy, and exsolution textures suggest that Y-980318 crystallized and cooled in the same or a similar environment as Moore County.

Discussion: Mineral chemistry and exsolution textures suggest that each cumulate eucrite experienced a different rate of subsolidus cooling, probably at depths ranging from 3 to 8 km [6]. Hence, a reasonable model for formation of these igneous rocks is in a series of magma chambers intruded into a basaltic crust formed by serial magmatism (see also [7] and [8]). Metamorphism of the crustal material surrounding these magma chambers was not solely the result of the geothermal gradient of 4 Vesta, but was complicated by contact metamorphism. Hence, limited volumes of noncumulate eucrites that were originally extruded onto the surface of 4 Vesta might have subsequently been metamorphosed at relatively shallow levels.

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MN-CR CHRONOLOGY OF THE D'ORBIGNY ANGRITE

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Introduction: Previous Pb-U-Th and Mn-Cr isotopic investigations of the Angra dos Reis (ADOR) and LEW 86010 (LEW) angrites demonstrated that the relative ⁵³Mn-⁵³Cr chronometer could be mapped onto an absolute time scale [1]. We have extended this research to include the D'Orbigny angrite where a precise Pb-Pb age for pyroxenes in this meteorite has recently been obtained [2]. Here, we report Cr isotopic abundances and Mn/Cr ratios in chromite (Chr), glass (Gls), and bulk rock samples from D'Orbigny.

Results and Discussion: Figure 1 shows ⁵³Cr excesses and Mn/Cr ratios determined for the various fractions of D'Orbigny. The data points for the bulk rock and chromite define an isochron whose slope corresponds to an initial ${}^{53}Mn/{}^{55}Mn$, I(Mn) = (2.85 ± 0.11) × 10⁻⁶ and an initial ${}^{53}Cr/$ 52 Cr, $\varepsilon(53)_0 = 0.35 \pm 0.06$ at the time of isotopic closure. The 53 Mn/ 55 Mn ratio for D'Orbigny is more than two-fold the ${}^{53}Mn/{}^{55}Mn$ ratio of (1.25 ± $(0.07) \times 10^{-6}$ previously calculated for LEW [1]. Since the Pb-Pb age of LEW has been precisely measured at 4557.8 ± 0.5 Ma [3], we calculate an absolute Mn-Cr age of 4562.2 ± 0.6 Ma for the D'Orbigny bulk rock, which is in close agreement with the Mn-Cr age of 4561.6 ± 0.5 Ma determined by [4]. Although the Pb-Pb age of 4557 ± 1 Ma for pyroxenes in D'Orbigny [2] is comparable to the Pb-Pb ages for ADOR and LEW [4], this age is considerably younger than the Mn-Cr bulk rock age for D'Orbigny. The older Mn-Cr age of the D'Orbigny bulk rock relative to the Pb-Pb age of pyroxenes could be due to the presence of glass in D'Orbigny, which has a higher ⁵³Mn/⁵⁵Mn ratio than the bulk sample (see Fig. 1).



Fig. 1.

Conclusion: The Mn-Cr age for the D'Orbigny bulk rock sample of ~4562 Ma is 4 to 5 Ma older than the Pb-Pb ages reported for the angrites ADOR and LEW. Therefore, D'Orbigny likely represents an earlier stage in the evolution of the angrites.

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LUNAR METEORITE SAU 169: AN EXTREMELY KREEP-RICH ROCK

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Introduction: Sayh al Uhaymir 169 is a new lunar meteorite [1] collected in Oman in January 2002 (Fe/Mn of 74–79; K/U of 535–1682; $\Delta^{17}O = 0.001 \pm 0.032\%$). Sayh al Uhaymir consists of an extremely KREEP-rich (Th = 32.7 ppm; U = 8.6ppm; K₂O = 0.54wt%; REE_{tot} = ~1330 ppm; P₂O₅ = 1.14wt%; Zr = 2835ppm), anorthosite-free impact-melt breccia and adherent KREEP-rich regolith (Th = 8.4 ppm).

Impact Melt Breccia: The fine-grained crystalline matrix consists of 85.1% shortprismatic, low-Ca pyroxene ($En_{61-64}Wo_{2-4}$), 26.4% interstitial plagioclase (An_{75-81}) intergrown with potassium feldspar. The remaining minerals are poikilitic ilmenite, whitlockite, olivine (Fo_{58-59}), zircon, and traces of troilite, kamacite, and tridymite. The impact melt breccia contains 25–40 vol% of strongly shocked magmatic rock and crystal clasts derived from norites, evolved magmatites, and granulites. Only one KREEP basalt clast was observed.

Regolith: The regolith contains two clearly separable parts. Both parts comprise crystalline and glassy volcanic rocks, magmatic lithic fragments, breccia fragments, fragments of mafic granulites, and crystal fragments. The younger regolith is bordered by a gas-bubble-rich, yellowish, flow-banded glass and contains yellow and orange glass fragments and beads, olivine-basalts, and pyroxferroite-bearing basalts.

Interpretation: Combined chemical and isotope information, regolith mineralogy, and remote sensing data [2–3] show that the rock most likeley represents a fragment from the Imbrium impact melt breccia excavated by another impact. After this event, the material remained >200 Ma as part of a regolith near the surface of the moon. Finally, it was launched into space at a maximum of 0.85 Ma ago before colliding with Earth at the end of the last large glaciation 9700 \pm 1300 yr ago.



Fig. 1.

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EXPERIMENTAL SHOCK REEQUILIBRATION OF FLUID INCLUSIONS

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Introduction: While fluid inclusions in terrestrial rocks are the rule rather than the exception, only a few fluid inclusion-bearing meteorites have been documented [1, 2, 3, 4]. This rarity of fluid inclusions in meteoritic material may be explained in two ways. First, it may reflect the absence of fluids on meteorite parent bodies. Alternatively, any fluid inclusions originally trapped on the parent body may have been destroyed by the extreme P-T conditions meteorites often experience during impact events. Just as textures, structures, and compositions of mineral phases can be significantly altered by shock metamorphism upon hypervelocity impact, fluid inclusions contained within component minerals may be altered or destroyed due to the high pressures, temperatures, and strain rates associated with impact events. Re-equilibration may occur when external pressuretemperature conditions differ significantly from internal fluid isochoric conditions. This may result in changes in fluid inclusion properties and/or textures. By understanding the effects of shock deformation on fluid inclusion density and textures, we hope to better constrain the pressuretemperature path experienced by shocked materials and also gain a more clear understanding of the reason that fluid inclusions are rarely found in meteoritic samples.

Results: Aqueous fluid inclusions in single crystal quartz disks were documented and their homogenization temperatures measured before and after flat plate accelerator impact experiments [5] over a range of maximum shock pressures of 5-30 GPa. By comparing the pre- and post-impact fluid inclusion data, the effects of shock re-equilibration were qualitatively (textures) and quantitatively (homogenization temperatures) observed. These results show that fluid inclusion textures undergo a systematic and gradual evolution with increasing, albeit modest (5-10 GPa), shock pressures. Slight stretching evolves to decrepitation (leaking), collapse, and finally complete disappearance of any pre-existing fluid inclusions as pressure increases to 10 GPa, modestly above the Hugoniot elastic limit [6]. Results of these experiments suggest that fluid inclusions undergo a decrease in volume (collapse) within the first few microseconds following impact as the shock wave moves through the sample, producing a relatively high pressure external environment compared to the lower pressure in the inclusion. If the fluid inclusions survive this event intact, the initial volume decrease is overprinted by stretching due to internal overpressures experienced during sustained high temperature conditions as the decompressed rocks cool following the shock event. This portion of the P-T cycle leads to an increase in inclusion volume and homogenization temperature and, possibly, decrepitation.

Conclusions: This experimental study suggests that fluid inclusion textures may provide constraints on the maximum shock pressure experienced by the sample. These results also indicate that the absence of fluid inclusions in meteoritic materials does not preclude the presence of fluids on meteorite parent bodies. Instead, relatively modest shock processes may have destroyed all previously trapped fluid inclusions.

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C₆₀ IN CONDENSED SOOT ANALOGS: IT SHOULD BE A COMMON METASTABLE ASTROPHYSICAL CARBON

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Introduction: The search for C_{60} among interstellar and circumstellar dust, including the solar nebula as enclosed in meteorites and interplanetary dust particles (IDPs), has not yet produced unambiguous evidence for this elemental carbon. Yet, He and Ne associated with carbon materials require efficient trapping sites, e.g., nanotubes or fullerenes [1]. A C-XANES study of the carbon-rich IDP L2008F4 showed a peak at 286.3 eV that could be due to C_{60} [2]. As part of a long-term program to identify carbon spectral signatures in astrophysical settings, a detailed study of condensed carbon onions, and chain-like aggregates (CLA) [3]. We report TEM and chemical analyses of soot grains.

Analog Production and Characterization: Soot samples are produced by arc discharge between amorphous carbon electrodes in a hydrogen and/or Ar atmosphere at 10 mbar pressure and preselected proportions of: 1) Ar = 100%; 2) Ar = 99.6%, H₂ = 0.4%; 3) Ar = 99.2%, H₂ = 0.8%, 4) Ar = 90%, H₂ = 10% and 5) Ar = 70%, H₂ = 30%. The condensed carbons are directly deposited onto silicon wafer chips for SEM analyses [3] and on glass slides for other analyses, such as high-resolution TEM. Soot samples where dissolved in toluene for HPLC and mass spectrometer analyses to identify low-number fullerenes and to search for C_n with n >240.

Results and Discussion: Individual soot grains of the CLA carbon [3] are crystallographically amorphous and consist of individual single-wall rings, i.e., mainly spheres with diameters from 0.7 nm to 10 nm that form random, close-packed arrangements. These rings are also observed in short and straight, or long and curved, liner arrangements called proto-fringes with a thickness corresponding to the diameters of the single-wall rings. The presence of proto-fringes (either a single one or a stack of 3–5 layers) suggests that very small-scale sorting occurred during agglomeration in soot grains. The single-wall rings resemble structures in synthetic C_{60} crystals, including C_{50} , possibly C_{32} , and larger elongated fullerenes [4]. Rare spherical structures (10–25 nm in diameter) surrounded by several concentric circular fringes are present within CLA soot grains. The fringe spacing is consistent with increasing diameters of nested fullerenes [5].

HPLC and mass spectroscopy analyses confirmed that the single-wall rings, 0.7 nm diameter, in the soot grains are C_{60} fullerene. Significant amounts of a C_{120} dimer were detected by HPLC. The TEM data of single-wall rings with a diameter >0.7 nm define a linear correlation that could correspond to an increasing number of carbon atoms in larger single-wall rings. When C_{60} is a metastable carbon, fusion of this fullerene into larger single-wall rings might be a spontaneous growth process that would lead to giant fullerenes. While such giant fullerenes are not confirmed in the samples, the exact physical conditions during C_{60} condensation may determine its long-term survival. Once "isolated" inside agglomerated soot grains, C_{60} might survive for a long, as yet undetermined, time in condensed circumstellar carbon dust that didn't suffer post-condensation thermal annealing. Presolar C_{60} would be a major find.

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CRYSTAL STRUCTURE OF METEORITIC SCHREIBERSITES: DETERMINATION OF ABSOLUTE STRUCTURE

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Introduction: The crystal structure of meteoritic schreibersite was solved and refined [1, 2] from data collected on rhabdite from the North Chile (Tocopilla) meteorite. The structure is identical to that found for synthetic compounds Ni₃P [3–5] and Fe₃P [6]. The space group $I\bar{4}$, in which schreibersite crystallizes, is non-centrosymmetric. This results in two possible spatial arrangements of atoms within the unit cell—so called absolute structure (see [7, 8] for details). Studies of the absolute structure were not performed in earlier single crystal refinements, and more recent powder diffraction studies did not allow checking the data for correct absolute structure.

Data Collection and Evaluation: Data for crystal structure refinements were collected using 4-circle, single-crystal diffractometers with MoK α radiation and processed with SHELX-97 [9] and WinGX [10] programs. The results of the refinements are given in Table 1.

Table 1. Results of the crystal structure refinement.

Meteorite	Carlton	Odessa, crystal 1	Odessa, crystal 2	Sikhote Alin	Toluca
Reflections collected	562	536	494	540	308
Bijvoet pairs	242	235	216	237	131
Reflections range (h)	-12, 12	0, 12	-12, 12	-12, 12	-10, 10
Reflections range (5)	-12, 13	-12, 12	-11, 12	-12, 12	0, 10
Reflections range (l)	-6,6	0, 6	-6, 6	-6, 6	0, 5
R _{All}	0.0434	0.0236	0.0292	0.0307	0.0851
wR _{All}	0.1114	0.0638	0.0719	0.0761	0.2152
Flack parameter (x)	0.06(8)	0.01(5)	0.18(5)	0.03(5)	0.1(1)
Absolute structure	inverted	inverted	normal	inverted	inverted

Conclusions: Four of five refinements carried out on schreibersites from various meteorites revealed the inverted crystal structure compared to the standard setting given in previous studies. The only structure compatible with the standard setting represents the refinement of rhabdite crystal from Odessa. This observation may imply some dependence of the absolute crystal structure of schreibersite on conditions of its formation and should be tested in more detail.

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EVIDENCE FOR SHOCK MELTING OF CARBONATES FROM METEOR CRATER, ARIZONA

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Introduction: The response of carbonate rocks to hypervelocity impact remains a controversial subject within the impact community. Many questions remain to be answered, such as the relative importance and role of impact melting versus decomposition. Here, we present the results of an analytical SEM study of carbonate-bearing, impact-melted materials from the Meteor Crater, Arizona.

Samples and Geological Setting: Cm-size, vesiculated impactites were collected outside the crater about 150 m down from the top of the crater rim on the SE slope. Of the hundreds that were sectioned, five are composed of >90% pyroxene accreta, internal pyroxene enclaves, and carbonates.

Petrography: The samples studied possess >95 vol% crystals, predominantly euhedral or skeletal clinopyroxene of variable composition (En₃₈₋₄₇Fs₇₋₂₃Wo₄₂₋₄₇), skeletal olivine (Fo₉₀₋₉₆Fa₄₋₁₀), carbonate, and barite (BaSO₄). These pyroxenes and olivines are more Ca- and Mg-rich, respectively, than in previously studied impactites from the Meteor Crater [1]. Fe-rich pyroxenes typically occur in circular to irregularly shaped enclaves in a "host" of more Ca-rich clinopyroxene. Carbonates are present in three distinct settings in these samples: 1) isolated spherules (up to ~200 µm in diameter) composed of either entirely CaCO₃, or zoned examples with rims of CaCO3 and Mg-rich cores; 2) euhedral to anhedral crystals of CaCO3 within a groundmass of clinopyroxene; and 3) irregularly-shaped "pockets" of carbonate within enclaves of Fe-rich pyroxene. A sharp contact between the two phases always exists, with euhedral crystals of calcite projecting into the pyroxene and vice versa. The pockets are typically zoned, from CaCO₃ to Mg-rich cores. SEM EDS analyses reveal that the carbonates in all these settings can contain up to ~0.8 wt% SiO2 and ~0.4 wt% Al2O3.

Origin of the Carbonates: Two explanations are possible for the origin of these carbonates: 1) aqueous alteration, or 2) impact melting. Vesicles are present within crystallized regions of these samples. However, they are typically irregularly shaped and are either empty or infilled by debris. It would be rather fortuitous if only the perfectly spherical vesicles were infilled by carbonate. Furthermore, no evidence for aqueous alteration has been observed in these samples, except on their surfaces. The presence of euhedral crystals of calcite within a groundmass of pyroxene and the intergrowth of calcite with pyroxene at the edge of carbonate pockets is hard to reconcile with an origin through alteration but is consistent with an impact melt origin for the carbonates. The presence of SiO₂ and Al₂O₃ in carbonates has been recognized at the Haughton and impact structure and is interpreted as rapid crystallization of carbonate minerals from a melt [2].

The melting of carbonates is also supported by the unusual composition of associated pyroxenes and olivines: Ca-rich pyroxene (diopside/ wollastonite) and Mg-rich olivine (forsterite) in these samples are common in carbonatitic igneous rocks. We also note that these minerals are also common products of the breakdown of siliceous carbonates during metamorphism. This suggests an origin for these impactites through the shock melting of part of the dolomite and sandstone-bearing Kaibab Formation.

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AL MALA'IKA (NWA 1669): A NEW SHERGOTTITE FROM MOROCCO/MINERALOGY AND PETROLOGY

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Introduction: Al Mala'ika (NWA 1669), a meteorite of 36 g found in 2001, has recently been identified as a shergottite. The single stone is covered with a desert varnish with a few remnants of fusion crust.

Al Mala'ika is a fine grained rock with two closely intricated pyroxenes: pigeonite $En_{58-25}Wo_{9-19}Fs_{32-61}$ and augite $En_{47-19}Wo_{39-24}Fs_{54-18}$. Their FeO/MnO ratio of 34 on the average is typical for a shergottite. Their Mg# indicate that augite crystallized first. Plagioclase transformed to maskelynite (Ab₄₁₋₅₃Or₁₋₆An₅₈₋₄₂) is injected between pyroxene phenocrysts. Accessory minerals are: merrilite, Cl-apatite, pyrrhotite, ulvöspinel, ilmenite, silica, and baddeleyite.

Impact melt pockets contain submicrometric stishovite needles. The rock is highly fractured at all scales: the cores of pyroxenes are crosscut by wide fractures while their margins are cut only by numerous small fractures. Maskelynite is marginally affected by a few of the largest ones.

Secondary carbonate is present in some fractures. The major and trace element composition is under study.

Oxygen Isotopes: $\Delta^{17}O = 0.30\%$, $\delta^{17}O = 2.85\%$, $\delta^{18}O = 4.91\%$. These values are in agreement with the martian origin of this meteorite.

According to the experimental works, the compositions of pyroxenes indicate that augite crystallized first followed by the syncrystallization of augite and pigeonite. According to the experimental work, this order of crystallization indicates a significant P(H₂O), on the order of 0.2 GPa, pointing out the significant abundance of water of the magma compared to the terrestrial basaltic equivalents.

NATIVE IRON, WÜSTITE, AND MAGNETITE IN IMPACTITES OF JANISJÄRVI AND GARDNOS CRATERS, THE BALTIC SHIELD S. A. Vishnevsky¹ and J. Raitala². ¹Institute of Mineralogy and Petrology, Novosibirsk-90, Russia. E-mail: nadezhda@uiggm.nsc.ru. ²University of

Introduction: To search for high-pressure carbon phases in the Jänisjärvi (a positive result, [1]) and Gardnos (a negative result) impactites, accessory magnetic opaques (magnetite, native iron, and wüstite) were derived from the impact melt rocks, tagamites, and detected by means of mineralogical, microprobe, and SEM study.

Description: All the minerals have a regular spherule form, i.e., they originated in a liquid state; some magnetite droplets with vesicles were even possibly superheated. Jänisjärvi magnetites separated from 9 samples are shiny and duly spherules, 20-114 µm in size. The shiny spherules show fine (<1-2 µm grain) texture in polished micro-sections, while the duly ones have a more coarse (3 to 7 µm grain) skeletal-like texture. Gardnos magnetites are duly spherules 75-90 µm in size separated from one sample and show zonal texture, more coarse in the center (6–15 μ m) than on the rim (<6 μ m). Jänisjärvi native iron (spherules 36 to 500 µm in size) was separated from two samples. One native iron spherule $83 \times 121 \ \mu m$ in size was found in Gardnos rocks. The iron from both the craters has a fine-grained tex-ure and contains tiny, <1 to 4 µm, droplet-like wüstite inclusions. Except for Fe (90.4-97.6 wt%, if recalculated to Fe₂O₃), Jänisjärvi magnetite has hightemperature isomorphic impurities of MnO (0.07-1.36 wt%), ZnO (from traces to 6.98 wt%), and SiO₂ (0.01–0.32 wt%). Gardnos magnetite contains impurity of MnO (0.79-1.11 wt%). Except for Fe (up to 100.76 wt%), Jänisjärvi native iron contains traces (0.01-0.09 wt%) of Ni, Zn, V, and Ti. Wüstite spherules (up to 85.6 wt% of FeO) were analyzed with the addition of the host iron (13.6-43.9 wt% of Fe) and show impurities of MnO (0.33-0.67 wt%), Cr₂O₃ (0.07-0.08 wt%) and traces of Zn, Ni, Mg, and Na. Gardnos native iron (98.2-100.37 wt% of Fe) contains impurity of Ni (0.42-0.43 wt%) and traces of Mn and Cr. Except for FeO, wüstite droplets here show traces of MnO, V2O5, and Na2O.

Discussion: Nickel-bearing (2-10 wt%) iron was earlier reported for Lappajärvi [2]. Jänisjärvi and Gardnos native iron, wüstite, and magnetite are first described here and can indicate: 1) high temperatures (above FeO, Fe, and Fe₃O₄ fusion points: 1370, 1530, and 1590°C, respectively) of the impact melts; 2) rather specific redox conditions of the melts (wüstite is stable at μO_2 from -60 to -80, and native iron at $\mu O_2 \le -70$). A free carbon could serve as a buffer for such strong reducing conditions. From 0.1 to 0.4 wt% of carbon is found in Gardnos tagamites [3]; Jänisjärvi target rocks also contain up to 1 wt% of graphite. Magnetite in both the astroblemes could originate as a result of shock melting of Fe-bearing target minerals with partial deoxidation of Fe. Jänisjärvi native iron and wüstite could originate by the similar way or by shock decay of biotite and some other Fe-bearing minerals. The origin of native iron was observed at shock compression of Fe-rich biotite [4]. As for the Gardnos native iron, the amount of Ni (0.43 wt%) does not exclude the meteoritic source of the mineral, but the problem needs further investigation. Anyway, geochemical traces of projectiles in Gardnos tagamites [3] are not in contrary with this conclusion.

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ON THE DISCOVERY OF COSMIC RAY INTERACTIONS IN METEORITES: THE HELIUM STORY

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Around 1930, F. A. Paneth and his coworkers in Königsberg (at that time Germany) had developed techniques for the microanalysis of helium. They were able to measure helium down to 10^{-8} ccSTP with high precision. Paneth was especially interested in using helium for age determination with the uranium/thorium-helium method. Soon, it turned out that this method was not reliable for rocks, because helium was partially lost by diffusion after crystallization of the rocks. Paneth correctly assumed that diffusion loss of helium would not occur in iron meteorites. In the thirties, Paneth's group carried out many helium determinations of iron meteorites. The high precision of their data can be seen by comparing with analyses made several decades later.

However, to obtain ages, U and Th analyses were necessary. For U, there existed a very powerful technique developed by F. Hernegger, using UV-fluorescence, which allowed determinations of 10^{-9} g U with good accuracy. For Th, alpha counting had to be used. It took years to obtain what was thought to be reliable values of U and Th in iron meteorites.

The calculated U and Th-He-ages caused great excitement as they ranged from about one million to 8,000 Myr, exceeding the age of the universe, which at that time was thought to be about 6,000 Myr old.

In 1947, C. A. Bauer had noticed that the highest helium concentrations measured by Paneth's group were found in meteorites of small mass. Bauer suggested that helium could be produced by the interaction of cosmic ray particles with the meteorite matter. He also pointed out that larger meteorites should show a depth effect and aside from helium-4, helium-3 should also be produced. Paneth, who in the meantime has moved to Great Britain, found no noticeable difference between surface and interior samples of the Treysa meteorite (recovered mass 63 kg). Later on, Paneth's group found the depth effect in meteorite Carbo (recovered mass 450 kg).

Paneth contacted A. O. Nier, the world's expert in isotope analysis, and asked him to provide about 10^{-4} ccSTP He for isotope analysis. Nier, who had just determined the ³He/⁴He ratio in Earth's atmosphere to 10^{-7} , thought of a ratio in this range and declined.

Paneth finally heard of a young man at Oxford who had just built a mass-spectrometer for rare gas analyses. His name was K. I. Mayne. He agreed to analyze ³He/⁴He in the He samples supplied by Paneth and found ³He abundances up to 31.5%. The corresponding paper by F. A. Paneth, P. Reasbeck, and K. I. Mayne in *Geochimica et Cosmochimica Acta*, Vol. 2, pp. 300–303 (1952) marks the discovery of the first cosmic ray produced nuclei in meteorites. Later on, it was found that practically all the helium (helium-3 and helium-4) in iron meteorites was due to cosmic ray interaction and that all the U and Th figures produced by Paneth's group were several orders of magnitude too high and obviously due to contamination, mainly from the glassware used for the chemical separations.

EVIDENCE FOR THE L CHONDRITE PARENT BODY BREAKUP EVENT? COSMIC-RAY EXPOSURE AGES OF 480 MYR OLD FOSSIL METEORITES

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Introduction: Schmitz et al. [1] estimated the meteorite flux 480 Ma ago to have been one to two orders of magnitude higher than today. Debris from the collisional breakup of an L chondrite parent body in the asteroid belt may have generated the elevated flux.

In a preliminary study [2], we have shown that cosmic-ray produced noble gases have been quantitatively retained in chromite grains of a fossil ordinary chondrite (Golvsten 001) during 480 Myr of shallow burial in marine limestone in southern Sweden [2]. The calculated exposure age is surprisingly low compared to present day chondrites. At the meeting, we will present exposure ages of fossil meteorites from different stratigraphic positions of the same location.

Samples and Experimental: The meteoritic chromite grains were not significantly affected by diagenesis, although the other mineral phases were completeley altered [1]. Chromite grains were extracted from the fossil meteorite as described in [2]. A continuous-wave Nd-YAG laser was used to melt the grains in an ultra-high vacuum. The measurement was made using an ultra-high sensitivity mass spectrometer with a compressor ion-source [3].

The gas amounts were calibrated by measuring olivine fragments from the pallasite Admire. Exposure ages were calculated using elemental production rates by [4] and average chemical composition of the chromites [1].

Results: All relict chromite grains from the meteorite Golvsten 001 contain excesses of cosmogenic ³He and ²¹Ne, and the contribution of terrestrial cosmogenic nuclides (<10–3%) and nucleogenic isotopes (~1.5%) can be neglected [2]. The calculated exposure ages on the order of ~300 kyr are unusally short for ordinary chondrites. Exposure ages from other meteorites of different stratigraphic locations will be presented at the meeting.

Discussion: If the low age is confirmed by our new measurements, the meteorites have arrived on Earth shortly after their release from the parent body. This might be consistent with dynamical modelling suggesting that, during a major asteroid breakup event, about 10% of the fragments produced will arrive on Earth within the first Myr [5]. The new data will allow us to rule on the alternative hypothesis that the young nominal age of Golvsten 001 is due to high shielding in an unusually large meteoroid.

Acknowledgements: We thank I. Leya and B. J. Gladman for discussions, N. Vogel for providing data on Admire olivines, and U. Wiechert for his expertise in setting up the laser system. ETH Zürich partially funded this project.

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FTIR AND RAMAN ANALYSES OF THE CARBON IN THE TAGISH LAKE METEORITE

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Introduction: The Tagish Lake (TL) carbonaceous chondrite has been investigated using the complementary FTIR and Raman microspectroscopies. Here, we present the first results of our analyses of fragments of the carbonate-rich lithology of the meteorite.

Analytical Methods and Results: Six fragments of a sample of TL have been crushed on KBr windows. All the FTIR spectra obtained (Fig. 1) are in agreement with those of [1]. We note the presence of aliphatic hydro-carbon absorption features in the region of 2700–3000 cm⁻¹. Other important features are dominant hydrated silicates signatures and the presence of carbonates. The Raman spectra obtained during this study show only the first-order graphite bands represented by the D and G bands (at ~1360 cm⁻¹ and ~1580 cm⁻¹, respectively). In Fig. 2, we plot the full width at half maximum of the D-band (noted FWHM[D]) versus the peak position (noted $\omega_{max}[D]$) for different carbonaceous chondrites. This representation shows that TL, like Orgueil, must be distinguished from the other carbonaceous chondrites.



Fig. 1. A typical FTIR spectrum of Tagish Lake.



Fig. 2. Comparison of the TL meteorite with other carbonaceous chondrites.

Conclusion: Two non-destructive analytical methods are used here to identify the carbonaceous component of the TL meteorite. FTIR data indicate that the studied sample belongs to the carbonate-rich lithology of TL [2]. The Raman data show that the carbon is highly disordered, supporting the fact that TL seems to be a new type of carbonaceous chondrite as already reported [3].

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EVIDENCE FOR THE SHOCK MELTING OF SULFATES FROM THE HAUGHTON IMPACT STRUCTURE, CANADA

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Introduction: It is now widely recognized that hypervelocity impact events have influenced the evolution of life on Earth (e.g., [1]). For example, it is apparent that the extinction of 60–90% of all marine and land genera at the Cretaceous-Tertiary (K-T) boundary is connected with the Chicxulub impact event [1, 2]. However, there continues to be considerable debate regarding the actual killing mechanisms by which impact-induced extinction events take place. One of the major extinction mechanisms proposed for the K-T boundary is a prolonged episode of global cooling caused by the stratospheric injection of sulfuric acid aerosols due to impact into an evaporite-rich sedimentary sequence [3].

Despite the suggested importance of the release of sulfur species during the Chicxulub event, the response of sulfates to hypervelocity impact has been little studied. Indeed, the effect of the cratering process on sedimentary targets continues to be a controversial topic. Previous work on the behaviour of sulfates during the impact process has focussed on experimental studies and computer-based simulations (e.g., [4, 5]). No detailed studies of naturally shocked sulfate rocks and minerals have been published to date. Such studies offer the only ground-truth data on the response of sulfates to hypervelocity impact.

Here, we present the results of a detailed investigation of naturally shocked sulfates from the allochthonous crater-fill deposits at the 24 km diameter Haughton impact structure, Canada.

Sulfates in the Allochthonous Crater-Fill Deposits at Haughton: Recent work has shown that these deposits are carbonate-rich impact melt breccias [6]. The textural and chemical features of the matrix-forming sulfates indicate that these phases, in addition to co-existing carbonates and silicates, crystallized directly from an impact-generated melt. Evidence for this includes: 1) the matrix-supported nature of the crater-fill lithologies; 2) sulfate-carbonate-silicate liquid immiscible textures; 3) possible quench textures in anhydrite; and 4) flow textures developed between anhydrite and silicate-rich glasses. Further, supporting evidence includes the presence of Si, Al, and Mg in the anhydrite structure, which were probably "trapped" by quenching from a melt. Irregular blebs and globules of shock-melted carbonates within anhydrite also suggest a common origin for the two phases. Field studies reveal that clasts of anhydrite-bearing target material are also present in the crater-fill deposits. Several clasts of anhydrite-quartz lithologies exhibit evidence for incipient shock melting in both phases. Previous assumptions about the response of sulfates and carbonates to hypervelocity impact (i.e., lack of melting) may, therefore, be incorrect.

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CHROMIUM ISOTOPIC COMPOSITION OF THE ACID-RESISTANT RESIDUES FROM CARBONACEOUS CHONDRITES

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We have shown earlier [1] that the bulk samples of carbonaceous chondrites (CC) reveal excesses in both ${}^{53}Cr({}^{53}Cr^*)$ and ${}^{54}Cr({}^{54}Cr^*)$ as compared to the terrestrial standard value and that ${}^{53}Cr^*$, ${}^{54}Cr^*$, and the respective ${}^{55}Mn/{}^{52}Cr$ ratios are correlated. We also studied the Cr isotopic composition in two Ivuna (CI) phases (a soluble phase and an acid-resistant residue) and found that an elevated ${}^{54}Cr/{}^{52}Cr$ in the total rock is due to the mixing of an abundant component(s) with a moderate deficit of ${}^{54}Cr$ (soluble phase) and a rare phase (residue) with a high excess of ${}^{54}Cr$ [1].

Here, we present new data on the Cr isotopic composition of the acidresistant residues from other types of CC: Murchison (CM) and Mokoia (CO). The bulk samples were treated with an HF/HNO3 mixture at room temperature. This dissolution left behind tiny acid-resistant residues highly enriched in Cr, most likely a chromite-spinel phase. The residues were dissolved in a bomb at 180°C. The Cr isotopic compositions in these residues are presented in Fig. 1. The 50Cr/52Cr ratio is assumed to be normal. The residues from Ivuna, Murchison, and Mokoia exhibit moderate deficits in 53 Cr of $-0.90 \pm 0.09\epsilon$, $-0.34 \pm 0.17\epsilon$, and $-0.19 \pm 0.11\epsilon$ and large 54 Cr* of $+13.2 \pm 0.20\epsilon$, $+5.35 \pm 0.29\epsilon$, and $+3.46 \pm 0.28\epsilon$, respectively. The variations of $\epsilon(^{53}\text{Cr})$ are not due to in situ ^{53}Mn decay because the $^{55}\text{Mn}/^{52}\text{Cr}$ ratios decrease in the sequence CI (0.17) – CM (0.10) – CO (0.02), while ε (⁵³Cr), instead, increases. The residue of the primitive Ivuna has the largest 53Cr deficit and ⁵⁴Cr*, while the more processed CM and CO chondrites show successively more moderate 53Cr deficits and 54Cr*. This may imply that Cr in the CM and CO residues is partially equilibrated with Cr from the soluble phases. We note also that (in contrast to the bulk CC samples) $\varepsilon(54)$ and $\varepsilon(53)$ in the residues are anti-correlated (Fig. 1). The observed linearity suggests that these Cr components of yet unknown origin may be a feature of all types of CC.



Fig. 1. The Cr isotopic composition of CC acid-resistant residues.

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NON-SPHERICAL LOBATE LOW-FEO PORPHYRITIC CHONDRULES IN THE Y-81020 CO3.0 CHONDRITE: EVIDENCE FOR SMALL DEGREES OF MELTING

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Most type-I (low-FeO) porphyritic chondrules in CO3 chondrites show large deviations from sphericity (Fig. 1). We surveyed 200 type-I PO and POP chondrules with apparent diameters $\geq 100 \ \mu m$ in CO3.0 Y-81020. There is a continuum of shapes ranging from irregular, non-spherical, multi-lobed objects (~70%) to those that appear "round" in thin sections (~30%). However, some of these "round" chondrules are probably cross-sections of lobes. We chose eight non-spherical and ten "round" type-I chondrules for a detailed study. The chosen non-spherical chondrules have larger apparent diameters (420 ± 140 versus $230 \pm 80 \ \mu m$) and a higher content of opaque phases (12 ± 5 versus $5 \pm 4 \ vol\%$) than the "round" chondrules. The two groups have similar olivine grain sizes ($20 \pm 5 \ versus 26 \pm 11 \ \mu m$) and similar olivine, low-Ca pyroxene, and Ca-pyroxene compositions (Fa_{1.0} versus Fa_{1.4}; Fs_{1.1}Wo_{2.2} versus Fs_{1.7}Wo_{1.9}; Fs_{1.0}Wo₃₈ versus Fs_{1.7}Wo₄₀).



Fig. 1. Lobate type-I chondrule in Y-81020. The image is 715 µm across.

The non-spherical chondrules are not chondrule fragments: they have rounded protuberant and embayed outlines inconsistent with fracturing.

Some researchers have modeled type-I chondrules as having formed from near-total melts during a single heating/cooling episode. However, nearly totally molten droplets the size of the non-spherical chondrules (with viscosities of 1–5 poise and a surface tension of 360 dynes/cm, appropriate for a basaltic melt) would collapse into spheres very quickly, i.e., in <<1 sec. It does not seem possible that the chondrules could have nucleated and grown their 20 μ m-size olivine phenocrysts within this short period of time. This indicates that the non-spherical chondrules did not form from near-total melts. Instead, they probably experienced only small degrees of melting during their final heating episode and solidified from highly viscous (102–103 poise) crystal-laden melts.

There are two end-member scenarios for forming the non-spherical chondrules: 1) collisions of crystal-laden spatter of similar composition in a small, hot, opaque formation region; and 2) deformation of individual objects due to heterogeneities in internal motions. In either case, the non-spherical chondrules achieved their present convoluted shapes before quenching. The "round" chondrules may have experienced higher degrees of melting than the non-spherical chondrules and lost a higher proportion of their opaque spherules by centrifugal action.

GEOCHEMICAL SYSTEMATICS IN DARWIN IMPACT GLASS

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Introduction: For the major elements, this study significantly extends the compositional ranges previously reported for Darwin glass [1, 2]. These data show large internal heterogeneity and between sample variations. Despite this heterogeneity, compositional groups and systematic chemical variation between glass end members are defined.

Analytical Method and Results: More than 100 fragments of Darwin glass, collected from across the strewn field, have been analyzed. Major elements were determined by electron microprobe. Trace elements were determined by laser ablation ICP-MS. For major and trace elements, 2 spots were analyzed on each glass fragment (216 analyses in total). A cluster analysis performed on the following major and trace elements data: Na₂O, MgO, Al₂O₃, SiO₂, K₂O, CaO, TiO₂, FeO, Sc, Cr, Co, Ni, Rb, Sr, Zr, and Ba results in 2 groups. Group 1 accounts for more than 80% of the samples and is close to "average" Darwin glass in composition. The ranges in major element composition in Group 1 are: SiO₂ (80.62-93.9%), Al₂O₃ (3.14-10.6%), TiO₂ (0.2-0.76%), FeO (0.8-4.23%), MgO (0.25-2.31%), and K₂O (0.7-2.7%). CaO and Na₂O are almost completely absent in all analyses. Group 1 glass is predominantly light to dark green, white, or sometimes black. The second population has a more limited range (76.4-84.4 %) and a lower average abundance of SiO₂ (81.16%). The average MgO (2.2%) and FeO (3.8%) contenst in this group are significantly higher than in Group 1 glasses, and Al₂O₃ is also slightly enriched. Most trace element data are similar between the groups. The exceptions are average Cr (162 ppm), Co (31 ppm), and Ni (416 ppm), which are significantly enriched in Group 2 relative to Group 1 glasses. Group 2 glass is predominantly black to dark green and rarely light green in color.

A principal components analysis (PCA) performed on the major and trace data shows that 97.5% of the total variation across the entire sample is explained by a single vector. Ratio plots show that this variation is between high SiO₂, low MgO, FeO and low SiO₂, high FeO, MgO end members (Fig. 1). The scatter of data points in Group 1 glasses define 2 fields that suggest the presence of 2 high SiO₂ end members—one with less Al₂O₃ relative to FeO (Fig. 1, dashed line). Repeat analysis on a single glass fragment can fall in different Al₂O₃ fields and this reflects internal heterogeneity and incomplete mixing in Group 1. Figure 2 also shows the variation between end members in the high silica Group 1 (high Zr, low MgO, Co) and low silica Group 2 (high Co, MgO, low Zr) glasses. MgO and the transition elements Ni, Cr, and Co control the remaining geochemical variation on axis 2 of the PCA. This suggests that another distinct end member rich in MgO, Ni, Co, and Cr contributed to Group 2 glasses. Studies in progress will determine if this end member is of extraterrestrial origin.



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THE CONDITIONS OF AQUEOUS ALTERATION REACTIONS RECORDED IN THE SAYAMA CM2 CHONDRITE

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Introduction: Sayama is a newly found CM chondrite [1], and its chondrules are hydrated in major parts but retain small amounts of anhydrous phases. Thus, it was assigned as a CM2 chondrite [1, 2]. In the present study, we extended the preliminary study [2] to further investigations of mineralogy and oxygen isotope signatures.

Results and Discussion: The chondrules are almost entirely replaced by serpentine and minor chlorite. In many places in the chondrules, preexisting anhydrous phases are pseudomorphically replaced. Modal analysis indicated that the average fraction of phyllosilicates in chondrules is 92% (n = 20). The matrix is mainly composed of coarse serpentine, which is typically 50 to 100 μ m across. Synchrotron X-ray diffraction (SR-XRD) showed that the serpentine 001 reflection appears at 7.20 Å, which is larger than that of other CM chondrites such as Murchison [3], suggesting a low Fe³⁺/Si⁴⁺ ratio in the tetrahedral layers in serpentine and the high degree of aqueous alteration. SR-XRD also indicated that PCP (tochilinite) is absent in the matrix. Instead, pyrrhotite and pentlandite are contained in the matrix. Dolomite is a dominant carbonate in both the matrix and chondrules.

Oxygen isotope ratios of olivine and serpentine in the chondrules and those of dolomite and serpentine in the matrix were measured by SIMS ims 6f at Kyushu University, with 1 sigma uncertainty up to $\pm 2\%$. Olivines in the chondrules have oxygen compositions from -9.5 to +2.1% $\delta^{18}O_{SMOW}$, falling on or close to the CCAM line in the three isotope diagram. The range of distribution is consistent with oxygen compositions of anhydrous phases in other CM2s [4]. The compositions of serpentine are clustered in a region close to the CM mixing line [5] around +10% $\delta^{18}O_{SMOW}$. Serpentines in he chondrules and matrix have identical compositions within errors, indicating that both serpentines were in equilibrium in exchange of oxygen isotopes during aqueous alteration. Two dolomite grains which had occured independently and were relatively large, more than 100 µm in size, were analyzed so far. The results showed that the 2 grains have similar compositions around +15‰ $\delta^{18}O_{SMOW}$ and +5‰ $\delta^{17}O_{SMOW}$, giving the lightest values among the CM2 carbonates reported [6, 7]. The results obtained so far indicate that the $\delta^{18}O$ fractionation between serpentine and dolomite ranges up to 8.4‰, which corresponds to the equilibrium at 120°C or higher in hydrothermal conditions [8, 9]. The temperature is higher than that for other CM2s such as Murchison (0~25°C) [4, 5, 7]. The aqueous alteration at high-temperature might have resulted in the unique mineralogy of Sayama, including the high degree of alteration of the chondrules, the presence of chlorite and coarse serpentine, and the absence of PCP.

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HAMADAH AL HAMRA AND DAR AL GANI: A COMPARISON OF TWO METEORITE FIELDS IN THE LIBYAN SAHARA

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Introduction: Most meteorites found in the Libyan Sahara are from two main areas: Hamadah al Hamra (HaH) and Dar al Gani (DaG). Some of the meteorites from HaH are known under the name Daraj. The geological setting of the DaG meteorite field has been described in [1], and an update is given in [2]. In this contribution, we compare both meteorite fields, HaH and DaG. Some basic facts are given in Table 1. The morphology of both regions is similar. Both plateaus originate from Tertiary marine sediments, which are eroded to a cm-sized, even-grained limestone grid. The content of fine grained quartz sand is higher at HaH as compared to DaG. While DaG has almost no permanent plants, HaH—closer to the Mediterranian Sea—seems to receive more rain or moisture, which results in some sparse vegetation. No lunar or SNC meteorite has ever been found on HaH, and the number of recovered achondrites is small.

Table 1: Comparison of two meteorite fields of the Libyan Sahara, Dar al Gani and Hamadah al Hamra.

	Dar al Gani	Hamadah al Hamra
Total area (km ²)	12000	50000
Area with meteorites (km ²)	5500	16000
Total number of meteorites	972	362
Total mass (kg)	759	277
Number of known strewnfields	>26	>3
Typical mass range (g)	50-100	75-200
Meteorites/km ²	0.18	0.023

Discussion: The recovery density of HaH is much smaller than that of DaG. This may be for several reasons: 1) meteorite searches were more intense at the DaG. The generally higher mass of HaH meteorites point to such an effect; 2) the recovery conditions are better at the DaG compared to HaH; and 3) conditions of meteorite preservation are better at DaG. With a few exceptions, terrestrial ages of Daraj meteorites are <10 ka [3]. Those of DaG chondrites tend to have ages >10 ka [4]. This implies that destruction of meteorites by weathering processes are faster at HaH than at DaG.

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Analysis of bulk samples of meteorites and lunar rocks suggest a well defined solar system boron isotopic ratio [1]. Data for meteoritic chondrules, on the other hand, suggested significant intra-chondrule as well as chondrule to chondrule variations in the ¹¹B/¹⁰B ratio [2–4]. However, based on an exhaustive analysis of chondrules from several different types of meteorites [5], the observed variation seen in that study was concluded to be well within statistical expectations, a view confirmed by new high precision analysis using the NanoSIMS (Hoppe, personal communication).

The observations of ¹⁰B excess in CAIs from in situ decay of ¹⁰Be provide further insight in this regard. A record of any initial boron isotopic heterogeneity should be better preserved in CAIs than in late-forming chondrules. Data for Be-B isotopic systematics are available for 17 CAIs (including 2 FUN inclusions) from 5 CV meteorites and 4 CM and CV hibonites [6–12], and it has been noted that the initial ¹¹B/¹⁰B ratios are often lower than the reference value [6, 8, 9]. The $\delta^{11}B_{initial}$ in CAIs span the range from -66‰ to +22‰ with large uncertainties and yield a weighted mean value of -14‰. Data for various solar system objects are shown in Fig. 1.





The solar system ¹¹B/¹⁰B ratio of ~4 represents a mix of two components: a high energy particle (GCR) produced component (¹¹B/¹⁰B ~2.5) and a low energy particle produced or a Type II supernova component enriched in ¹¹B, with the former appearing to be more plausible. The ¹¹B/¹⁰B ratio of 3.4 ± 0.7 in interstellar diffuse clouds [13] indicates the solar system value to be representative of the local galactic neighborhood. The variations in initial ¹¹B/¹⁰B in CAIs do not appear to be caused by terrestrial contamination (e.g., see [9]) and they cannot be reconciled easily with a proposed homogeneous B isotopic reservoir [8]. These variations may be better understood by postulating initial B isotopic heterogeneities in the nebula that did not persist up to the time of chondrule formation and that provide a hint for the presence of an anomalous ¹¹B component of cosmogenic origin in the CAIs.

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AERODYNAMICAL ACCRETION

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Introduction: Within a few tens of million years, the micron-sized dust grains in a protoplanetary nebula grow to planet-sized bodies, which is assumed to be due to collisions of solid bodies. In the early stages of planetesimal accretion, size-dependent gas drag results in gentle relative velocities, and surface forces allow small dust grains to stick in collisions and grow to cm-sized agglomerates [1]. At later stages, when bodies have reached km sizes, gravity will takeover and ensure growth. However, in ranges of intermediate size, sticking is not well understood. As collision velocities increase with increasing particle size, fragmentation of colliding bodies occurs rather than growth. Wurm et al. [2, 3] suggested that nebular gas flow may return ejected dust grains to a growing body, and after one or more bounces, the particles can stick to the surface due to a reduced collision velocity. We attempt to investigate the importance of this aerodynamical accretion for planetesimal growth with the aid of a simple Monte Carlo model.

Computational Model: We assume a centrally condensed, rotating solar nebula in hydrostatic equilibrium, which contains a distribution of spherical solid bodies that range from cm to maximum km sizes. Drag forces cause solid bodies to spiral inward with a velocity depending on their size and geometry [4]. As a consequence, collisions between these protoplanetesimals occur. We describe the collisional evolution of the largest body in the population as a function of its initial size and distance from the central star. We apply a model of the outcome of collisions that includes either an elastic rebound, a cratering, or a catastrophic disruption of one or both bodies, depending on collision parameters and material properties. The trajectories of individual ejected fragments are calculated, whereby the gravitational force of the parent body and the drag force from the nebular gas flow are considered (Fig.1). Depending on the hydrodynamic regime, we apply different types of flows past the parent body. We compute the net erosion or accretion as a function of initial conditions and model parameters using a statistical approach in which several 100,000 impacts are simulated.



Fig. 1.

Results: Simulations indicate a strong dependence on the type of gas flow. A laminar flow past the parent body carries away most of the fragments and inhibits the growth of a proto-planetesimal, while a molecular flow or certain turbulent flows may yield growth for some parent body sizes. Model results are also strongly influenced by the outcome of collisions.

References: [1] Weidenschilling S. J. 2000. Space Science Reviews 92: 295–310. [2] Wurm G. et al. 2001. Physical Review E 64: 46301. [3] Wurm G. et al. 2001. Icarus 151:318–321 [4] Weidenschilling S. J. 1977. Monthly Notices of the Royal Astronomical Society 180:57–70.

THE DAR AL GANI METEORITE FIELD IN THE LIBYAN SAHARA A. M. Ghadi,¹ A. E. Abu Aghreb,¹ J. Schlüter,² L. Schultz,³ and F. Thiedig⁴. ¹Industrial Research Center (IRC), Geological Research and Mining Department, Tripoli, Libya. ²Mineralogical Museum, University of Hamburg, D-20146 Hamburg, Germany. ³MPI für Chemie, D-5520 Mainz, Germany, ⁴University of Münster, D-48149 Münster, Germany

Introduction: More than 970 meteorites have been found on a plateau of stratiform Tertiary marine sediments. A detailed discussion of the geological setting and possible pairing of meteorites is given in [1]. Here, we present an updated version of the meteorite find locations (Fig. 1) and present additional information on this area with conditions favorable for the recognition and preservation of meteorites.



Fig. 1. Satellite image of the Dar al Gani area with meteorite finds until 2002. The width of the picture is about 175 km. To the east, the large volcanic complex of Jabal Haruj is seen. The light, rounded areas are depressions caused mainly by eolian deflation. Two large meteorite strewnfields can be recognized on the top and the lower left.

Discussion: Most terrestrial ages of DAG meteorites are less than 25 ka and are comparable with those of other desert finds [2]. However, SNC and lunar meteorites tend to have higher ages, possibly because they contain no metal. For chondrites with appreciable amounts of metal, the fact that these meteorites survived the wet periods of past climates (11 to 3 ka before the present) is surprising. Several factors contribute to this, including a chemical environment that does not favor rusting and the rapid elimination of surface water. These conditions are present at the DAG region. Meteorites that had accumulated during earlier arid periods were likely covered by soil and thus protected against physical and chemical weathering during wet periods. Today, winds have removed this cover and again exposed the meteorites on the surface.

References: [1] Schlüter et al. J. 2002. *Meteoritics & Planetary Science* 37:1079–1093. [2] Welten et al. K. C. 2003. Abstract #1866. 34th Lunar and Planetary Science Conference.

EXTREME OXYGEN ISOTOPIC HETEROGENEITY IN A CHONDRULE OLIVINE PHENOCRYST

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We report an olivine phenocryst in a chondrule having extreme oxygen isotopic heterogeneity (~18‰ in Δ^{17} O). The host chondrite purchased from Blaine Reed was labeled as Lahmada 003. Since Lahmada 003 was classified as L6 [1], we suspect that the sample (SNU-014) was mislabeled or the meteorite is brecciated. SNU-014 is an ordinary chondrite having abundant chondrules (>80 vol%) without CAIs. Chondrules have sharp boundaries and their typical size is ~1 mm. The average of fayalite contents in olivine and the relative standard deviation are 20 and 67%, and those of ferrosilite contents in pyroxene are 15 and 62%, respectively, indicating that the chondrite is highly unequilibrated and probably type 3.5 or less. SNU-014 contains a finegrained clast having few chondrule fragments.

We measured O isotopes of silicates in 7 chondrules and in the clast using Titech Cameca ims 1270 with a primary Cs⁺ beam of ~5 μ m in diameter and with an EM. All except one spot have O isotopes and fall near the TF line (average $\Delta^{17}O = -1.0 \pm 0.5\%$). A spot (OL13) on a type-II chondrule (Chd76; average fa = 36) shows ¹⁶O-enrichment ($\Delta^{17}O = -19.1 \pm 2.2\%$), similar to CAIs, while the other 3 spots on the same grain and 5 spots on the other grains have normal chondrule O isotopes (Fig. 1; spot OL13 was measured twice). Figures 2, 3, and 4 show Mg X-ray, BSE, and transmitted optical images of part of Chd76, respectively. Fig. 4 shows that the phenocryst having O isotope heterogeneity is a glommerocryst that consists of several olivine grains, even though it appears as a single homogenous grain in major element X-ray mappings and the BSE image.



Figures 1-4.

Extreme oxygen isotopic heterogeneities have recently been reported in carbonaceous chondrites [2, 3]. These and our observations suggest that, both for ordinary and carbonaceous chondrite groups, chondrule precursors had O isotopic heterogeneity, and some chondrules never reached O isotopic equilibrium during the heating and cooling of the chondrules.

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THE ASSEMBLAGE MASKELYNITE—POST-STISHOVITE SILICA POLYMORPHS IN THE SHERGOTTY METEORITE: NEW STRINGENT CONSTRAINTS TO PEAK-SHOCK PRESSURES

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Introduction: Shock pressure and temperature histories of the SNC (Martian) meteorites have been a subject of intensive investigations in the last two decades [1-5]. Some reports [1, 2, 4, and 5] exclusively use the refractive indices (R.I.) of maskelynite as an absolute indicator for estimation of peakshock pressures. Recently, two new shock-induced, very dense poststishovite polymorphs (a-PbO2 and monoclinic P21/c) of SiO2 were reported from the Shergotty meteorite [6, 7]. Chen and El Goresy [3] also presented ample evidence that maskelynite in many SNC meteorites is a dense glass quenched from shock-induced dense melt at high pressures and is not diaplectic plagioclase glass, as claimed by [1, 2, 4, and 5]. The pressure the of equilibrium phase transition of cristobalite to a α-PbO₂ post-stishovite polymorph was experimentally determined to be >40 GPa [8, 9]. Hence, petrographic settings of both maskelynite and the α -PbO₂ post-stishovite polymorph in Shergotty should reveal evidence for the mode of the phase transformation to the post-stishovite polymorphs and provide clues to the equilibrium peak-shock pressure.

Results: Shergotty maskelynite contains abundant fragments (<2 μ m) of intact post-stishovite silica that display drag and twisting at their edges, evidencing floating and flow in a dense maskelynite (Msk) melt (Fig. 1, arrows). This is ample evidence that the maskelynite liquid was acting as a pressure medium and that the pressure at which the α -PbO₂ formed is the equilibrium pressure. The peak-pressure of the assemblage was definitely >40 GPa before quenching. This is in sharp contrast to the 28.4 ± 1.7 GPa estimated by [5]. We caution that R.I. of maskelynite indicates only its degree of densification (or relaxation) after decompression but gives no clues to its formational process, if due to quenching from dense liquid or to solid-state transformation of plagioclase feldspar to diaplectic glass.





References: [1] Stöffler D. et al. 1986. Geochimica et Cosmochimica Acta 50:889–903. [2] Stöffler D. 2000. Abstract #1170. 31st Lunar and Planetary Science Conference. [3] Chen M. and El Goresy A. 2000. Earth and Planetary Science Letters 179:489–502. [4] Fritz J. et al. 2002. Abstract #1504. 32nd Lunar and Planetary Science Conference. [5] Fritz J. et al. 2003. Abstract #1335. 34th Lunar and Planetary Science Conference. [6] Sharp T. G. 1999. Science 284:1511–1513. [7] El Goresy A. et al. 2000. Science 288: 1632–1634. [8] Dubrovinsky L. 2001. Chemical Physics Letters 333:264– 270. [9] Dubrovinskaia 2001. European Journal of Mineralogy 13:479–483.

COMPOUND CHONDRULE FORMATION: CLUES FROM OXYGEN ISOTOPIC RATIOS AND MAJOR-ELEMENT CONCENTRATIONS

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Thirty sets of compound chondrules were identified from Allende and Axtell CV3, including 24 adhering and 6 enveloping types, based on the compound-chondrule classification [1]. The adhering type consists of two chondrules fused together (Fig. 1), while the enveloping type has a core chondrule within a host chondrule (Fig. 2). SIMS analysis indicated that olivine and low-Ca pyroxene in 8 out of 9 adhering types have similar oxygen compositions that distribute in a range from –5 to 5‰ $\delta^{18}O_{SMOW}$ and from – 10 to 0% $\delta^{17}O_{SMOW}$ and cluster around the CCAM line. On the other hand, oxygen compositions differ between the two constituent chondrules in one adhering type. Olivines at the core of a chondrule ("Right" in Fig. 1) are ¹⁶Orich down to $-15\% \delta^{18}O_{SMOW}$ (indicated by arrows in Fig .1), while those at outer portions of this chondrule and those in entire portions of the other chondrule showed similar ¹⁶O-poor compositions. This indicates that, when the two chondrules fused together, the core of the former chondrule was not melted, while the outer portions of both chondrules were melted. This facilitated exchanges with ¹⁶O-poor nebular gas. In fact, petrologic observation showed that no boundary plane was recognized between the two chondrules, confirming the melting of outer portions of both chondrules. These results suggest that the adhering type was formed during a single heating event by a collision between 2 totally and partially molten particles. In the 3 isotope diagram, all oxygen data of 9 adhering compound chondrules fall on the typical area obtained from single chondrules. Therefore, the two precursors of the adhering types were originated from the same dust reservoirs as that of single chondrules.



Figures 1 and 2.

We found, from the electron-microprobe analysis of the enveloping types, that the host chondrules tend to have higher FeO and lower Al₂O₃ and CaO contents than the core chondrules. The results are consistent with the enveloping-type formation model [1], which shows that the enveloping type was formed by a flash melting of a porous Fe-rich dust clump on a preexisting chondrule. Thus, it needs 2 times of heating for the formation. Oxygen isotope measurements of 2 enveloping types indicated that the core and the host chondrules have similar compositions (Fig. 2). On the other hand, another 2 enveloping types showed different oxygen compositions between the core and the host chondrules: one enveloping type has a ¹⁶O-rich core and a 16O-poor host, while the other has a 16O-rich host and a 16O-poor core. All oxygen data of the 2 enveloping types lie on or close to the CCAM line in a range of $\delta^{18}O_{SMOW}$ from -20 to 5‰. This indicates that the enveloping types were formed by two times of heating, during which the oxygen compositions of chondrules, accreting Fe-rich dust, and the nebular gas have stayed along the CCAM line.

References: [1] Wasson et al. 1995. *Geochimica et Cosmochimica Acta* 59:1847–1896.

EXPLOSIVE DISPERSAL OF HYDRATED ASTEROIDSBY IMPACTS AS A MECHANISM TO PRODUCE INTERPLANETARY DUST

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Dust particles collected on the Earth's surface (micrometeorites) are similar in chemistry and mineralogy to the matrix of hydrated, porous CI and CM chondrites (e.g., [1–3]). However, such meteorites comprise only 2.8% of recovered falls. This large difference in relative abundances has been attributed to "filtering" by the Earth's atmosphere [4], that is, the CI-CM chondrites are so friable that they are preferentially fragmented and destroyed during atmospheric entry.

We have performed a series of shock-recovery experiments on the Murchison CM and Allende CV chondrites. Both meteorites contain major volume fractions of porous matrix, but the matrix of Murchison is hydrated (\sim 12 wt% H₂O), while the matrix of Allende is anhydrous. The Murchison samples were shocked at peak pressures from 4 to 49 GPa [5], and the Allende samples were shocked at peak pressures from 27 to 49 GPa.

SEM observations reveal that the matrix of Murchison shocked at 26– 30 GPa exhibits very noticeable changes. Narrow, subparallel fractures (1–50 μ m wide) form at high density in directions roughly perpendicular to the compression axis, reducing the sample into minute particles. The fractures increase with increasing pressure and extend throughout the matrix at 30 GPa. At 21–35 GPa, local melts occur in the matrix and increase in amount with pressure. In contrast, the matrix of Allende does not exhibit such fractures even at 37 GPa. High-density fractures form at 41 GPa but only in ~10 vol% of the matrix. The matrices of both meteorites are totally melted at 49 GPa.

The sudden increase of fractures in the matrix of Murchison shocked at ~25 GPa was probably caused by an increase of expansive force upon release of the pressure. The local melting at 21–35 GPa indicates that shock heating also increases dramatically, simultaneously with the comminution. The heating must cause dehydration of hydrous minerals and evaporation of H₂O, and as a result, contribute to generation of great expansive force.

We suggest that if hydrated porous asteroids are shocked at pressures higher than 25 GPa, the shocked materials would be densely comminuted and/or melted, and the comminuted and melted particles would be explosively dispersed as dust into interplanetary space. In the case of anhydrous asteroids, much higher shock pressures would be required to comminute shocked materials, and dispersion of the particles would be less effective. As a result of these differences in shock response, CI-CM-like materials would become the predominant kind of dust particles produced by mutual collisions of asteroids. Therefore, we suggest that the different relative abundances of hydrated material in micrometeorites and meteorites are established before contact with the Earth's atmosphere.

References: [1] Kurat G. et al. 1994. Geochimica et Cosmochimica Acta 58:3879–3904. [2] Genge M. J. et al. 1997. Geochimica et Cosmochimica Acta 61:5149–5162. [3] Nakamura T. et al. 2001. Geochimica et Cosmochimica Acta 65:4385–4397. [4] Bawldwin B. and Scheaffer Y. 1971. Journal of Geophysical Research 76:4653–4668. [5] Tomeoka K. et al. 1999. Geochimica et Cosmochimica Acta 63:3683–3703.

THREE-DIMENSIONAL STRUCTURES OF METAL-SULFIDE GRAINS IN CO CHONDRITES: FORMATION OF METAL-SULFIDE CHONDRULES

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Introduction: Metal and/or sulfide grains, as well as chondrules and matrix, are some of the major constituents of chondrites. In general, they are not considered as metal-sulfide droplets because of their irregular shapes. However, their behavior during chondrule formation has not been well-known. Here, we made a working hypothesis that: 1) these metal-sulfide grains were experienced heating and cooling processes as well as chondrules; and 2) most of spherical metal-sulfide grains were deformed by rigid chondrules and became irregular in their shapes during or after accretion as chondrites. To verify this hypothesis, we examined 3-D structures of metal-sulfide grains in ALH 77003 (CO3.5) and Kainsaz (CO3.1) using X-ray computed tomography (CT).

Experiments: We used CO chondrites because they have metal-sulfide grains and a sufficient amount of matrix, which may preserve spherical metal-sulfide grains. The samples were previously imaged by an industrial X-ray CT scanner (ELESCAN) to choose grains suitable for further work. Rods of about 4 mm in diameter, which includes such grains, were cut out and imaged at beamline BL20B2 of SPring-8 using a micro-tomography system (SP-μCT, [1]) with the spatial resolution of about 13 μm. Metal, sulfide, and silicates can be distinguished in CT images. Most of the chondrules were also identified as they were embedded in FeO-rich matrix. 3-D images of metal-sulfide grains and chondrules were made using an image analysis technique (Fig.1a). After imaging, some samples were cut physically and observed under an SEM (Figs. 1b and 1c) to compare CT images.



Fig. 1. A 3-D structure and SEM images of ALH 77003: a) a spherical silicate chondrule enclosed by a partially irregular metal-sulfide grain; b) an SEM image of (a); c) an SEM image of a spherical metal-sulfide grain surrounded by deformed silicate chondrules (upper left and right). The metal-sulfide grain near the chondrules show reaction textures, while the surface in contact with matrix shows no reaction texture. All scale bars are 100 µm long.

Results and Discussion: With the 3-D image, we observed that many chondrules are present on concavities of irregular metal-sulfide grains (Figs. 1a and 1b). Spherical metal-sulfide grains surrounded by matrix were also observed. These results strongly suggest that metal-sulfide chondrules were formed by the melting of solid precursors as well as silicate chondrules, and most of ductile metal-sulfide chondrules were deformed by rigid silicate chondrules at low temperatures. As we did not find any foliated structures in the chondrites, the deformation should occur during accretion as chondrites. We also observed a spherical metal-sulfide surrounded by silicate chondrules (Fig. 1c), showing that a solidified metal-sulfide chondrule and molten silicate chondrules had collided with each other. This feature suggests recycling of metal-sulfide and silicate chondrule formation.

Reference: [1] Uesugi et al. 1999. SPIE Proceedings 3772:214-221.

THE ORIGIN AND EVOLUTION OF THE SAARIJÄRVI IMPACT STRUCTURE

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Background: The Lake Saarijärvi structure in Taivalkoski, northern Finland ($65^{\circ}17.4'N \ 28^{\circ}23.3'E$) was confirmed to be an impact structure in 1997 when PDFs in quartz were discovered [1, 2, 3] at the bottom of a 156 m thick Vendian-Cambrian sedimentary rock sequence which now fills most of the structure [4, 5]. The sedimentary rock sequence deposited in the crater has a diameter of ~1.5 km, but shatter cones in Archaean granitoids and Palaeoproterozoic metadiabases might indicate a larger diameter of ~2 km [5]. Here, we describe some of the enigmatic features of Saarijärvi and our ongoing multidisciplinary research project.

Morphology: The morphology of the Saarijärvi structure is not that of a classical simple crater. The most prominent deviation from a simple crater is the presence of an elongated island approximately in the center of the structure. Detailed electromagnetic (VLF-R) studies indicate, however, that the island has underwater continuations [6], making it a long and narrow feature, quite unlike true central uplifts. Moreover, the direction of the whole central feature coincides with the direction of a fracture valley immediately north from the lake. Thus, the island is most likely the result of tectonic modification that took place after the impact. The true plan view of the structure, as revealed best by aeroelectromagnetic (AEM) studies, is not circular but somewhat hexagonal and slightly larger than the depression filled with sediments. Polygonal craters are quite common on other planets, but not usually recognized [7]. The crater has an asymmetric cross-section evident in gravimetric studies [8]. The southern side is deeper and steeper than the northern side. Possible explanations are an oblique impact or tilting of the crater-containing block. We are currently processing a 3D-gravity model.

Geochemistry: INAA-studies of the central island's lithic granitoid breccias, most likely of tectonic origin, have revealed elevated abundances of Ni (140–980 ppm), Cr (20–60 ppm), and Co (15–40 ppm) compared to unbrecciated granodiorite (Co and Cr 6 ppm, Ni below detection). The Ni/Crratio is 5.6–8.7, somewhat higher than crustal or granitoid averages (usually \sim <1). However, the breccia appears to be hydrothermally altered and it is in contact with metadiabase, which has 120–130 ppm Ni and 250–280 ppm Cr (XRF method). Thus, this anomaly can be, at least partly, the result of some unspecified hydrothermal process, and not necessarily wholly due to meteoritic contamination.

Age: The age of the structure still remains elusive. According to our ongoing micropalaentological studies, the oldest sediments are Vendian (~600 Ma), yielding a possible minimum age [4, 5]. Palaeomagnetic ages (1.2 Ga or 2.1 Ga [5]) may be inconclusive, as the structure has gone through tectonic modification.

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LEAD ISOTOPIC STUDY OF GLASSES FROM THE D'ORBIGNY ANGRITE

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Introduction: Angrites are mafic rocks that formed very early in the history of the solar system [1]. The newly found angrite D'Orbigny [2] has attracted much attention worldwide. Several isotopic studies have been performed [3, 4]. We obtained a U-Pb age of 4557 ± 1.5 Ma [5]. Here, we present further results of our Pb/U isotopic study of its unusual glass phase [6].

Experimental: Four different glass samples of 5 to 20 mg were cleaned by leaching with diluted HCl: glass 1 and 2 with 0.5 n, glass 3 with 0.75 n, and glass 4 with 0.02 n HCl for 16 min. in an ultrasonic bath. Glasses 1 to 3 were spiked with a mixed ²⁰⁵Pb-²³⁵U-²²⁹Th spike. Our chemical separation procedure followed that of [5].

Results and Discussion:

- U/Pb Isotopic Systematic: The Pb-Pb isotopic data of glasses 1 to 4, pyroxene, and plagioclase are compiled in Table 1. The isotopic compositions of the glass samples differ greatly. We found both low and high radiogenic lead ratios. One possible explanation for the heterogeneity might be the high sensitivity of the glass grains against acid media. Therefore, the Pb/U isotopic system could be affected by weathering. Much of radiogenic lead that possibly came from an older, pre-existing mineral would be lost in part. The measured (²⁰⁷Pb/²⁰⁶Pb)* ratio of glasses 1 and 2 is very high, yielding an unrealistic high Pb-Pb age of ~4.7 Ga. We assume that the excess of ²⁰⁷Pb probably originated from the decay of ²⁴⁷Cm (now extinct) via excess ²³⁵U [7].
- 2. *Question of Formation:* The D'Orbigny glass shows chondritic relative abundances of all refractory lithophile elements excluding formation by partial melting. No shock features are present. The remarkably high ²⁰⁶Pb/²⁰⁴Pb ratio in two of our samples indicate that the plagioclase from D'Orbigny was not melted to form the glass. From our Pb-Pb ages of samples 1 and 2, the glass seems to be "older" than the rock. However, clearly, the glass was added to the rock after its formation, possibly by a fluid phase. This phase had chondritic relative abundances of refractory elements and contained an older isotopic component, maybe from a pre-existing mineral.

Table 1. Pb/Pb isotopic data of the D'Orbigny angrite.

Sample	206/204	207/204	208/204	(207/206)*	207/206 age (Ma)
Px	168.94	109.33	296.11	0.620414	4557 ± 1.5
Glass 1	145.11	103.6	197.94	0.695955	(~4722)
Glass 2	826.73	569.6	1012.4	0.685572	(~4700)
Glass 3	21.56	20.61	52.52		
Glass 4	26.27	20.51	45.80		
Plag	18.13	15.56	37.88	0.596586	(~4499)

References: [1] Lugmair G. W. and Galer S. J. G. 1992. *Geochimica et Cosmochimica Acta* 56:1673. [2] Kurat G et al. 2001. Abstract #1737. 32nd Lunar and Planetary Science Conference. [3] Nyquist L. E. et al. 2003. Abstract #1388. 34th Lunar and Planetary Science Conference. [4]. Tonui E. K. et al. 2003. Abstract #1812. 34th Lunar and Planetary Science Conference. [5] Jagoutz E. et al. 2002. Abstract #1043. 33rd Lunar and Planetary Science Conference. [6] Jotter R. et al. 2002. *Meteoritics & Planetary Science* 37: A73. [7] Jagoutz E. et al. 2003. *Meteoritics & Planetary Science*. This issue.

MOON EXOGENOUS SEISMICITY: METEOROID STREAMS, MICROMETEORITES AND IDPS, SOLAR WIND

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Introduction: We briefly outlne the results of previous research which linked lunar seismicity (Nakamura Catalogue) and cosmogonic objects and processes.

The Mapping of Impact Processes from Meteoroid Streams and Solar Wind on the Moon into Durations of Seismograms: We analyzed data of annually constructed histograms (distributions) for durations of seismograms from exogenous actions on the moon. The peculiarities of these actions and their comparison with data of optic lunar events were taken into consideration. We have found that dust-gas plasma of meteoroid streams and solar wind are modulated by free oscillations of the sun, and histograms from meteoroid streams with an intensity of 4–8 impact/ day contain durations according to periods of free lunar oscillations.

The Temporal Structure of Meteoroid Streams and Lunar Seismicity—The Peculiarity of the Shape of Histogram Envelopes: The shapes of histogram envelopes for the anneal interval change from Gauss to a more complicated curve. It betokens the unsteady state of seismic processes and, at times, the similarity of these to earthquake recurrence curves for a region of mines and/or to energy distribution for high-power solar bursts.

Simple Estimation for Nongravitational Effects on the Moon: Assessments of the integral pressure to the Moon by solar wind (under undisturbed sun and sun burst) and gas-dust components of meteoroid streams have been made. The energy of these disturbances (under sun bursts or its maximum stream density) is enough for free moon oscillation initiation and recording of lunar seismic events.

Conclusions: Lunar seismicity suggests that the moon is a unique cosmogonical and astrophysical detector.

OMANI-SWISS METEORITE SEARCH 2001–2003: PROJECT OVERVIEW

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Introduction: During three field seasons in January-February, 2001, December, 2001-January ,2002, and September, 2002-January, 2003, meteorites were collected in a joint project in the central deserts of the Sultanate of Oman with the aim to obtain a representative collection of meteorites from this area which would be suitable for find and fall statistics analysis, to study the weathering of the meteorites, and to recover rare meteorites. Searching was performed visually from one or two 4WD vehicles by a group of 2 to 4 persons. During the first campaign, we searched existing fields and areas nearby. Later on, "new" areas were successfully explored. In total, we invested approximately 1 man year in the search, completed 9600 search km in the desert, and recovered approximately 3700 meteorite samples with a mass close to 1050 kg. Excluding obvious strewnfields, the recovered number of individual meteorites is approximately 150. Among these are one Martian (SaU 094) meteorite, one Lunar (SaU 169) meteorite, a small strewnfield of a primitive achondrite, one octaedrite (the first iron from Oman), and several unusual chondrites (3C, 1E, 1R). The mean mass of the recovered meteorites (outside strewnfields) is 1125 g (median = 179 g). Including finds from the very large JaH 073 L6 strewnfield [1] and some other smaller strewnfields, the mean mass of all the stones is 282 g (median = 33.5 g). Test searches by foot indicate that this difference is not due to the overlooking of small stones outside strewnfields. The median mass (excluding strewnfields) is larger than in Antarctic finds. When strewnfields are included, the values are very similar. Based on this observation, it appears possible that the abundance of small stones in the Antarctic collection may be mainly due to the presence of large numbers of paired stones from showers. The low abundance of irons in Oman (1 among several 1000 finds) may be a result of early human collection, rapid sinking in the soil due to high density, or a combination of these effects. In addition to meteorites, numerous soil samples were collected [2]. Our successful search campaigns demonstrate that large numbers of meteorites, including rare types, can be recovered during scientifically motivated searches in hot deserts at comparatively low cost

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MANGANESE-CHROMIUM ISOTOPE SYSTEMATICS OF A HIGHLY UNUSUAL DIFFERENTIATED METEORITE: NWA 011 O. Bogdanovski¹ and G. W. Lugmair^{1, 2}. ¹Max-Planck-Institute for Chemistry, Cosmochemistry, PO Box 3060, 55020 Mainz, Germany. ²Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093–0212, USA

Introduction: The basaltic meteorite Northwest Africa (NWA) 011 was at first classified as a eucrite with an anomalous Fe/Mn ratio [1]. Later studies have shown that the REE and trace element compositions of NWA 011, as well as its oxygen isotopes, are different from those of eucrites [2]. It was proposed that NWA 011 derived from a different parent body (PB) [2], possibly even from Mercury [3].

Results: So far, we have measured the Mn-Cr isotope systematics of a ~300 mg bulk sample of NWA 011. The concentrations of Mn, Cr, and other major and trace elements were measured by ICP-OES and are in agreement with INAA data [2, 4]. The Mn/Cr ratio in bulk NWA 011 is 1.88 ± 0.04 (55 Mn/ 52 Cr = 2.13 ± 0.05). The Cr isotopic composition was obtained from, so far, 58 individual measurements of 300 ratios each. We have found excesses in both 53 Cr and 54 Cr relative to the terrestrial standard of $+0.85 \pm 0.06\epsilon$ and $+1.45 \pm 0.11\epsilon$, respectively ($\pm 2\sigma_{mean}$).

Discussion: When these results are compared with Mn-Cr data from the HED meteorites [5], we observe that the data point of NWA 011 falls below the HED whole rock isochron. While the 55 Mn/ 52 Cr ratio of NWA 011 is identical to that of the eucrite Caldera [5], its 53 Cr/ 52 Cr is lower by ~0.28ε. This fact alone already indicates the lack of any genetic relationship between NWA 011 and the HED PB. More noteworthy, this is also confirmed by the large excess in 54 Cr, which was not detected in the HED meteorites. Indeed, this 54 Cr excess is similar to values obtained from the CI carbonaceous chondrites (CC) Ivuna and Orgueil [6] (Fig. 1). So far, there are no Mn-Cr data on CR chondrites, the oxygen isotopes of which are close to NWA 011 [2]. However, NWA 011 does not follow the correlation of ϵ^{53} Cr- ϵ^{54} Cr found in CC, which is probably mainly due its high 53 Cr excess combined with a much higher than chondritic Mn/Cr ratio. Thus, our data may indicate that NWA 011 is a differentiation product from a relatively large PB, which is related to CI (or CR?) meteorites.



Fig. 1. ε^{53} Cr- ε^{54} Cr excesses in bulk CC [6] and NWA 011.

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WEATHERING OF METEORITES FROM OMAN: THE INFLUENCE OF SOIL CHEMISTRY AND CORRELATION OF CHEMICAL/MINERALOGICAL WEATHERING PROXIES WITH ¹⁴C TERRESTRIAL AGES

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Introduction: During three meteorite field search seasons in Oman (2001–2003), approximately 150 individual meteorites were recovered plus several strewnfields (>3000 stones were collected from a single strewnfield). 141 soil samples were collected from different regions in the Oman interior desert. Two types of soil samples were collected: soil under meteorite (SUM) and reference soil samples (RSS) 10 m away from SUM. Meteorites and soil powders were subjected to major and trace element analysis using a combination of INAA, ICP-MS, and ICP-OES. The same set of samples was analyzed for ¹⁴C.

Analytical Results and Discussion: The measured 14 C terrestrial ages of the investigated meteorites is in the range of 2.2 to >49 kyr, with many ages between 10 and 40 kyr. Generally, the older meteorites are more weathered. Meteorites from the same strewnfield may have different weathering grades depending on burial conditions and the size of the meteorite. Comparing the meteorites' color powders with the rock color chart show that meteorites with the lowest weathering grade are represented by a dark gray color (N3), and meteorites with a high weathering grade are commonly represented by light brown colors (5 YR 6/4). Comparing the chemical analyses of the investigated meteorites with mean compositions of H and L chondrites [1], enrichments of Sr and Ba are most prominent. Both elements are positively correlated with 14 C age and weathering grade.

Geochemical analyses demonstrated that the soil chemistry is very homogeneous all over the interior Oman desert and largely independent of the region or the bed rock lithology (all bed rocks are flat-lying marine and lacustrine limestones [2]). Comparing the bulk soil (RSS) geochemistry with the average composition of the upper continental earth crust [3] showed that the soil samples are strongly enriched in Cr with significant enrichments of Ni and Se. SUM samples are more strongly enriched in Ni than the RSS, indicating leaching of Ni from the meteorites. Heavy mineral separation and microprobe analysis showed that ophiolite-derived chromite is an abundant soil constituent. Ni in RSS samples possibly has the same source.

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THE HABHAB STRUCTURE OF CENTRAL OMAN: NOT AN IMPACT CRATER

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Introduction: The 6 km near-circular Habhab structure located in Central Oman (19°55'N, 57°0'E, 75 km east of Hayma) has been suggested to represent a possible impact structure based on satellite imagery [1–4]. This interpretation has been challenged recently [5]. The structure is located on a vast near-flat desert plain made up of shallow marine Fars group limestones of middle Miocene age. It consists of two concentric, near-circular shallow depressions. We investigated the structure on the ground in January, 2002, December, 2002, and January, 2003. The discovery of several ordinary chondrites in and near the structure motivated us to reinvestigate its origin. Based on the field observations and seismic profiles, we conclude that the Habhab circular structure is not an impact crater. This conclusion is based on the following observations:

- Undisturbed, bedded Miocene limestone was observed at the rim of the structure as well as in its center. No shock effects (brecciation, intense fracturing) were observed in the beds or in the abundant fossils contained therein.
- The topographic relief between the different features observed in satellite imagery is only a few meters, too little for a crater of young age. The flanks of the structure are not uplifted.
- Absence of any ejecta from stratigraphically deeper strata.
- Seismic profiles indicate the presence of a salt plug exactly below the Habhab circular structure.

We consider that the Habhab circular structure is most likely caused by salt dissolution/salt tectonics related to a near-surface salt plug.

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PORPHYRITIC OLIVINE CHONDRULES: CONSTRAINTS ON FORMATION CONDITIONS FROM TEXTURES AND EXPERIMENTAL SIMULATIONS

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Introduction: Based on several lines of evidence, we conclude that most porphyritic olivine (PO) chondrules were formed by partial (i.e., subliquidus) melting of an olivine-rich precursor material. The melting event was followed by moderately rapid (on the order of 100°C/hr) cooling. Observed crystal size distributions and iron-rich overgrowths on the olivine grains in PO chondrules are consistent with the proposed cooling and growth rates.

Partial Melting: The recognition that most porphyritic chondrules did not crystallize from a complete melt has revolutionized the understanding of the physical conditions of chondrule formation. In particular, the role of nucleation in determining the texture is diminished if a significant proportion of the crystals in a chondrule are relicts. Incomplete melting also provides a partial explanation for the high abundances of alkalies and other volatiles in the chondrule mesostases. If chondrules were subjected to lower peak temperatures, the problem of volatilization is diminished. Partial melting of crushed UOC demonstrates that textures similar to those seen in some chondrules can be produced from subliquidus ($T \sim 100-300^{\circ}C$) melting [1]. Crystal size distributions (CSDs) from higher intensity partial melting experiments ($T \sim 5-50^{\circ}C$) closely match other PO chondrules from UOC and CO chondrites [2].

Cooling Rate: Extensive experimental simulation studies have established that textures resembling those of many PO chondrules can be produced by cooling rates on the order of 100°C/hr [3]. This is consistent with estimates from nebular shock models [4]. Given a temperature range of approximately 250°C between the liquidus and solidus of chondrule melts, cooling at these rates provides approximately 1–5 hr during which crystals can grow.

Growth Rate: The rate at which olivine crystals grow in chondrules is difficult to constrain. However, the evolution of textures during chondrulesimulation experiments is consistent with a growth rate (dr/dt) on the order of 10–7 cm/s. This is similar to olivine growth rates determined by other techniques [5]. A growth rate of this magnitude is also consistent with petrographic evidence. The thickness of Fa-rich rims on olivine in Type II chondrules is frequently in the range of 5 to 20 μ m [6]. Assuming a crystallization interval of 250°C and a cooling rate of 100°C/hr, the production of a rim 10 μ m thick would require a growth rate of 1.1 × 10⁻⁷ cm/s.

Summary: The textures of porphyritic chondrules provide strong evidence for multiple episodes of melting, in which the peak temperatures remained below the liquidus. The relict grains were up to 100 μ m in size at the end of the melting event, which means that the crystals did not have to grow to their final size during the last heating/cooling cycle. Cooling was relatively slow, on the order of 100°C/hr, which is consistent with chondrule formation in a comparatively dense region of the nebula. An olivine growth rate on the order of ~10–7 cm/s is consistent with the observed 5–20 μ m thick Fe-rich rims on olivine grains in Type II chondrules and with measured and inferred growth rates from crystallization experiments.

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PRESERVATION OF SPACE WEATHERING PRODUCTS IN REGOLITH BRECCIAS

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Introduction: Our understanding of the processes and products of space weathering comes almost exclusively from studies of lunar soils [1]. However, space weathering is highly dependent on the environment in which it occurs, and thus, its products are expected to vary from body to body. How does space weathering manifest itself on asteroids, and how does that affect our remote sensing data? Unlike the moon, we unfortunately have no direct asteroidal regolith to study surface processes. We do however have regolith breccia meteorites, which begs the question: what happens to space weathering products when regolith is fused into rock? Are the products of space weathering, such as rims of nanophase iron on grains, preserved? Are other products produced which are unique to regolith breccias? To answer these questions and to gain insight into the regolith breccias of varying degrees of friability/compaction and weathering extent.

Breccias Versus Soils: Important differences were observed between ordinary lunar soil and regolith breccia grains. The biggest difference was the amount of glass present in the breccia in the form of glass splashes and coatings on grains (Fig. 1) [2]. Distinct from the vapor/sputter deposited coatings present in both the soils and breccia grains, these glass coatings appear to have been acquired just moments before the breccia was lithified. The composition of the glass rims is variable, but generally similar to that of agglutinate glass, and like agglutinates, they contain ubiquitous nanophase iron.



Fig. 1. SEM BSE image of a grain from lunar regolith breccia 10068 with an extensive glass coating on the right hand side. The grain was separated using a freeze-dry technique [3].

Preservation of Weathering Products: A range of regolith breccias have been studied including 79035 (friable), 10068 (friable to coherent), 15505 (moderately coherent/shocked), and QUE 93069 (highly compacted and shocked). As was expected, weathering products became increasingly difficult to identify with increasing degrees of shock and compaction. Decreased porosity makes lunar agglutinates difficult to recognize because their vesicules are closed. Often, the only evidence of weathering products are regions containing, and grains surrounded by, high concentrations of metallic iron blebs. On the other hand, even in the most shocked and compacted sample (QUE 93069), space weathering products, though rare, were still observed. These observations suggest that it will be difficult, but not impossible, to find evidence of space weathering preserved in regolith breccia meteorites. Their physical form, however, depends on the degree of compaction experienced by the individual breccia.

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LARGE PLATES OF ANORTHITE-OLIVINE INTERGROWTHS IN THE D'ORBIGNY ANGRITE

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Introduction: The shape, structure, and texture of D'Orbigny and its mineral and bulk chemical compositions indicate an unusual genesis under changing redox conditions [1–3]. Empty shells, large plates, very high porosity, druses with augite and abundant glasses are outstanding peculiarities of this rock. Here ,we report on a study of a huge plate consisting of anorthite-olivine intergrowths.

Results and Discussion: The anorthite-olivine plate, 12 mm long and 200-800 µm thick, crosscuts the dense lithology of the investigated sample D'Orbigny G (PTS, NHM, Vienna). The center of the plate consists of large anorthites that are intimately intergrown with mostly anhedral olivines (up to 100 µm), commonly in a graphic way, and rare euhedral Al-Mg-Fe spinel. At the surface of the plate, subhedral to euhedral anorthite and anhedral olivine crystals (both >300 µm in size) form abundant off-springs of short branches. The interstitial space outside the plate contains large augite-hedenbergite and olivine-kirschsteinite with sulfides and ulvöspinel. Anorthite is chemically pure, olivine in the plates is mostly ~Fa₃₅La₁—rarely metasomatized to Fa₈₀La₁₉ as is common outside the plate, and spinel is Cr₂O₃-poor (7.5 wt%) but rich in FeO (22 wt%). Trace element (TE) contents of all phases are high and variable. In particular, olivines have highly variable TE contents (Fig. 1) with olivines inside the plate being much poorer in TEs than those outside [4]. The trapped olivines indicate an origin from a system that was enriched to about 10 \times CI in Sc, Sr, Nd, and Eu, about 20–50 \times CI in the HREE and >100 × CI in La, Ce, and Nb (partition coefficients from [5]). The latter two groups of elements are far out of equilibrium between olivine and angrite bulk. The first group seems to be in equilibrium as are the elements V, Mn, Cr, and Co. TEs have high (2-3 × CI) abundances in late olivines, except Sr, and are far out of equilibrium with the bulk rock, except for V, Mn, Cr, and Co. This situation leaves us with the following scenario: anorthite-olivine intergrowths precipitated from a fluid, covered spheres of an unknown, now vanished mineral, and formed large freely floating plates. A change in redox conditions caused the phase constituting the spheres to decompose, ultimately leaving hollow shells. This process liberated large amounts of TEs and Ca, and consequently, late olivines and augites, kirschsteinite, and hedenbergite grew from an environment very rich in TEs and Ca. Therefore, it is possible that CaS, a major host phase of TEs under reducing conditions [6], was constituting the spheres. The unfractionated pattern, similar to that of some olivines of carbonaceous chondrites [7-9], suggests a reservoir with chondritic relative TE abundances.





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MINERALOGY AND NOBLE GAS SIGNATURES OF VIGARANO METEORITE: EVOLUTION OF PLANETARY SURFACE MATERIAL ON CV PARENT BODY

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Introduction: The Vigarano CV3 chondrite is a breccia and contains clasts that suffered aqueous alteration [1, 2, 3]. In this study, we performed mineralogical and noble gas studies on the Vigarano meteorite to elucidate the evolution of the surface material of its parent body.

Results and Discussion: Texturally and mineralogically, there are two types of lithology in the matrix: porous matrix that includes abundant lathshaped olivine crystals and compact matrix that consists of fragmental materials with interstices filled by sub-µm particles. There are sharp boundaries between the two types of matrices. However, it is interesting that there are also places where these two types of matrices merge into each other. These two types of matrices are basically anhydrous with minor amounts of ferrihydrite and phyllosilicate [4]. On the other hand, dark rims around chondrules and dark clasts in the matrix contain abundant phyllosilicates. Most of them have about 1.0 nm lattice fringes, which indicates that saponite is dominant [3]. Synchrotron radiation X-ray diffraction patterns of these phyllosilicate-rich materials do not show obvious (001) peaks of saponite although the (001) fringes can be observed by TEM. This suggests the low crystallinity of saponite. The mesostases of chondrules enclosed by the dark rims contains interlayered mixtures of phyllosilicates with about 1.0 nm and 1.4-1.5 nm lattice fringes. Their chemical compositions suggest that they are a mixture of Na-bearing phlogopite and chlorite.

Laser-microprobe noble-gas analysis [5] was performed on thin Vigarano slices. The results clearly indicate that the noble gas compositions reflect textural differences: the porous matrix contains primordial noble gases but lacks solar gases, while the compact matrix contains both solar and primordial noble gases. Ne isotopic ratios of the porous matrix are plotted along the Ne-A and Ne-cosmogenic mixing line, while those of the compact matrix are plotted close to the Ne-SEP and Ne-cosmogenic mixing line. ²⁰Ne and ⁴He concentrations in the compact matrix are higher than those in the porous matrix due to the presence of solar gases, but the concentrations are much lower than those in other chondrite regolith breccias (e.g., [5]). The low abundance of solar gases implies: 1) short-duration exposure to solar wind; 2) dilution of solar-gas concentrations by the addition of materials depleted in solar gases; and 3) loss of solar gas due to later thermal metamorphism and/or aqueous alteration. Although it is indicated that the compact matrix once existed on the surface of the parent body, processes other than simple mechanical gardening in the regolith must be considered to explain the gradual textural change between the porous and the compact matrix, and the low solar-gas abundance in the compact matrix.

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A NANOSIMS STUDY OF C-, SI-, AND BA-ISOTOPIC COMPOSITIONS OF PRESOLAR SILICON CARBIDE GRAINS FROM THE MURCHISON METEORITE

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Introduction: Barium is among the astrophysically diagnostic elements in presolar SiC. Ba-isotopic compositions of presolar SiC were reported for bulk samples studied by TIMS and SIMS [1–3] and, recently, also for individual grains (2.3–5.3 μ m) measured by RIMS [4]. Here, we report the first NanoSIMS Ba-isotopic data, along with C- and Si-isotopic compositions (for SiC classification) for six individual presolar SiC grains (1.5–2.6 μ m) and for eight SiC grain aggregates (1.2–5.3 μ m, subgrain size: <1 μ m) from the Murchison CM2 meteorite.

Experimental Method: The NanoSIMS was operated in a combined measurement mode using four different magnetic fields and four detectors. A rastered O⁻ primary ion beam (10 pA) was used to measure ¹³⁴Ba, ¹³⁵Ba, ¹³⁶Ba, ¹³⁷Ba, ¹³⁸Ba, along with ²⁸Si, ⁸⁸Sr, ⁹⁰Zr, ¹³³Cs, ¹³⁹La, and ¹⁴⁰Ce. High resolution (300 nm) ion images of ²⁸Si and ¹³⁸Ba were acquired to make sure that contributions from contaminating Ba could be neglected. C- and Si-isotopic ratios were measured after the Ba analyses by high resolution ion imaging using a focused (100 nm) primary Cs⁺ ion beam (<1 pA).

Results and Discussion: Ba concentrations range from 25 to 110 ppm in grain aggregates and from 7 to 100 ppm in individual grains $(0.5-7 \times \text{the})$ Si-normalized CI concentration). All individual SiC grains belong to the mainstream group, as evidenced by ¹²C/¹³C ratios ranging from 22 to 73 and Si-isotopic ratios along the characteristic Si mainstream line [5]. The ¹³⁶Banormalized Ba-isotopic patterns are characterized by slight enrichments in ¹³⁴Ba (most aggregates and all individual grains) and depletions in ¹³⁵Ba, ¹³⁷Ba, and ¹³⁸Ba (Fig. 1), the signature of s-process nucleosynthesis in 1.5–3 M_O AGB stars (e.g., [4]). The patterns are qualitatively consistent with those from previous studies [1-4]. However, compared to the previous measurements on individual grains [4], the range in Ba-isotopic compositions seems to be somewhat more restricted, possibly due to the smaller sizes of the grains of this study, indicating higher relative contributions of s-process matter in the envelope of the parent stars. On average, ¹³⁴Ba/¹³⁶Ba, ¹³⁵Ba/ ¹³⁶Ba, ¹³⁷Ba/¹³⁶Ba, and ¹³⁸Ba/¹³⁶Ba are slightly lower in the aggregates as compared to individual grains, confirming earlier observations on the grainsize dependency of Ba-isotopic compositions (e.g., [4]).



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APPLICATION OF IMAGE ANALYSIS SYSTEMS TO INVESTIGATION OF METAL AND SULFIDE PHASES IN H AND L CHONDRITES

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Compositions, types, and sizes of metal and sulfide phases of chondrites were explicitly studied in the past [1–3]. Digital microscopy reveals new horizons in chondrite studies. Modern image analysis systems allow measuring a lot of stereological and morphological characteristics for meteoritic phases. Some morphological characteristics were recently obtained for L chondrites [4].

The following H, L, and LL meteorites of 3–6 petrologic types are researched in this work: Doroninsk H6, Kulp H6, Lancon H6, Zvonkov H6, Ichkala H6, Pribram H5, Pultusk H5, Timochin H5, Vengerovo H5, Orlovka H5, Sverdlovsk H4/5, Alexandrovsky H4, Kashin H4, Chernyi Bor H4, Muslyumovo H4, Vyatka H4, Dhajala H3, Kunashak L6, Mbale L5–6, Farmington L5, Tarbagatai L5, Tsarev L5, Ergheo L5, Mt. Tazerzait L5, Botschetschki L4, Saratov L4, Savtschenskoje LL4, Manych LL3, Parnallee LL3, Rakity L3, Krymka LL3, and Knyahinya L/LL5. A NEOPHOT 32 microscope with a TV camera and SIAMS 600TM and SIMAGIS image analysis software are used to capture digital images of metal and sulfide in nonetched, polished sections of meteorites. The total area analyzed amounts to 3300 mm². Modal analysis is performed for each meteorite. The morphological characteristics of large metal grains with areas exceeding 10000 mkm² are obtained.

Separation of the phases in images by difference in reflectance (256 grades) is realized with the SIMAGIS smart imaging spreadsheet. It is easy to perform modal analysis and measure the morphological characteristics of a definite phase. Modal analysis shows that the amount of large metal grains in H chondrites exceeds that in L chondrites. It is noted that troilite in L chondrites generally contains grains with an area less than 500 mkm². However, larger grains of troilite appear and the amount of large metal grains increases with the increase of the petrologic type.

A 3D-image of Tsarev L5 metal grains is reconstructed by processing 35 sequential sections of the meteorite. Shape factor values are shown to be stable for all sections of every explored metal grain. Standard (area and perimeter) and morphological (circle shape factor FS, compaction factor FC, elongation factor FL, and roughness factor FR) [4] characteristics are measured for every large metal grain in 32 chondrites. The most evident is the dependence of the FR value upon the petrologic type. The increase of the FR value for both H and L chondrites from 0.45 (Rakity, type 3) to 0.75 (Zvonkov, type 6) is revealed.

In many cases, the silicate and sulfide inclusions (islands) are detected in large metal grains. These islands may appear to be due to sectioning of the grains with a complex surface, may precipitate from a super-saturated solid solution, or may result from concurrent crystals growth. The portion of islands and their average size are found to decrease with an increase of the petrologic type.

Use of modern image analysis systems allows the discovery of quantitative differences in chondrite structures. Nevertheless, it is also necessary to consider the influence of phase and structure composition, degree of shock metamorphism, and terrestrial weathering upon metal morphology.

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EARLY VOLCANISM ON THE NWA 011 PARENT BODY

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Introduction: NWA 011 was originally identified as a non-cumulate eucrite [1]. However, its O-isotopic composition resembles that of CR chondrites rather than HED meteorites [2, 3]. Its somewhat unusual chemical composition [2] contributed to the suggestion that NWA 011 might come from Mercury [4], from which the meteoritic yield should be ~1% of that from Mars [5, 6]. Previously reported K-Ar and Ar-Ar ages of 2.0 ± 0.3 Ga [2] and >3.2 Ga [7], respectively, are consistent with the formation of younger impact-remelted rocks from mercurian surface rocks of estimated solidification ages of ~3.7–4.4 Ga [5] but also with other origins. We have determined the Sm-Nd age of NWA 011 to further elucidate the origin and history of this unique meteorite.

Sm-Nd Age: Sm-Nd data for plagioclase and pyroxene mineral separates are shown in an isochron plot in Fig. 1.



Fig. 1. Sm-Nd data for NWA 011 and EET 90020 [8].

The Sm-Nd age of NWA 011 of 4.46 ± 0.04 Ga is identical within uncertainty to the 4.51 ± 0.04 Ga age of eucrite EET 90020 [8]. There also are close similarities between NWA 011 and EET 90020 for other types of mineralogical, compositional, and isotopic data. Positive $\varepsilon_{Nd} = 1.5 \pm 0.3$ and 1.0 ± 0.5 , respectively, suggest both were derived from LREE-depeleted source regions. The only basaltic asteroid other than 4 Vesta is 1459 Magnya at ~3.15 AU [9]. The old age of NWA 011, its close similarity to EET 90020, and the probability that its unusual O-isotopic composition is a consequence of formation of its parent body adjacent to carbonaceous asteroids of similar O-isotopic composition in the outer main belt, suggest that it is of asteroidal rather than mercurian origin.

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GLASSES IN THE D'ORBIGNY ANGRITE

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Introduction: The angrite D'Orbigny is exceptionally rich in glass, a feature that makes this rock a unique member of the angrite group (e.g., [1–4]). The chemical composition of these glasses is incompatible with a formation by partial melting of a chondritic source rock. Also, there are no indications that glass filling open spaces could have been produced by shock melting or have been incorporated from an external source. Glass in D'Orbigny seems to have a genesis not considered so far for glasses in meteorites.

Results and Discussion: The investigated samples are: PTS "D'Orbigny B" and different types of glasses separated from rock specimens and rock debris (all from NHM, Vienna). Glasses fill open spaces, form pockets, and occur as inclusions in olivines [1]. Their petrographical occurrence clearly indicates that most of the glasses have been incorporated after the formation of the empty spaces in the rock. However, the lack of interconnected glass veins crosscutting the rock indicates that glasses were not introduced from outside the rock. Glasses in D'Orbigny are as ancient as the rock itself [2], making a shock origin highly improbable but, rather, indicating that they are of primary origin, having formed contemporaneously with the rock. The chemical composition of the glasses filling pore space and hollow shells resembles that of angrite bulk rocks, in particular that of D'Orbigny, Asuka 881371, and Sahara 99555. The abundances of major refractory elements are about 10 × CI and those of FeO and MnO are similar to those in CI chondrites. The CaO/TiO2 and FeO/MnO ratios are also close to those in CI chondrites. The contents of C and N in glass inclusions is comparable to that observed in glass inclusions in olivines from carbonaceous chondrites [3]. Trace element abundances in D'Orbigny glasses appear to be governed by volatility. All refractory lithophile elements in the glass have flat abundance patterns, which suggests that the source for the glass had the same CI-normalized refractory elemental abundances. The contents of V, Cr, Mn, Fe, and Li are approximately in equilibrium between olivine and its glass inclusions. These elements could have been added to the glass (and rock) in a late metasomatic event [4]. Because the Fe/Mn ratio of the glass (and rock) is close to chondritic, the source of that metasomatic agent likely had chondritic elemental abundances. Because D'Orbigny glasses share many, if not all, of their features with glass inclusions in olivines from carbonaceous chondrites [5] they could be the result of a similar formation process. They could have been formed by vapor-liquidsolid growth or liquid phase epitaxy [5-7] during olivine formation. The precursor liquid of the glass must have been present in small amounts such as a thin film wetting the crystal-vapor interface and interstitial spaces and facilitated growth of large crystals from the vapor. Glass inclusions, as well as glass pockets, could represent a sample of this melt, trapped and subsequently quenched during olivine formation.

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REGOLITH HISTORY ON THE AUBRITE PARENT BODY

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Introduction: Some characteristics of the aubrites are long cosmic-ray irradiation records and heterogeneous chemical compositions. Large isotopic shifts of Sm and Gd related to neutron capture reactions were found in aubrites [1], which suggested a near-surface irradiation history of aubrites on the parent body. Recent noble gas isotopic studies of aubrites also reveal regolith processes on their parent body [2]. In particular, the large variations in cosmic-ray-produced ²¹Ne_c concentrations in the small Pesyanoe mass (3.4 kg) between light and dark phases [3] are inconsistent with shielding effects during space irradiation. The discrepancies in exposure ages for two samples [2] make the Pesyanoe meteorite suitable for studies of the regolith history. We present here new Sm and Gd isotopic data of aubrites, including Pesyanoe, to investigate the regolith history of their parent body.

Samples: Six samples from two different Pesyanoe fragments (PES-90 and PES-92), three from Pena Blanca Spring (PBS), and one from Norton County (NC), Shallowater (SW), and Khor Temiki (KT) were used in this study.

Results and Discussions: The calculated neutron fluences for all six Pesyanoe samples are very large (2.2 to 2.9×10^{16} n cm⁻²) and variable. The variations observed in the neutron fluences are due to the irradiation history in the regolith. Only minor differences are expected during space irradiation due to shielding depths and variation of the chemical compositions.

Figure 1 shows a plot of neutron fluences versus CRE ages of aubrite samples. The data from our early study [1] are also plotted in the figure. There is apparently no correlation between the neutron fluences and CRE ages. However, the data suggest the subdivision of aubrites into subgroups with only space irradiation (Mt. E, SW, PBS, NC, MB) and a subgroup with regolith history (ALH, PES, BV, CF).



Fig. 1. A plot of neutron fluences versus CRE ages of aubrites. ALH: ALH78113, BV: Bishopville, CF: Cumberland Falls, MB: Mayo Belwa, Mt.E: Mt. Egerton. The CRE ages are cited from [2].

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SI ISOTOPIC MEASUREMENTS OF SMALL SIC AND SI $_3\mathrm{N}_4$ GRAINS FROM THE INDARCH (EH4) METEORITE

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Last year we reported NanoSIMS C and N isotopic measurements on small SiC grains, including 182 grains from the Indarch (EH4) SiC-rich separate IH6 (diameter $0.25-0.65 \ \mu m$) [1]. Here, we report C and Si isotopic analyses on 585 grains from IH6. Measurements were made in multi-detection mode by counting C and Si ions in five electron multipliers.

Acid residues from enstatite chondrites contain silicon nitride (e.g., 1, 2, 3]). Among the analyzed IH6 grains, we identified 442 SiC and 143 Si₃N₄ grains. The Si isotopic ratios of SiC grains are shown in Fig. 1. We found 361 mainstream grains (81.7%), 23 A+B grains (5.2%), 3 X grains (0.7%), 27 Y grains (6.1%), and 28 Z grains (6.3%). While the abundances of A+B and X grains are very similar to those obtained for >2 μ m grains [4, 5], the abundances of Y and Z grains are much higher [6], in agreement with previous observations on SiC from the Murchison and Acfer 094 meteorites [7, 8].



Fig. 1.

Previous ion microprobe analyses of single Si_3N_4 grains from Qingzhen and Indarch [1, 2] yielded isotopic anomalies in C and N. While Alexander et al. [2] believed that these were due to attached SiC grains, Amari et al. [1] considered the possibility that some were of presolar origin. Among the Si_3N_4 grains of this study, we found one of type X [3, 4, 9]. Most of the other grains cluster around normal Si isotopic compositions (Fig. 2). Although deviations from normal are larger than those of terrestrial Si_3N_4 standards, they might be due to attached SiC grains. This is less likely for grains A and C, although such an explanation cannot be strictly excluded.



Fig. 2.

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FLIGHT ORIENTED MICROMETEORITES

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Introduction: Barred olivine (BO) spherules are micrometeorites that formed as completely molten droplets during atmospheric entry heating and have unusual textures dominated by dendrites of parallel growth olivines [1]. These spherules have superficial similarities to BO chondrules. However, in contrast to chondrules, BO spherules have relatively uniform textures and particle shapes. Typical BO spherules have ovoid (egg) shapes with bars of olivine oriented perpendicular to the long-axis of the spherule. The shape of BO particles has always been assumed to be a consequence of the growth of the barred olivine. However, we present new evidence to suggest that BO spherule shapes and their textures arise due to flight orientation.

Textures of BO Spherules: Evidence for the flight orientation of BO spherules during the high temperature portion of their heating is provided by particles that demonstrate systematic variations in their textures parallel to their long axes. These BO spherules generally show increasing olivine bar widths from the bottom (the low curvature end) of the particle to the top (the high curvature end). One particle CP94-50-T1, however, consists of three discrete textural domains: 1) radiate olivine at the bottom of the particle; 2) barred olivine across the middle of the particle; and 3) porphyritic olivine at the top of the particle. Like other systematic BO particles, the width of olivine bars increases towards the top of the particle. The textures observed in CP94-50-T1 correspond to different ranges of peak temperatures (increasing in the series: porphyritic, barred, radiate, due to the destruction of crystal nuclei) and strongly imply the existence of a significant temperature gradient over the long axis of the particle at peak temperature.

Flight Orientation: The presence of temperature gradients within systematic BO spherules suggests such particles were oriented during entry heating since the thermal behavior of small, homogeneous particles precludes large temperature gradients [2] except where they are heated only from one side. Systematic BO spherules, therefore, must have flown with their long axes parallel to the direction of motion with their low curvature end as the lead hemisphere. Metal droplets, when present in BO spherules, are always located at this end of the particle, which further supports their flight orientation.

The influence of the temperature gradient on the texture of particle CP94-50-T1 indicates the destruction of crystallization nuclei at temperatures above the liquidus. The orientation of the temperature gradient with respect the long axis of the particle, therefore, suggests that ovoid droplet shapes arose prior to crystallization. The characteristic ovoid shapes of BO spherules are, therefore, probably fluid dynamical instabilities that arise during atmospheric flight.

Implications: Flight orientation of micrometeoroids during atmospheric entry will significantly influence the nature of their heating and the peak temperatures that are attained by particles. Entry heating models that treat micrometeorites as homogeneous, spherical, unoriented particles will, therefore, not fully describe the distributions of micrometeorites collected on Earth.

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THE CHEMICAL COMPOSITION OF THE BASALTIC LUNAR METEORITE EET 96008 AND THE LITHIUM DISTRIBUTION ON MOON

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Introduction: The previous mineralogical, petrological, and chemical investigations of the basaltic breccia EET 96008 indicate pairing with EET 87521. The origin of these meteorites was interpreted as a nearly pure Ti-poor (VLT) mare basalt [1] or an evolved segregation from a basalt flow with a substantial amount of material of highland affinity [2].

Chemistry: The chemistry of major, minor, and trace elements analyzed with INAA from our split 27 of EET 96008 matches remarkably well with that of EET 87521–6 [3] and confirms the pairing of these 2 lunar meteorites. Warren and Kallemeyn [3] concluded that EET 87521 is dominated by Ti-poor mare basalts with an admixture of highland material. The high Co content of 49.5 ppm and the Fe content of 14.9% reflect the mare character of EET 96008. Because of the high Fe content, the Fe/Sc ratio of 4000 indicates an origin from low Ti mare basalt as well as from highland material. The Na/Eu ratio of 3500 is typical for highland breccias and KREEP. The concentrations of the highly incompatible elements K, U, Th, and REE also indicate a significant amount of KREEP in EET 96008.

Lithium and the halogens were determined via pyrohydrolysis of an aliquot of the bulk sample. The low Cl (10 ppm) and Br (16 ppb) concentrations are similar to those in mare basalts. The high I content of 0.5 ppm is the result of weathering in Antarctica. The F content of 33 ppm and the Li content of 7.5 ppm fit the observed F/Li ratio of 4 in lunar mare and highland samples.

Lithium Distribution in Lunar Rocks: Lithium is a moderately incompatible trace element in magmatic systems, and its behavior is similar to Yb. In lunar samples, Li correlates well with the refractory lithophile elements Be, Zr, and Yb. Lithium, with a condensation temperature of 1225 K, belongs to the moderately volatile elements like Cr and Mn. Nevertheless, it is very surprising that in lunar mare and highland samples, the mean Li/Zr ratio of 0.04 [4] is a factor of 9 lower than the CI ratio of 0.38. The same holds for the Li/Yb ratio of 1.1 in lunar mare basalts and KREEP, which is a factor of 8 lower relative to CI. Such a high depletion of Li compared to the refractory LIL elements cannot be explained by volatility. The Li abundance in the primitive Earth's mantle is 0.74 relative to CI + Si [5]. A similar abundance would be expected for the moon. The only mineral phase on the moon which differs in the partitioning of Li and Yb or Zr compared to mare basalts or KREEP is anorthosite. We measured a Li/Yb ratio of 208 in the Apollo 16 sample 65315-52, which is nearly 100 % plagioclase. Philpotts et al. [6] determined a Li/Yb ratio of 97 in the pure anorthosite 61016-184. In contrast to Yb or Zr, Lithium seems to be concentrated preferentially in the plagioclase, which crystallized very early from the magma ocean and causes the supposed Li depletion in the mare basalts.

In all lunar highland meteorites and in the highland breccias with a considerable portion of anorthosite, the Li/Yb ratio increases to values in the range of 2 to 5.4.

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EVIDENCE FOR THE ORIGIN OF SIO₂ FROM MICRO-RAMAN STUDY

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Introduction: Silica occurs as minor constituent (<0.1 vol%) in some chondritic meteorites (e.g., [1]). Its occurrence is not predicted from equilibrium condensation calculations in a gas of solar composition [2]. Four possible formation mechanisms have been proposed to account for the occurrence of silica: 1) fractional condensation in the solar nebular [3–6]; 2) a magmatic origin on the parent body [7]; 3) reduction of enstatite on the parent body [8]; and 4) sulfurization on the parent body [9].

At 1 bar, SiO_2 has several polymorphs depending on temperature. Knowing the SiO_2 -polymorphism is crucial to elucidate the mechanism of SiO_2 formation, because the four mechanisms described above have different temperature-time paths and different peak temperatures (Fig. 1). Silica-polymorphs can easily be distinguished using micro-Raman spectrometry. We currently perform a systematic micro-Raman analysis of SiO_2 in 38 thin sections from 26 different chondrites covering most types of chondrites.



Fig.1. Time-temperature paths for SiO_2 of different formation origins: 1) fractional condensation; 2) magmatic origin on a parent body; 3) oxidation; and 4) sulfurization on a parent body. Approximate time-scales are days for (1) and million years for (2–4).

Preliminary Results and Discussion: We found SiO_2 in about twothirds of the thin sections analyzed so far (17). Most parageneses of SiO_2 -rich components (SRC) are metal-free SiO_2 -orthopyroxene or SiO_2 -pyroxeneolivine assemblages, and if metal is present, it contains Ni. Reduction or sulfurization of enstatite can, therefore, be excluded, as this should produce metal without Ni.

We found SiO_2 in chondrites of all petrologic types. An exclusively metamophic orgin of SiO_2 is, therefore, unlikely. Bovedy (L3) and Seres (H4) contain SRCs with textures and chemical compositions resembling SRCs in CH chondrites [6] and may have a similar formation history, i.e., by fractional condensation and subsequent flash reheating. Micro-Raman analysis of these SRCs are in progress.

Micro-Raman analysis of a clast in Parnallee (LL3.6) surprisingly revealed a polymorphic zonation of SiO₂-laths with tridymite in the center and quartz in the rim, supporting a magmatic origin [7].

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MATHEMATICAL PREDICTION AND COMPARISON OF POTENTIAL HYDROTHERMAL ZONES ON CHICXULUB, MEXICO AND ISIDIS PLANITIA, MARS

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Synopsis: Chicxulub [1] is among the largest impact craters on Earth and a good analogue for Mars impact processes. Mars' Isidis Planitia [2] is one of the largest impact Planitias on Mars with a diameter of about 1,238 km. Isidis is located at 14.1°N and 271.0°W and is the boundary between ancient highlands and the Northern Plains. The exceptionally well-preserved Chicxulub crater is located in the Peninsula of Yucatan in Mexico, and research has identified at least 3 concentric structural rings, which comprise a complex ~200 km diameter impact basin. Isidis is the landing site for the Mars Express Beagle 2 lander. We compare Isidis to the Chicxulub crater and make estimates on the location of the potential hydrothermal zones for both of these impact basins. We will discuss the nature for the potential hydrothermal zones for both Chicxulub and Isidis Planitia craters according to their lithologies.

Analytical Method and Results: Our model shows that the formation of Isidis and Chicxulub [3] produced enough energy (~2.8 E33 Ergs and ~1.2 E30 Ergs, respectively) to create zones that could potentially favor hydrothermal systems in the water-rich environment that existed during their formation. This model predicts that a concentric zone from the impact centers of ~70–618 km in Isidis [4], and ~61–100 km in Chicxulub would have the highest probability of hydrothermal activity. Estimated sedimentary compositions in Isidis could generate hydrothermal systems lifetimes of ~69– 137 Myr with uncertainties of ~ $\pm 0.7281\%$ to $\pm 4.9304\%$, and for carbonaceous compositions in Chicxulub, would have generated hydrothermal lifetimes of ~19,514–30,460 years with uncertainties of ~ $\pm 0.6094\%$ to $\pm 1.6658\%$. The authors will discuss the influence in the uncertainties associated to the shapes (circular or elliptical) in both Isidis and Chicxulub craters, respectively.

Implications of This Model for the Earth and Mars: Hydrothermal systems have long been proposed as good candidates for niches of life. The impacts in Isidis and Chicxulub may have produced such environments conducive to life. This model develops a first order estimate for the location and longevity of these hydrothermal systems.

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NWA 1559: ANOTHER ANOMALOUS CK3 CHONDRITE?

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Introduction: Most CK chondrites studied so far are metamorphosed (petrologic types 4–6). Among the unequilibrated CK chondrites, several meteorites were described as CK3-anomalous with a suggested relationship to CV3 chondrites (e.g., [1–3]). Here, we report on the petrography and mineralogy of the recently described CK3 chondrite NWA 1559 [4], which was purchased as a single stone with a mass of 284 g in the Zagora region, Morocco. Our sample, a cut piece weighing 17 g, is a greenish-gray compact stone covered in part by a black fusion crust. Various well-pronounced chondrules and inclusions can be seen on the cut surface.

Results: Microscopically, the meteorite consists of matrix (mean grain size about 10–20 μ m) and clearly distinguishable chondrules and inclusions. Matrix constituents are predominantly olivine, minor pyroxene, plagioclase, magnetite, and rare sulfides. No metal could be detected within the section investigated. Chondrules (mainly BO, PO, and BPO) have diameters ranging from <0.5 to 2 mm. The different types of inclusions include concentrically layered olivine aggregates with plagioclase and minor fassaite, various olivine-plagioclase intergrowths of irregular shape, and coarse-grained olivine objects consisting of large (up to 0.5 mm) single olivine crystals with either glassy or fine-grained mesostasis and fluffy plagioclase-diopside intergrowths. One large coarse-grained CAI (>4 \times 7 mm²) was studied in detail and consists of fassaite, plagioclase, Mg-Al spinel, minor olivine, and grossular and rare magnetite and pentlandite.

Olivines in chondrules and coarse-grained objects are strongly zoned having Fe-rich rims (~Fa₃₄) and Fe-poor cores (~Fa_{1.5}). Their contents of MnO and NiO are positively correlated with Fa contents in the range of 0.3– <0.02 wt% MnO and 0.4–<0.02 wt% NiO. Most matrix olivines have a rather restricted composition of Fa₃₄₋₃₇ with ~0.3 wt% MnO and 0.4–0.5 wt% NiO. The Ca-rich pyroxenes are mainly diopsidic (5.7–11 mol% Fs) and Al-poor (~0.1–0.3 wt% Al₂O₃). The composition of magnetites is characterized by high contents of Cr₂O₃ (2.5–3.8 wt%), MgO (0.7–1.0 wt%), and NiO (~0.5 wt%) and relatively low contents of V₂O₃ (~0.3 wt%).

Discussion: The presence of Cr-rich magnetite as the most abundant by far opaque phase, the absence of metal, and the NiO content of olivine indicate that NWA 1559 is a CK chondrite. The range of the Fa content and its positive correlation with NiO and MnO contents in chondrule olivines is similar to what has been described for chondrule olivine from the CK3-an chondrite Dar al Gani 431 [3]. Furthermore, the restricted range of Fa content and the NiO concentration of matrix olivine is comparable to those of matrix olivine in the CK3 meteorite Watson 002 [1]. However, previous studies of CK3 meteorites [1–3] revealed that on the basis of mineralogy, bulk chemistry, and oxygen isotopic composition, there is a relationship between CK3 and CV3 chondrites. Conversely, the recently studied CV3 chondrite Sayh al Uhaymir 085 [5] shares some mineralogical features with CK meteorites. Although petrography and mineral chemistry indicate that NWA 1559 is a member of the CK chondrite group, a possible relationship of this meteorite to the oxidized subgroup of CV chondrites cannot be excluded.

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FROM STARDUST TO PLANETS: FT-IR SPECTROSCOPY OF FINE-GRAINED PLANETARY MATERIALS

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Introduction: Dust occurs in many astrophysical environments around stars, ejecta from supernovae, in the interstellar medium, in dust clouds, and in our solar system as interplanetary dust particles (IDPs) or GEMS (glass with embedded metal and sulfides).

Dust is the basic building block of all larger bodies formed in the solar system: planets, comets, and asteroids. Some of these dust grains actually have survived until today (as IDPs or presolar grains) and are analyzed in laboratories by planetary scientists. Most of the presolar grains analyzed are carbonaceous (SiC, graphite, diamond). Only few interstellar silicates have been measured [1].

Another source of data about dust comes from a different scientific community. Information about the composition of dust particles is available from astronomical observations, e.g., the ISO satellite. Here, IR spectra provide information about mineral composition, structure, and size of these particles. Crystalline silicates have been identified in IR spectra of cometary dust [2, 3], around protostars [4], protoplanetary nebulae [5], and circumstellar discs [6–9].

For comparison, IR spectra obtained in laboratories of "pure" minerals are needed. So far, mainly amorphous glasses (e.g., [10]) or fine grained smokes [11] have been used as standard materials, rather than natural minerals. Also, these studies mostly concentrated on pure end-members, which are rare in nature.

Minerals from meteorites are probably a better fit for the astronomical analyses, since they formed in a similar environment to the dust grains. So, the aim of this project is to provide a database of infrared and optical spectra of well characterized minerals from representative meteorites.

Techniques: Mineral grains in size fractions $<250 \mu m$ will be first characterized with electron beam methods and XRD. IR spectra will be obtained with a Perkin Elmer Spectrum One FT-IR microscope over a wavelength range of ~ 2.5 to 25 μm . If possible, oriented grains in their original morphology will be used to get spectra similar to those from unprepared grains in space. For IR spectra of randomly oriented grains (diffuse reflectance) will also be produced. To simulate the effects of changing environment on the spectra, measurement will be conducted at a range of temperatures with a heating/cooling stage. Also, effects of irridation, size, morphology, and coating with organic material will be investigated.

The data presented will be from mineral separates from type 3 ordinary chondrites: Parnallee (LL 3.6), Khohar (L 3.6), and Brownfield (H 3.7).

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PETROGRAPHY AND OXYGEN ISOTOPIC COMPOSITION OF ACCRETIONARY RIMS AROUND CHONDRULES IN CV CHONDRITES

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Introduction: Accretionary rims (ARs) around chondrules, Ca-Al-rich inclusions (CAIs) and other components in carbonaceous chondrites [1, 2] can be used to probe nebular conditions at the time of their formation as well as possible later processing in the parent body. We studied the petrography and in situ isotopic composition of olivines from ARs around chondrules as well as matrices from the CV chondrites Leoville, Vigarano, and Allende. The isotopic analyses were performed with a Cameca IMS 6f ion microprobe (e.g., [3]).

Petrography and Isotopic Results: ARs around CV chondrules as well as CV matrices consist primarily of FeO-rich olivine, but the matrix is usually more poorly sorted in grain size and mineralogy. We studied the ARs around two type I porphyritic olivine (PO) chondrules in Leoville USNM 3536-1. The rims and matrix consist largely of very fine-grained (<1 µm) fayalitic olivine in the compositional ranges of Fa55-75 and Fa50-60, respectively. Larger forsteritic olivines (Fa5-10) can seldom be found in the rims. Isotopically, all olivines are ¹⁶O-poor and plot close to the intersection of the CAI and terrestrial fractionation (TFL) lines ($\Delta^{17}O = -4$ to +1%; 2σ ~ ± 3 ‰), but the matrix analyses show a slightly smaller isotopic range (Δ^{17} O = -2.5 to +0.5%). The rim around a type I PO chondrule in Vigarano USNM 477-5 only partially surrounds the chondrule and consists mostly of submicron-sized FeO-rich olivine (Fa50-65). All rim olivines are depleted in $^{16}O(\Delta^{17}O = -3.5 \text{ to } 0\%)$ and scatter to the right and left of the CAI line, close to the TFL. Matrix olivines are chemically and isotopically similar (Fa₅₀₋₆₀; $\Delta^{17}O = -5$ to -1.5%). The AR around a porphyritic olivine and pyroxene chondrule in Allende TS25-F1 comprises fine-grained (<15 µm) olivine of a narrower range in mineral chemistry (Fa50-60) and isotopic composition $(\Delta^{17}O \sim -3\%)$ compared to the reduced CVs. Allende matrix olivines are indistinguishable from those in the AR.

Discussion: AR olivines around CV chondrules are texturally, chemically, and isotopically similar to matrix material, suggesting that they all formed from the same reservoir and/or underwent similar processing. Additionally, they share the same characteristics as the outer layer of ARs around CAIs in the same meteorites [3, 4], which suggests that chondrules and CAIs accreted fine-grained materials from the same nebular reservoir from which matrix derived. Olivines from the ARs and matrices are very homogeneous in mineral composition but are more isotopically variable. It is possible that these olivines were originally MgO-rich and relatively enriched in ¹⁶O and later exchanged with an FeO-rich, ¹⁶O-poor reservoir as proposed for the ARs around CAIs [4]. The faster Fe-Mg diffusion rate compared to that of O could explain the mineral chemistry homogenization relative to the isotopic composition of these olivines. The reduced CVs Leoville and Vigarano show a general wider chemical and isotopic compositional range than the oxidized Allende. This difference might have resulted from higher thermal equilibration in the Allende-region of the CV parent body [5].

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NWA 1500: THE FIRST BASALTIC UREILITE?

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Introduction: This 3.3 kg meteorite was purchased in Zagora/Morocca in 2000. The stone is a nearly complete individual and shows a red-brown colored surface with some patches of fusion crust. The cut face shows a gray-black interior with weak layering and brecciation.

Petrography and Mineralogy: Thin sections show the texture of typical monomict ureilites with abundant triple junctions and curved intergranular boundaries. Olivine crystals (about 90 vol%) of 0.2–0.5 mm are embedded in a dark vein material with finely dispersed graphite and metal. Minor components are augite, orthopyroxene, plagioclase, chromite, metal, and troilite. The plagioclase grains are 0.5–3 mm across and in igneous contact with olivine. The larger grains poikilitically enclose rounded olivine grains.

Mineral compositions were determined by SEM and a Link EDAX system:

Olivine: Fo₇₂; molar Fe/Mn 57; Cr₂O₃,CaO <0.1% Augite: En₄₄Wo₄₅; Cr₂O₃ 0.74% Orthopyroxene: En₇₀Wo₂; Cr₂O₃ 0.11% Plagioclase: An₃₇Or₀ Chromite: Fe/(Fe + Mg) 0.75; Cr/(Cr + Al) 0.75 Kamacite: Ni 1.5%; Co 0.4%; Si 0.3% Texture and mineralogy reflect a typical monomict type 2 (olivine-

augite-orthopyroxene) ureilite [1] but with additional plagioclase and chromite. NWA 1500 is the first monomict ureilite containing feldspar and, after LEW 88774, the second with primary chromite [2]. With Fa_{28} , it is the most ferroan ureilite known. The molar Fe/Mn ratio in olivine is higher than in other ureilites, but it follows their trend for Mg/Fe versus Fe/Mn [3].Ca and Cr in olivine are much lower than in other ureilites, but the presence of chromite. Plagioclase composition meets the intermediate feldspathic clasts in polymict ureilites [4].

According to these mineralogical data, NWA 1500 has to be discussed as the first member of the, until now, missing basaltic ureilites, although it bears, in addition to feldspar, dense minerals like metal and sulfide and does not meet the model of Ikeda [5].

Oxygen Isotopes: NWA 1500's O-isotopes are $\delta O^{-17} + 1.58$ and $\delta O^{-18} + 4.56$ and do not fall in the ureilite field, but on the border of the winonaite/ IAB field. The closest match with chondritic meteorites is with the CR/CH group. O-isotope data of felsic clasts from polymict ureilites clasts fall in the ureilitic field [4, 6], but only one result from a Nilpena feldspathic clast shows delta-values nearly as low as those in NWA 1500 ($\delta O^{-17} + 2.92$, δO^{-18} + 6.80) [7]. For the missing basaltic ureilite formed by partial melting of an ultramafic source, we expect the melt to move to the right of the source composition on the O-isotope three-isotope graph due to the well-known mass-dependent isotopic fractionation. This is the opposite of what we have seen in NWA 1500.

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VESICLES IN METEORITES: THE ANGLE ON ANGRITES

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Introduction: Although common among basaltic rocks on Earth, vesicular basaltic meteorites from asteroids are extremely rare. McCoy et al. [1, 2] combined petrography and computed tomography and computational modeling of vesicles in eucrites to understand their formation, concluding that they formed from 50–200 ppm of CO₂ at depth (>5 km) inside 4 Vesta. Apparently contradictory features of vesicular angrites pose a more vexing problem, which we consider here.

Angrites and Their Vesicles: We studied basaltic angrites form two distinct clusters. Asuka 881371, LEW 86010, and LEW 87051 (all less than 12 g) lack vesicles, while D'Orbigny and Sahara 99555 (both >2 kg) contain vesicles. Computed tomography of a 154.4 g fragment of D'Orbigny revealed 100 evenly-distributed vesicles ranging in volume up to 88 mm³ (average 7.7 mm³) and occupying 1.38 vol% of the rock. Although vesicles in D'Orbigny are two orders of magnitude larger than those in the eucrite libitra, they occupy roughly the same vol% of the host rock. A 36.5 g piece of Sahara 99555 contained 8 vesicles with an average volume of 7.3 mm³, nearly identical to that of D'Orbigny.

Computational Modeling: The inputs for computational modeling of angrite vesicle formation are poorly constrained. We assumed a 20 cm wide magma body [2], a 50 km radius parent body [3], CO² as the dominant volatile [2], and a viscosity (~3.5 poise) appropriate to an angrite melt at its liquidus (1680 K).

Stoke's flow calculations [1] for vesicles in a lava flow suggested rise times on the order of 3–30 min, reflecting the low gravity of the parent body and fluidity of the magma. This would require near-quenching of the magma near the surface of the body. However, vesicular near-surface flows on small, airless bodies are probably unstable, [2] and D'Orbigny, while rapidly cooled [4], is not a quench-textured rock.

Formation in a dike provides a solution. We calculated the bubble growth from nucleation (5 μ m radius) to a final radius of 2.8 mm (the largest vesicle in D'Orbigny). Bubbles grow by diffusion of gas, decompression, and coalescence (which is particularly efficient in the low viscosity melt) and move upward both by rising through the magma and by movement of the magma within the dike. CO² concentrations greater than 50 ppm would cause gas pockets much larger than normal 5 μ m radius bubbles to form as melting begins, in contrast to what we see in angrites. At 50 ppm, bubbles reach a 2.8 mm radius at ~20 km depth and a ~1 m radius at depths where the dike solidifies near the surface. The vesicles in angrites are produced by bubble growth at CO² concentrations of 10–20 ppm during migration of magma through a dike and solidification near the surface.

Implications: Large vesicles in angrites result from efficient coalescence and growth at the expense of small vesicles. Small angrites sample areas between these large vesicles, while we expect all large basaltic angrites to be vesicular.

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RIETVELD STRUCTURE REFINEMENT OF TROILITE FROM CAPE YORK IRON METEORITE AND ITS SYNTHETIC ANALOGUE

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Introduction: The crystal structure of troilite was first determined by Alsen [1] on the material from Alta Mine, Del Norte County, California, USA. In this refinement, troilite was considered to be hexagonal with space group P6₃/mmc and a unit cell volume of 59 Å³. However, later studies revealed that the refinement of Alsen, based on powder data, was not correct. More recently, Evans [2] solved and refined the crystal structure of troilite on material from the moon. The space group is P62c and the cell volume is 361 Å³. The behavior of stoichiometric FeS under elevated pressures and/or temperatures is discussed in [3]. Effects of high temperatures on troilite were addressed in [4]. The same authors [5] found that the space group P62c is also common for off-stoichiometric compositions down to formula Fe_{0.975}S.

Sample, Synthesis, and Data Collection: For this study, troilite nodules from the Cape York iron meteorite and synthetic FeS were used. The meteoritic troilite appeared completely polycrystalline when examined with a 4-circle, single-crystal diffractometer. Synthetic FeS has been prepared from iron powder (99.998% Alfa Aesar Johnson Matthey GmbH) and sulfur powder (Specpure Johnson Matthey GmbH) in an evacuated, sealed silica tube heated to 800°C for 838 hr. X-ray powder diffraction data have been collected employing a Stoe STADI P diffractometer in transmission geometry with PSD and CoK α 1 radiation.

Data Evaluation and Results: Rietveld crystal structure refinement has been carried out with the program FullProf [6] with a graphical shell of WinPlotr [7]. Both meteoritic troilite and synthetic stoichiometric FeS display identical powder diffractograms, compatible with space group P62c and unit-cell dimensions of a ~5.973 and c ~11.77 Å. Number of formula units Z = 12. The atomic coordinates refined for synthetic FeS are listed in Table 1. The unit cell dimensions for the same material are: a = 5.9730(3) Å, c = 11.7666(6) Å, and V = 363.55(3) Å³.

Table 1. Atomic coordinates in the structure of synthetic FeS

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Atom Wyck. x y	Z
Fe 12i 0.3797(3) 0.0552(3)	0.1214(2)
S1 2a 0 0	0
S2 4f 1/3 2/3	0.0188(4)
S3 6h 2/3 0.9965(6)	1/4

Conclusions: Stoichiometric FeS is hexagonal, with space group $P\overline{6}2c$, unit-cell dimensions of a ~5.973 Å and c ~11.77 Å, and Z = 12. This confirms results of earlier refinements in [2–5].

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IRON ISOTOPE COMPOSITION OF ALLENDE MATRIX, CAIS, AND CHONDRULES

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Introduction: We have studied the petrography and Fe-isotope composition of: 1) 9 chondrules; 2) 6 matrix aliquots; and 3) 2 CAIs from Allende (CV3). A range of textural-chemical chondrule types are represented, allowing us to examine the Fe-isotope signature in material with different thermal histories. Analytical procedures are detailed elsewhere [1, 2, 3].

Fe-Isotope Fractionation: The overall variation in δ^{56} Fe is 2.24‰ and in δ^{57} Fe is 3.16‰. EM-1 (non-porphyritic chondrule) is most isotopically heavy and EM-3 (porphyritic chondrule) is most isotopically light, with all other measurements falling on a mass fractionation line between these two end-members.





Discussion: The Fe-isotope composition of Allende matrix aliquots are very similar, possibly indicating isotopic equilibration of matrix components. Chondrules are in isotopic disequilibrium with matrix. The Fe fractionation of Allende chondrules is less than that expected if they had experienced extensive open-system evaporation [4]. The largest chondrules are most isotopically heavy and light, and smaller chondrules fall closer to matrix compositions. Thus, larger chondrules better preserve Fe-isotope compositions, but smaller chondrules may be more susceptible to metasomatic induced isotopic exchange. CAI Fe-isotope compositions are similar to, or slightly lighter than, the matrix signature. Thus, iron contained within CAIs may have derived from the matrix, as pristine CAIs contain little or no iron. The Fe metasomatism is not associated with significant Fe-isotopic fractionation.

Porphyritic and non-porphyritic chondrules have differing thermal histories, being produced by incomplete melting and total melting, respectively. However, Fe-isotope fractionation does not appear to vary systematically with texture. Nor is systematic variation observed with respect to bulk composition or metal content. We conclude that chondrule Fe-isotopic signatures represent that of the precursor material. Melting history may also influence the Fe-isotopic signature, with the isotopically heaviest signatures deriving from the most melting events. Further analyses will develop these theories further.

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SILICON AND TITANIUM ISOTOPIC ANALYSIS OF SILICON CARBIDE GRAINS OF TYPE X AND Z

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We measured Ti isotopic ratios of 4 X and 2 Z grains from the Murchison KJG SiC separate (average size: $3 \mu m$) [1]. These are the first Ti isotopic analyses of Z grains and are of particular interest. Z grains are believed to have formed in low-mass, low-metallicity asymptotic giant branch (AGB) stars [2]. Measurements of Si and Ti isotopic ratios of Z grains provide us with the opportunity to examine both the galactic chemical evolution of these elements and neutron-capture processes in the He-shell of AGB stars, because both effects are of comparable magnitude.

Candidates of X and Z grains were located by ion imaging with the CAMECA-3f. This was followed by C, Si, and Ti isotopic ratio measurements with the NanoSIMS. All four X grains have excesses in ⁴⁹Ti and ⁵⁰Ti relative to ⁴⁸Ti (Fig. 1a). Grain KJGN2–345–1 shows unusual Si and Ti isotopic features. In contrast to most X grains, it has a larger ²⁹Si (δ^{29} Si/²⁸Si = $-589 \pm 5\%$) than ³⁰Si (δ^{30} Si/²⁸Si = $-412 \pm 6\%$) depletion (see also [3]) and almost equal excesses in ⁴⁶Ti and ⁴⁷Ti. The Ti isotopic patterns of the X grains are similar to those of previously analyzed SiC X [4–6] and low-density graphite grains [7]. Three grains show the initial presence of ⁴⁴Ti in the form of ⁴⁴Ca excesses with inferred ⁴⁴Ti/⁴⁸Ti ratios ranging from 5.2 × 10⁻⁴ to 6.7 × 10⁻².





The two Z grains have relatively high ${}^{12}C/{}^{13}C$ ratios (93.5 ± 0.6 for KJGN2-249-1 and 81.1 ± 0.5 for KJGN2-415-3) but exhibit the typical Si isotopic signature of Z grains with ²⁹Si depletions and ³⁰Si enhancements $(\delta^{29}\text{Si}^{/28}\text{Si} = -130 \pm 5\% \text{ and } -108 \pm 5\%; \ \delta^{30}\text{Si}^{/28}\text{Si} = 201 \pm 6\% \text{ and } 392 \pm 5\%$ 6‰ for 249-1 and 415-3, respectively) [2]. Their Ti isotopic patterns are striking (Fig. 1b). ⁴⁶Ti, ⁴⁷Ti, and ⁴⁹Ti are depleted relative to ⁴⁸Ti to almost the same degree for the two grains, while their 50 Ti/48 Ti ratios are quite different. Grain KJGN2–415–3 has a ⁵⁰Ti excess (δ^{50} Ti/⁴⁸Ti = 276 ± 26‰), while grain KJGN2-249-1 has a deficit (δ^{50} Ti/⁴⁸Ti = -66 ± 25‰). These ⁵⁰Ti/⁴⁸Ti ratios are positively correlated with the 30Si/28Si ratios of these two grains. Apparently, all original Si and Ti isotopic ratios in the parent stars of the two Z grains were lower than solar, indicating stars of low metallicity. During the third dredge-up, the 30Si/28Si and 50Ti/48Ti ratios in the envelope are expected to increase more than the other Si and Ti isotopic ratios, leading to relative ³⁰Si and ⁵⁰Ti excesses. The correlation thus reflects the result of nuclear processes in the He-shell.

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LA-ICP-MS STUDY OF IIIAB IRONS AND PALLASITES: HSE BEHAVIOR DURING MAGMATIC FRACTIONATION

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Introduction: The IIIAB iron meteorite group and Main Group pallasites are believed to be magmatically linked, although the exact crystallization history may be complex (e.g., [1]). Here, we report spatially resolved concentrations of these elements in FeNi-metal (kamacite and taenite) from a suite of IIIAB irons (Henbury, Wabar, Grant, and Mt. Edith) and in the Brenham Main Group pallasite with the aim of uncovering the relationships between them.

Experimental: LA-ICP-MS analyses employed a quintupled Nd:YAG laser delivering a 213 nm UV beam (1.0 ± 0.2 mJ beam energy, 10 Hz ablation rate and 80–120 µm spot sizes) coupled to an Agilent 7500a ICP-MS, which was operated in dual detector (pulse and analogue) mode, allowing Ni to be used as a major element internal standard. Internal Ni concentrations were determined using a CAMECA SX-50 EMP. The effect of matrix differences between standard and analyte signals were negligible [2].

Results: IIIAB irons exhibit extreme variation in HSE content. Two groups are evident: 1) Henbury and Wabar: high PGE_{tot} coupled with depletion in Pt, Ru, Rh, Pd, and Au relative to Re, Os, and Ir; and 2) Mt. Edith, Grant, and Brenham: low PGEtot, low Re, Os, and Ir concentrations and high Pt, Ru, Rh, Pd, and Au contents.

Discussion: HSE systematics are driven by: 1) magmatic fractionation; and (2) subsolidus partitioning between FeNi-metal phases. Here, we concentrate on magmatic fractionation. Re and Os are highly compatible, while Ru, Pt, and Pd behave increasingly incompatibly [3]. Thus, Henbury and Wabar crystallized early, whereas Grant and Mt. Edith crystallized later from an already depleted melt. A strong genetic link between IIIABs and pallasites is supported by: 1) similarity in HSE content; and 2) very systematic compatible-incompatible element behavior. However, a simple fractional crystallization model cannot account fully for the trace element systematics in IIIAB irons (e.g. [4, 5]). HSE data suggest that Brenham derives from an extensively fractionated source, as previously suggested [6]. Mt. Edith FeNi-metal derived from a source even more fractionated than that of Brenham, i.e., after excess of 80% crystallization [6]. Thus, the source from which Brenham FeNi-metal crystallized continued to either temporally or spatially evolve. Inclusions of olivine in Brenham does not appear to affect the magmatic HSE systematics. Variations in Re/Os and Ir/Os between Mt. Edith and Grant indicate that the conditions experienced during late evolution of these two fractions may have been different.

Calculated solid metal/liquid metal partition coefficients are as follows (elements placed in order of increasing compatibility): Au and Pd are less than 1, Rh is close to 1, Ru and Pt fall between 2 and 10, and Re, Os, and Ir are in excess of 300.

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PESYANOE-F XENON: A NEW ISOTOPIC SIGNATURE

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The signature of solar-type xenon was identified in the low-temperature (1000°C) gas release of the Pesyanoe meteorite [1]. Although the data also indicated the presence of an additional component, its identification proved to be difficult, as the heavy Xe isotopes are also affected by fission Xe [2]. The information based on the Ar isotopic abundances is limited because of the presence of a significant spallation component. Kr data permitted the identification of two distinct trapped components [3], one of solar-type, released at 600-1000°C, mass-fractionated favoring the light isotopes, while Kr in the 1700°C fraction was mass fractionated in the opposite direction. The Xe isotopic systematics were investigated again by [4], who observed fractionated Xe and Ar components (Pesyanoe-F) in another Pesyanoe chip. The fact that Pesyanoe-F xenon was revealed only at the highest temperatures (>1200°C), above release temperatures of fission Xe and radiogenic ⁴⁰Ar components, suggested the approach of component identification by mineral separation, if siting in enstatite is confirmed. A clean enstatite-concentrate was prepared by hand-picking of enstatite crystals, eliminating brecciated and intergrown materials.



Fig. 1. Xe in the >1400°C steps of the Pesyanoe enstatite separate expressed as permil deviations from SW Xe [4] (uncertainties C.L. ~25‰ for the heavy isotopes). The dotted lines represent isotopic fractionations corresponding to 128 Xe/ 130 Xe ratios in Pesyanoe-F and terrestrial Xe.

We report the Xe data observed in this 19 mg separate which releases a small (~5% of total) solar-type Xe component ($\leq 1000^{\circ}$ C) and a significant component (132 Xe = 58 × 10⁻¹² cm³STP/g) of Pesyanoe-F Xe at $\geq 1200^{\circ}$ C, with a maximum release in the melting step at 1550°C. Fig. 1 shows the isotopic signature of Pesyanoe-F and of a calculated "spallation-free" component. However, the relatively high concentration renders exposure age related spallation Xe unimportant (<3% for 126 Xe; inside error limits). As Fig. 1 shows, Pesyanoe-F Xe shows a fractionation pattern of the type observed in terrestrial Xe, but differs in detail. The fractionated Pesyanoe-F signature relative to those observed in the atmospheres of planets Earth and Mars is of obvious interest.

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AQUEOUS REDUCTION PROCESSES IN ASTEROIDS

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Although oxidation by water and release of H_2 is a major process during aqueous alteration on parent bodies of chondrites (asteroids), reduction could also have occurred locally and/or temporarily. Evidence for reduction includes conversion of magnetite to fayalite [1], deposition of Fe-carbides and metal alloys from solution, and synthesis of aliphatic hydrocarbons from aromatic polymers (meteoritic kerogen). Here, we propose that reduction occurred in lower-temperature outer zones of asteroids at the same pressure as in the hotter inner zones, as well as during processes of cooling and increases in pressure, salinity, and pH.

Hydrogen production in hot inner zones via oxidation of Fe-metal and separation into a gas phase can account for increased pressure inside an asteroid. Tiny gravity forces would allow gas bubbles to move into outer cooler zones. In porous asteroidal bodies, both low- and high-temperature zones would have similar hydrogen fugacity (fH₂). In an aqueous environment, lowering temperature at the same fH2 favors reduction and can account for the magnetite to favalite conversion [1] (Figs. 1 and 2) as well as the formation of secondary Fe-Ni alloys (e.g., awaruite) and carbides (e.g., cohenite). Simultaneous organic reactions in low-temperature zones would include break-up of polymers into smaller aromatic molecules, alkylation of aromatic hydrocarbons (e.g., benzene to toluene, see Fig. 1), and conversion of aromatic hydrocarbons to aliphatic hydrocarbons (naphthalene to decane) and unsaturated aliphatic hydrocarbons to saturated hydrocarbons (ethylene to ethane). Basically, these organic reductive pathways represent hydrogenation of the polymeric material, a process leading to production of CH₄ as a final product. In addition, in the cooler outer zones, lower temperature, elevated fH2, the availability of a H2-rich gas phase, and the presence of Fe-Ni metal all favor synthesis of CH₄ and other simple hydrocarbons from H₂ and oxidized carbon species (CO_{aq}, CO_{gas}, HCO₂⁻, CO₃²⁻).



Throughout asteroid interiors, reduction reactions could also be caused by increases in pressure, pH, and salinity. All of these changes could be driven by serpentinization, which leads to pore closure (pressure increase) and consumption of water from solution (pH and salinity increase). A pressure increase would elevate the fH_2 , an increase in salinity would raise the SiO_2 activity (a) in solution, which helps the magnetite to fayalite conversion. High pH also favors precipitation of alloys and carbides. Finally, reductive processes would be terminated by H_2 escape, which boosts oxidation [2], and by explosive destruction of an asteroid via overpressure [3].

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Introduction: INAA anlyses of a hexahedtitic Wu-chu-mu-ch'in (Wuchu) iron sample with skeleton schreibersite showed 3.5% Ni, the lowestknown Ni-content in iron meteorites. Trace elements plot in the Bellsbank grouplet led to the intention to define the IIG chemical group of iron meteorites with Ni 3.5–5.2%, Ga 33–45 ppm, Ge 37–70 ppm, and Ir 0.02– 0.15 ppm and hexahedric structure with skeleton schreibersite [1]. Former anlyses and descriptions of Wu-chu samples show 18% Ni [2] and 25% Ni with the finest Widmannstätten pattern [3, 4]. Wasson [5] confirms a high Ni composition of 22% and shows trace elements close to the silicate-bearing anomalous Britstown meteorite (plessitic octahedrite). Similarly, but with lower Ni-content, are the anomalous plessitic octahedrite Elephant Moraine 84300 [6]. Silicate inclusions are reported from Wu-chu, too [3].

A further Wu-chu piece, sampled from the main mass about 20 cm from the hexahedritic area, shows a pearlitic-ataxitic structure with different orientation.

Discussion: Although the various chemistry (3.5–25% Ni) and structure (hexahedritic, octahedritic, ataxitic) observed in this unique iron do not meet the diffusion process models in iron meteorite parent bodies [7] and give the imagine of a polymict iron breccia, there are some similarities between most elements Wasson found in high-Ni Wu-chu [5] and the "IIG" irons [8].

In regard to the heterogenous Wu-chu composition, whether or not the two very different South African meteorites Bellsbank (close to low-Ni Wu-chu) and Britstown (close to high-Ni Wu-chu) are from the same parent body and may be paired has to be discussed. That these meteorites, which reflect both very rare different metal types recovered in the single Wu-chu mass, may be found rather close together is strange. The Bellsbank find site is weakly described [9], but the place that the Britstown iron was found is not known. There are reports that Mr. Brandau got the meteorite from Mr. Wipplinger in Britstown before 1910 [9] but without any find location.

A large cut through the main mass of the heterogenous Wu-chu meteorite and detailed metallographic and trace element studies would shed some light in its formation and the relationship between the "IIG" group and the "Britstown grouplet." The results may lead to the definition of a new chemical group of iron meteorites with extreme variable Ni-contents (3 to 25%) and metallographic pattern. Perhaps, many of the still anomalous iron meteorites can be classified in this new group in the future.

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HED METEORITES: GROUND TRUTH TO INVESTIGATE PETROGENESIS ON VESTA

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Introduction: We will soon be able to directly test theories about the parent body of one class of meteorites. The Dawn mission will launch in 2006 and arrive at Vesta in 2010 for a year of detailed study from orbit [1]. To fully utilize this opportunity, it is necessary to link the detailed petrographic information of HEDs studied in earth-based laboratories with their counterparts on the surface in geologic context. The principal tools are mapping instruments with sufficient spatial resolution to characterize geologic features: a camera system (supplied by DLR, which has high spatial resolution) and an imaging spectrometer (supplied by IAS, which covers the full spectral range to 5 μ m, \leq 10 nm resolution). Although spectroscopy was central in identifying Vesta as the parent body for HED meteorites [2], we must sharpen our analytical capabilities in order to address the range of important geological issues raised by the HEDs.

Bidirectional spectral reflectance properties of typical howardites, eucrites, and diogenites in the RELAB public data (http:// www.planetary.brown.edu/relab/) acquired by T. Hiroi, T. Burbine, R. Binzel, and J. Wasson are shown in the figure below. These include 51 individual meteorites H:E:D = 14:27:10 and illustrate the types of mineralogic information that is readily discerned [3, 4, 5, 6].



Fig. 1.

The variation in band center of pyroxene absorptions near 1 and 2 μ m captures the higher Mg content of diogenite pyroxenes compared to eucrites, with howardites being a mixture. For eucrites, crystalline plagioclase is indicated by the inflection near 1.25 μ m (although Ca-rich pyroxenes and olivine exhibit a similar feature), but this feature is absent for diogenites and most howardites (where plagioclase is often converted to maskelynite). Additional features include a broad absorption due to a Ti-phase in eucrites such as Bouvante. To progress beyond the general characteristics, however, requires that much more thorough quantitative links be made between key petrographic and spectral properties. For example, we need to determine pyroxene Mg and Ca contents more accurately, estimate grain size, identify the Ti-phase, characterize maskelynite, etc. To accomplish this, we must invert the process and use coordinated analyses of HEDs as ground truth for Vesta-specific applications.

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FISCHER-TROPSCH TYPE SYNTHESIS OF ORGANICS USING IRON-SILICATE GRAINS

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Introduction: Fischer-Tropsch type (FTT) synthesis produces hydrocarbons by hydrogenating carbon monoxide via catalytic reactions. The overall reaction is represented by:

$$nCO + (2n + 1)H_2 + catalyst - >C_nH_{2n+2} + nH_2O + catalyst$$

The products of these reactions have been well-studied using "natural" catalysts [1], and calculations of the efficiency of FTT synthesis in the solar nebula suggest that these types of reactions could make significant contributions to the composition of material near three AU [2]. We use FTT synthesis to coat Fe-silicate grains [3] with organic material to simulate the chemistry in the early solar nebula. This work differs from previous studies because we focus on the carbonaceous material deposited on the grains. In our experiments, we roughly simulate a model of the nebular environment where grains are successively transported from hot to cold regions of the nebula. In other words, the starting gases and FTT products are continuously circulated through the grains at high temperature with intervals of cooling (see Experiments section). We also examine the efficiency of the catalyst as organic solids are deposited on the grains. Overall, organics generated in this manner could represent the carbonaceous material incorporated in comets and meteorites. We will present the results of these experiments.

Experiments: We circulate CO, N_2 , and H_2 gas through Fe-silicate grains that are maintained at a specific temperature. The gases are passed through an FTIR spectrometer and are measured to monitor the reaction progress. Each cycle begins with 75 torr N_2 , 75 torr CO, and 550 torr H_2 before the grains are brought to temperature (i.e., 400, 500, 600°C). After the gas has circulated for a predetermined amount of time, the heating element is turned off and the gas is pumped away. We repeat this process from 20 to 40 times. Some of the catalyzed grains are then subjected to either thermal annealing or hydration to determine how these processes affect the deposited organic layers. Samples are analyzed using FTIR, GCMS (including pyrolysis), and potentially by NMR spectroscopy.

We thermally annealed the 500°C post-catalyzed grains under vacuum at 600°C and 700°C. Thermal annealing of the coated grains (particularly at 700°C) deposited an oily brown residue on the walls in the cooler regions of the reaction vessel. Three separate aliquots of the catalyzed grains at 500°C were hydrated at room temperature (\sim 23°C), \sim 65°C, and 90°C (at atmospheric pressure), respectively.

Initial Results: We examined the above-mentioned brown oily residue for organic compounds using pyrolysis GCMS. The results indicate an organic content as rich and varied as the Tagish Lake meteorite organics [4]. This residue contains primarily saturated and unsaturated hydrocarbons. The following were also identified: alkyl-benzenes, alkyl-phenols, alkyl-phenyl ethers, alkyl-styrenes, alkyl-naphthalenes, alkyl-quinolines, and traces of polycyclic aromatic hydrocarbons. If these results are any indicator, we may have uncovered some clues about the origins of meteoritic organics.

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IS NWA 1463 THE MOST PRIMITIVE WINONAITE?

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Introduction: Winonaites are stony meteorites with chondritic mineralogy and chemistry but non-chondritic textures. Extensive metamorphism, partial melting, and brecciation in the winonaite-IAB parent body have erased the chondritic texture of the precursor [1]. Winonaites occupy a compositional gap intermediate between enstatite and ordinary chondrites and it is unclear whether the precursor chondrite also occupied this gap or whether, for example, reduction of an ordinary chondrite protolith, produced the winonaites [2]. In this abstract, we report on the new meteorite NWA 1463, which appears to be the most primitive winonaite and may help solve this puzzle.

Results: The meteorite contains orthopyroxene ($F_{S_{7.4}}W_{O_{1.2}}$), olivine ($F_{a_{3.2}}$), plagioclase ($An_{12.6}$), clinopyroxene ($F_{S_{3.4}}W_{O_{45}}$), phosphate (whitlockite), chromite ($Chr_{47.3}$ Pchr_{46.1}), phosphide, troilite, and abundant Fe, Ni metal. Mineral compositions are consistent with the classification of NWA 1463 as a winonaite [1]. NWA 1463 extends the trend in oxygen fugacity and temperature derived from the olivine-chromite thermometer for other winonaite-IAB silicates (Fig. 1), plotting at log fO₂ ~IW – 3 and a temperature of ~870°C. The oxygen isotopic composition, which would confirm this classification, will be reported at the meeting. Texturally, NWA 1463 resembles a petrologic type 5 chondrite with abundant relict chondrules set in a recrystallized ground mass. This contrasts with other winonaites, which exhibit granulitic textures, equant mineral grains, and triple junctions indicative of extensive metamorphism. In addition, NWA 1463 lacks the evidence for parent body melting (e.g., Fe, Ni-FeS veinlets) that is common in other winonaites, and Fe, Ni metal is more abundant than in other winonaites.



Fig. 1. Log fO₂ vs 1/T for the IAB-winonaite group.

Discussion: The low olivine-chromite equilibration temperature, abundant relict chondrules, and overall chondritic texture imply that NWA 1463 is the most primitive winonaite. This suggests either that chondritic rocks similar in mineralogy and mineral composition to winonaites did exist or that, e.g., reduction of a more oxidized chondritic protolith happened at lower temperatures than previously envisioned. The question of whether NWA 1463 could represent the protolith for all winonaites and IAB irons remains unresolved.

Acknowledgments: We thank Alan Rubin for providing material for thin section work and oxygen isotopic measurement.

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VANADIUM, CR, SI, AND THE MG/SI RATIO IN THE EARTH

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Introduction: It has long been known that the Mg/Si ratio of Earth's primitive upper mantle (PUM) is elevated relative to most types of chondrites. Some workers attribute this to extraction of Si into Earth's core [1, 2]. The abundances of V and Cr are well-established in planetary mantles and are depleted relative to Si. If Si were extracted into planetary cores, elements more siderophile than Si should be as well. Drake and Righter [3] note that the few experiments that exist suggest that Si remains lithophile under redox conditions pertaining to Earth's core formation. They argue that the Mg/Si ratio of PUM is the bulk planet ratio, with profound implications for the accretion of Earth and the width of the "feeding zones" during accretion in the inner solar system. Understanding whether Si can be extracted into planetary cores is also important to interpreting chemical analyses of surface rocks on other planets, either from orbital data, in situ analysis, meteorite analysis, or returned sample analysis.

Results: Drake et al. [4] systematically investigated the partitioning of V and Cr between metal and silicate at 1260°C and one bar as a function of oxygen fugacity. While Si was present in their charges, it was not reported for metal because of fluorescence effects from Si in surrounding silicate. We have carefully reanalyzed these samples for V, Cr, and Si using the electron probe, specifically avoiding the fluorescence problem using the techniques developed in our group [5, 6].

Conclusions: These results, when taken in concert with those reported by [7], [8], and [9] indicate that under all experimental conditions for which data exist (1 bar to 250 kbar, 1260°C–2300°C, redox states of IW to IW-5), V and Cr are always more siderophile than Si. Had Si been extracted into Earth's core, presumably during metal/silicate equilibration in a magma ocean event [10], the abundances of V and Cr in Earth's mantle would be much lower than observed. This result leads inexorably to the conclusion that the Mg/Si ratio of Earth's upper mantle is an intrinsic bulk property of the silicate Earth and that Earth accreted from material which in aggregate is distinct from material accreting to Mars and the asteroids.

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IDENTIFICATION OF SMALL PRESOLAR OXIDE GRAINS BY MULTI-DETECTION ISOTOPIC RASTER IMAGING

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Introduction: Oxygen isotopic analysis of individual grains from the spinel-rich Murray CG (average size $0.45 \,\mu$ m) and CF (average size $0.15 \,\mu$ m) residues with the NanoSIMS revealed a higher abundance of presolar spinel in the smaller size fraction CF (15/628 versus 9/753 in CG) [1]. We applied another method of grain analysis, multi-detection raster ion imaging, to tightly packed regions of the same Murray CG and CF grain dispersion mounts. This led to the identification of 81 presolar spinel and 3 presolar corundum grains among ~51,700 grains in the CF residue and 171 presolar spinel and 29 presolar corundum grains among ~21,500 CG grains.

Experimental: Isotopic analyses were made by rastering a ~100 nm large Cs⁺ primary beam over 15 × 15 or 20 × 20 μ m² areas on the sample mount. Negative secondary ions of the three oxygen isotopes as well as MgO⁻ and AlO⁻ were counted in five different electron multipliers. ¹⁷O/¹⁶O and ¹⁸O/ ¹⁶O isotopic ratio images were produced from O secondary ion images (Fig. 1).



Fig. 1. ¹⁷O/¹⁶O (left) and ¹⁸O/¹⁶O (right) images displaying deviations from normal isotopic ratios in permil. Presolar grains have large anomalies.

Results: Although presolar spinel has been believed to be extremely rare (e.g., [2]), single grain analysis of small spinel grains from the Murray CG and CF residues led to the discovery of 26 presolar spinel grains [1]. Through raster ion imaging, we discovered 252 additional presolar spinel and 32 corundum grains in a shorter amount of time. The isotopic compositions and the abundance of CG presolar spinel agree with previous results (Fig. 2). The abundance of CF presolar spinel grains found in this study is comparatively smaller because, due to their small size, their anomalies are diluted by surrounding isotopically normal grains. Still, we are able to identify anomalous grains from CF. Thus, ion imaging is effective in detecting rare presolar spinet spinet and 200 nm. This has already led to the discovery of presolar silicates in IDPs [3] and will be employed in the search for presolar silicates in meteorites.



Fig. 2.

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CLASSIFICATION OF TWENTY ONE NEW METEORITES FROM ALGERIA AND LIBYA

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Introduction: The 21 meteorites classified in the present study represent additional specimens that were recovered through the continuing fieldwork of 2 of the authors, Richard and Roland Pelisson [1]. Ten of the meteorites come from the Dar al Gani region of Libya, 2 coming from Hamada al Hamra, and 3 from new find sites. In addition, 6 new stones from Acfer, Algeria are classified, which include 2 previously undescribed specimens from the original (pre-1991) James M. DuPont Collection. The locations of the Pelisson meteorites have been carefully recorded with GPS coordinates and have been photographed in situ for proper documentation. The two DuPont stones were purchased in 1989 along with the original Acfer 001 and other finds.

Analytical Procedures: The mineralogical analyses of the primary silicate phases for each meteorite were performed on the JEOL 773 electron probe microanalyzer at the University of Illinois, Chicago. The petrographic types were obtained through standard optical techniques according to the criteria of [2].

Results: The classification of the 21 meteorites examined in this study is presented in Table 1. Among the 21 stones are 18 ordinary chondrites, one CR chondrite, a potential CR3 chondrite, and 1 monomict eucrite. The suggested CR3 classification for Acfer 324 is pending further study. Acfer 324 was found in close proximity to Acfer 209, a CR2, and is probably a related find. It also seems apparent that many of these stones are paired with previously reported finds in their respective areas. The three Libyan stones Kufra, Murzug Idhan, and Rebiana were found on dunes and are not part of any established strewnfield.

Table 1. Representative sampling of meteorites analyzed in the present study

Name	Туре	Fa at.	Fs at.	Wo at.	Mass
		wt%	wt%	wt%	(g)
Acfer 321	Н5	17.1	15.1	1.4	157
HaH 292	H4	17.3	15.9	1.4	3570
DaG 970	L5	25.8	19.9	1.4	251
DaG 972	L5	24.4	20.6	1.5	121
DaG 969	L/LL6	26.2	24.2	1.2	3145
Rebiana	L/LL5	26.2	22.4	1.4.	459
Acfer 324	CR3	7.5	13.9	2.3	69
DaG 974	CR	9.3	12.9	3.8	107
DaG 973	Eucrite	-	42.2	6.3	82

References: [1] Cole K. J. et al 2002. *Meteoritics & Planetary Science* 37:A139. [2] Van Schmus W. R. and Wood J. A. 1967. *Geochimica et Cosmochimica Acta* 31:747–765.

A HIGH SENSITIVITY, HIGH SPATIAL RESOLUTION TOF-SIMS INSTRUMENT WITH LASER PHOTOIONIZATION FOR THE STUDY OF INTERSTELLAR GRAINS

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Introduction: Interstellar grains separated from meteorites have been studied using ion probes for over a decade, and many measurements of isotope ratios of major abundance elements (Si, C, O, Mg, N) for micron sized, or larger, grains have been published (e.g., [1] and references therein). Grains studied spectroscopically in interstellar environments are, however, much smaller with a submicron mean size [1]. Grains studied in the laboratory to date, therefore, may not be typical of the majority of grains in space. Although the Cameca Nano-SIMS [2] is helping to fill this gap through the capability of measuring isotope ratios of major elements with a spatial resolution down to 50 nm, analysis is still restricted to the major abundance elements. A further disadvantage is that only one or two elements at a time can be measured, during which time, most of the sample is destroyed. Therefore, we have taken a different approach to the problem and constructed a new TOF-SIMS instrument (Time-of-Flight Secondary Ion Mass Spectrometer) with the capability for UV photoionization of sputtered neutral atoms.

TOF-SIMS with UV Laser Photoionization: Our new instrument has been built with a similar design to the BIO-TOF instrument designed at UMIST and Pennsylvania State University [3]. It uses a pulsed gallium primary ion gun to sputter secondary ions and atoms from the sample with a spatial resolution down to ~100 nm. In SIMS mode, secondary ions are extracted and their mass analyzed using a reflectron to provide mass resolutions of up to 3000. The primary beam may be rastered over the sample to build up an image, each pixel of the image containing a complete mass spectrum. A major advantage of TOF-SIMS compared with the nano-SIMS instrument is the simultaneous detection of ions of all elements so that information on all element and isotope ratios is acquired and not lost with the destruction of the sample. Molecules may also be detected. The disadvantages are a lower ionization efficiency for many elements than the Cs gun of the nano-SIMS and poor duty cycle meaning a much longer time required to acquire good counting statistics. To overcome the problem of relatively poor ionization efficiency, we use a 157 nm fluorine excimer laser (GAM lasers, 750 Hz, 4 mJ per pulse) to photoionize all elements with ionization potentials below 7.9 eV (the vast majority of the heavier elements of the periodic table).

Working parameters and data acquired demonstrating the capabilities of the instrument will be given.

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EXTREME FRACTIONATION OF HIGHLY SIDEROPHILE ELEMENTS AMONG CHONDRITE COMPONENTS

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Re-Os isotopic analysis of separated components from Ochansk (H4) yielded a precise internal isochron (Fig. 1). The high precision of the age allows comparison with the previous high-resolution Re-Os isochron ages for iron meteorites [1]. The Ochansk age is resolvably older than the ages of IIA, IVA, and IVB irons, and overlaps with the IIIA isochron. The initial ¹⁸⁷Os/ ¹⁸⁸Os ratio plots exactly on the evolution line defined by the major iron groups. On the isochron plot, the data form three distinct groups. Most of the metal fractions plot very close to the bulk rock, while coarse metal fractions and some individual large metal grains have much higher Re/Os. The lower end of the isochron is defined by non-metal fine fractions of matrix. The mass balance shows that ~20% of Os (and Ir and Ru) in Ochansk is hosted by non-metal phases.



Fig. 1. Re-Os mineral isochron for Ochansk.

HSE distribution patterns, determined along with Re and Os, are variably fractionated. They provide evidence that the Re-Os systematics of Ochansk were set by a metamorphic event on the parent body. The prominent Pd depletion in all non-magnetic samples, along with low Re/Os, suggests that the main non-magnetic HSE-bearing phase is metamorphic chromite.

Conclusions: These results demonstrate the capability of the Re-Os system, combined with concentration data for other HSE, to provide useful age constraints on the timing of the redistribution of HSE during post-formation, metamorphic events in chondrites. In the case of Ochansk, the redistribution occurred very early. The relatively high concentrations of HSE in non-metal fractions imply high sensitivity of the Re-Os system to mild alteration processes, such as hydrothermal metamorphism, as has been suggested by studies of bulk chondrites [2].

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TOF-SIMS STUDIES OF LIGHT ELEMENTS IN AXTELL AND ALLENDE MATRIX AND CAIS

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Introduction: Matrix varies greatly between meteorite types, but in the least altered meteorites, it is usually made up of micron scale mineral grains of very heterogeneous composition. The very fine scale and diverse nature of this material has meant that there have been very few detailed studies of matrix. For, while SEM and TEM analyses have studied the chemical composition of matrix, isotopic measurements have been extremely difficult to obtain. The very light elements are also difficult or impossible to detect using electron beam techniques. TOF-SIMS (Time-of-Flight Secondary Ion Mass Spectrometry) offers high spatial resolution (~100 nm) and complete and simultaneous coverage of the whole periodic table. It is, therefore, a useful tool for studying meteorite matrix. This work describes a preliminary study of Axtell and Allende (CV3) matrix and CAIs using a new TOF-SIMS instrument described in a companion abstract [1].

TOF-SIMS of Light Elements: One of the traditional drawbacks of TOF-SIMS has been relatively poor mass resolving power and, therefore, an inability to resolve isobars, a requirement for acquisition of accurate isotope ratios. While this limitation is no longer true (e.g., [1, 2]), in fact, for the lighter elements, Li, B, Be, only relatively low resolving powers (~600) are required to resolve isobars, which is well within the capabilities of high transmission TOF-SIMS instruments. Furthermore, Li, like Na and K, does not form a hydride in SIMS, making measurements of 7Li/6Li relatively straightforward. TOF-SIMS instruments also have the capability of forming images of the sample under study in whichever mass range is desired, allowing isotope ratio maps of areas to be acquired. The ionization efficiency for the light elements is also fairly high [2], lithium, in particular, being over an order of magnitude more easily ionized than Si [2]. Mass resolved images of Axtell and Allende matrix were obtained at places on a thin section of each where the matrix looked fresh and unaltered. The surface was coated with carbon, but then, areas of up to several 100 nm² were rastered clean with the Ga primary beam. No charge compensation was required to obtain stable secondary ion beams. At several places, Li-rich areas were found up to a few microns in diameter. The nature of these Li-rich grains is as yet uncertain, but the fact that the Li signal was clearly defined in an area of only a few microns, only appeared after the surface was cleaned, were relatively rare (only 3 discovered so far in a total area that sampled up to thousands of grains), and the lack of a large Li signal from elsewhere within the matrix argues that the Li-rich areas are not terrestrial contamination but inherent within the meteorite. $^{7}Li/^{6}Li = 11.7 \pm 0.3$ for these areas, which agrees with measurements from terrestrial lithium = 11.92 ± 0.13 (mean of 17 measurements). Both are the same as the standard Li_{NBSLSVEL} [3] within error. Chaussidon and Robert [3] suggested that micron scale heterogeneity in Li isotopes in meteorites cannot be ruled out, and the apparent presence of Li "hot-spots" within the matrix clearly has implications for the mass balance of Li within the meteorite. This preliminary study will seek further evidence to validate these observations and the nature, isotopic composition, and distribution of light element hot-spots.

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GROWTH OF FERROUS OLIVINE IN THE OXIDIZED CV CHONDRITES DURING FLUID-ASSISTED THERMAL METAMORPHISM.

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The CV carbonaceous chondrites are subdivided into the oxidized (Allende-like $[CV_{oxA}]$ and Bali-like $[CV_{oxB}]$) and reduced subgroups [1], which reflect complex alteration histories experienced by CVs [2]. Although recent mineralogical [3–5] and isotopic [6–8] studies show that CV alteration occurred in the presence of aqueous solutions and lasted for at least several Ma, the origin of secondary ferrous olivine (Fa_{40–60}) remains controversial. Two types of models have previously been proposed: 1) gas-solid condensation from an oxidized nebular gas [9]; and 2) dehydration of phyllosilicates during thermal metamorphism [10, 11]. Here, we argue that ferrous olivine in the oxidized CVs formed during fluid-assisted metamorphism by several mechanisms (1–4) described below:

- 1. Replacement of opaque nodules in CV_{oxB} chondrules by fayalite $(Fa_{>90})$ [2, 12] is a two-stage process involving oxidation of metal to magnetite, $3Fe(s) + 4H_2O_{(1,g)} = Fe_3O_{4(s)} + 4H_{2(g)}$, and replacement of magnetite by fayalite, $2Fe_3O_{4(s)} + 3SiO_{2(aq)} + 2H_{2(g)} = 3Fe_2SiO_{4(s)} + 2H_2O_{(1,g)}$. In MET 00430, which is intermediate between CV_{oxA} and CV_{oxB} , the opaque nodules are replaced by ferrous olivine (Fa_{60-80}), while those in Allende are replaced by less Fe-rich olivine (Fa_{40-50}). This probably reflects higher alteration temperatures experienced by the CV_{oxA} compared to the CV_{oxB} [3].
- 2. Direct precipitation of ferrous olivine from a supersaturated fluid in pore space, $Fe^{2+}_{(aq)} + Mg^{2+}_{(aq)} + SiO_{2(aq)} = (Fe, Mg)_2SiO_{4(s)}$, is indicated by the presence of euhedral ferrous olivines overgrowing Mg-rich olivines and pyroxenes in chondrules and AOAs in oxidized CVs and by the ¹⁶O-poor compositions of the ferrous olivines in Allende AOA [13]. Large compositional variations of the ferrous olivines (Fa₅₀₋₈₀) within individual AOAs in Kaba and complex Fe-Mg zoning (Fa₅₀₋₈₀) of individual ferrous olivines in MET 00430 probably reflect fluctuations of fluid compositions on a local scale.
- 3. Replacement of low-Ca pyroxene by ferrous olivine is commonly observed in the CV_{oxA} and CV dark inclusions (DIs) [11, 14]. The presence of phyllosilicates coexisting with these olivines [14, 15] suggests that this process occurred in the presence of aqueous solutions, $Fe^{2+}_{(aq)} + MgSiO_{3(s)} + H_2O_{(1, g)} = (Fe, Mg)_2SiO_{4(s)} + H_{2(g)}$.
- 4. Formation of ferrous olivine by dehydration of phyllosilicates is inferred from fibrous textures of some of the ferrous olivines in the Allende DIs [10], and from the presence of inclusions of pentlandite and poorly-graphitized carbon in the CV_{oxA} matrix olivines [16]. However, the Mg-rich compositions of phyllosilicates in CVs, the rarity of fibrous olivines, and the lack of O-isotopic evidence for extensive hydration-dehydration of CVs [17] suggest that a direct substitution of olivine for phyllosilicates has played a minor role in the origin of ferrous olivine. Growth of ferrous olivine in the presence of fluid released during dehydration of CVs seems more likely.

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(4)

AMOEBOID OLIVINE AGGREGATES IN PRIMITIVE CARBONACEOUS CHONDRITES: RECORDS OF HIGH-TEMPERATURE NEBULAR PROCESSING

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Amoeboid olivine aggregates (AOAs) are the least refractory objects genetically related to Ca-Al-rich inclusions (CAIs) and are chemically most similar to magnesian (Type I) chondrules, providing a possible link between CAIs and chondrules. AOAs are the most common type of refractory inclusions in CR, CM, CH, CB, CV, CO, and ungrouped carbonaceous chondrites (CCs) Acfer 094 and Adelaide [1-5]. AOAs in primitive CCs are uniformly ¹⁶O-enriched (Δ^{17} O ~-20‰) [3, 6] and consist of forsterite (Fa_{<1}), FeNi-metal, and a refractory component (fine-grained minerals and individual CAIs) composed of Al-diopside, anorthite, ±spinel, and rare gehlenitic melilite (Åk_{<15}). Although CAIs in AOAs are mineralogically similar to fine-grained, spinel-rich CAIs generally showing Group II REE patterns, most AOAs have unfractionated (~10 CI) REE patterns, suggesting formation in different reservoirs, separated spatially or in time [7]. Melilite in AOAs is replaced by a fine-grained mixture of spinel, Al-diopside, and anorthite. Spinel is corroded by anorthite. In ~2% of >500 AOAs studied, forsterite is replaced by low-Ca pyroxene. These observations and thermodynamic analyses [8, 9] indicate that AOAs are aggregates of solar nebular condensates that originated in a ¹⁶O-rich gaseous reservoir [10]. Some of the CAIs were melted prior to aggregation into AOAs. However, the AOAs escaped extensive melting. Before, and possibly after aggregation, melilite and spinel reacted with SiO(g) and Mg(g) to form a Ca-Tschermakite-diopside solid solution and anorthite:

 $3Ca_2Al_2SiO_7 + MgAl_2O_4 + 5SiO_{(g)} + Mg_{(g)} + 6H_2O_{(g)} =$

$$[4CaAl_{2}SiO_{6} + 2CaMgSi_{2}O_{6}]_{(px ss)} + 6H_{2(g)}$$
(1)

$$Ca_{2}Al_{2}SiO_{7} + 3SiO_{(g)} + 3Mg_{(g)} + 6H_{2}O_{(g)} = 2CaMgSi_{2}O_{6} + MgAl_{2}O_{4} + 6H_{2(g)}$$
(2)

 $Ca_{2}Al_{2}SiO_{7} + 3SiO_{(g)} + Mg_{(g)} + 4H_{2}O_{(g)} =$ $CaAl_{2}Si_{2}O_{8} + CaMgSi_{2}O_{6} + 4H_{2}O_{(g)}$

$$CaAl_2Si_2O_8 + CaMgSi_2O_6 + 4H_{2(g)}$$
(3)
$$CaMaSi_2O_8 + 0.5Si_2O_8 + 0.5Si_2O$$

 $MgAl_{2}O_{4} + CaMgSi_{2}O_{6} + 0.5SiO_{(g)} + 0.5H_{2}O_{(g)} = 0.5C_{2}Al_{2}SiO_{4} + 0.5H_{2}O_{5} + 0$

Solid or incipiently melted olivine in some AOAs reacted with
$$SiO_{(g)}$$
 in the

$$Mg_{2}SiO_{4} + SiO_{(g)} + H_{2}O_{(g)} = Mg_{2}Si_{2}O_{6} + H_{2(g)}$$
(5)

Low-Ca pyroxene replacing ¹⁶O-rich olivine (Δ^{17} O ~-20‰) in a CR AOA is ¹⁶O-poor (Δ^{17} O ~0‰).

Although bulk compositions of AOAs are rather similar to those of Type I chondrules, on a projection from spinel onto the plane $Ca^2SiO_4-Mg_2SiO_4-Al_2O_3$ [11], these objects plot on different sides of the anorthite-forsterite thermal divide, suggesting that Type I chondrules cannot be produced from AOAs by an igneous fractionation. Formation of low-Ca pyroxene by reaction of olivine with $SiO_{(g)}$ moves bulk compositions of AOAs towards chondrules and may provide the first evidence for transformation of refractory materials into chondrules or chondrule precursors. This is consistent with the ¹⁶O-poor composition of low-Ca pyroxene in the CR AOA.

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DIFFUSION KINETICS OF K IN MELILITE AND DIOPSIDE: CONSTRAINTS ON THE ACCRETION TIME SCALE AND THERMAL HISTORY OF CAI PARENT BODY

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Important constraints on the time scales of events in the early history of the solar system can be derived from the presence and absence of the decay products of the short lived radionuclides, such as ²⁶Al (half-life, $t_{1/2}$: 0.72 Myr), which decays to ²⁶Mg, ⁴¹Ca ($t_{1/2}$: 0.15 Myr), which decays to ⁴¹K, etc., in the CAI minerals, which represent the earliest formed crystals in the solar system. Among these minerals, ²⁶Mg was detected in anorthite [1]. On the other hand, we have failed to detect any ⁴¹K in melilite and fassaite grains in CAI [2]. However, in an earlier study [3], ⁴¹K was detected in fassaites in CAI but not in melilite.

LaTourrette and Wasserburg [4] have suggested that the CAI had experienced a peak temperature (T_P) of 650°C in a parent body of 15 km radius or were preferentially stored in the outer part of larger parent body, in order that the radiogenic ²⁶Mg could be retained in anorthite. In this work, we report the results of our ongoing project on the K diffusivity in melilte and fassaite and apply these data to further constrain the TP, and from that, the accretion time of the CAI parent body after CAI formation. Because of the difficulty in finding fassaite crystals of appropriate size and quality for diffusion kinetic studies, we have measured K diffusion in diopside, which should closely approximate the diffusion property of fassaite.

We have determined the diffusion coefficients of K in oriented grains of melilite and diopside as a function of temperature by tracer diffusion experiments at 1 bar. The diffusion profiles were measured by depth profiling in SIMS and modeled to retrieve the diffusion coefficients. These diffusion data, together with that for Mg diffusion in anorthite [4], were applied to calculate the closure temperature (T_c) of K diffusion in fassaite and melilite and of Mg diffusion in anorthite as function of T_P, grain size and cooling rate, according to the method of [5, 6]. Using the appropriate grain size for the CAI minerals, and T_P 650°C, these calculations yield T_c (fassaite) ~650°C, irrespective of the cooling rate, and depending on it, T_c (melilite) = 600°C and T_c (anorthite) = 460°C. Thus, the CAI parent body must have been heated above 600°C in order for the melilite to loose ⁴¹K, but not above 650°C, since, otherwise, ²⁶Mg would not be significantly retained in anorthite [4]. This tight constraint on the peak temperature requires that the CAI parent body must have accreted ~1.7 Myr after CAI formation so that there was just enough ²⁶Al to cause heating of the parent body to 600-650°C by the heat release through its decay to 46Mg. The formation of CAIs after neucleosynthesis must have taken place within a time interval that is comparable to the half-life of the short lived radionuclides, such as ${}^{41}Ca$ ($t_{1/2}$: 0.15 Myr), in order that these radionuclides were incorporated in the CAI minerals in significant quantities.

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NO EVIDENCE FOR PRIMORDIAL NOBLE GASES IN CAIS

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Introduction: Several studies [1–3] have reported the presence of, for example, Ne-E, Ne-HL (Ne-A), or solar Ar in CAIs, which would provide important constraints on CAI formation. To reexamine these findings, we measured Ne and Ar in Allende (A) and Efremovka (E) CAIs. E CAIs contain less secondary phases than those of A [4], thus, alteration should be minor.

Experimental: Samples from 5 fluffy and 4 compact A CAIs and 1 fluffy E CAI were separated under a binocular microscope. At the conference, data from Axtell will also be presented. Gases were extracted by IR-laser (CW-mode). Blanks of $\leq 2 \times 10^{-13}$ cm³STP for ²⁰Ne and ³⁶Ar contributed \leq 9% to measured signals.

Results: Unlike the matrix, all CAIs in the figure fall on a line between normal chondritic cosmogenic Ne and ~ the origin, where Ne-E (essentially pure 22 Ne) also plots. However, the data are more straightforwardly explained by fractions of cosmogenic Ne having been produced from Na and Al rather than by admixture of Ne-E. Calculated cosmogenic Ne compositions in Naand Al-rich minerals in CAIs [5], indeed, plot on the same line as the CAIs. Since the shift of 21 Ne/ 22 Ne to lower ratios is mainly due to cosmogenic Ne production in secondary Na-rich phases, E CAIs should plot close to chondritic cosmogenic 21 Ne/ 22 Ne, which is indeed the case. No CAI shows enhanced 20 Ne/ 22 Ne, which would indicate, for example, Ne-HL.



Fig. 1.

 36 Ar/ 38 Ar of compact A CAIs scatter between 0.7–1.7, those of fluffy A CAIs between 2.2–4.8. We explain this by higher Cl and lower Ca concentrations in fluffy A CAIs due to more pronounced alteration compared to compact ones: the cosmogenic 36 Ar/ 38 Ar produced from Ca and Cl are ~0.65 and ~100, respectively. E CAIs are less altered than A CAIs, and the pre-atmospheric size of E was smaller than that of A, leading to smaller cosmogenic production of Ar from Cl. This explains the low 36 Ar/ 38 Ar (0.7–0.8) of the fluffy E CAI.

Conclusion: The studied CAIs contain no primordial Ne-HL. Although we cannot conclusively exclude Ne-E or primordial Ar, the Ne data are straightforwardly explained by cosmogenic Ne production from Na- and Alrich minerals. The enhanced ³⁶Ar/³⁸Ar of fluffy A CAIs are best explained by cosmogenic production of Ar from Cl particularly abundant in altered fluffy A CAIs.

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EBSD STUDY OF AMOEBOID OLIVINE AGGREGATES IN THE Y-81020 CO3.0 CHONDRITE

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Introduction: Amoeboid olivine aggregates (AOAs) are irregularlyshaped objects that are composed of fine-grained forsteritic olivine and Ca, Al-rich minerals. The grain sizes of the constituent minerals are usually measured using BSE images because they are too fine-grained to observe in the optical microscope. However, determining a grain boundary is also difficult for AOAs from the Y-81020 CO3.0 chondrite that has adjacent grains of uniform chemical composition [1].

To study the grain sizes and crystallographic orientation of the constituent minerals in AOAs, the electron back-scattering diffraction (EBSD) technique was employed. EBSD can provide crystallographic information for micron-sized regions on the surface of thin sections.

Methods: A NORAN phase ID EBSD system attached to a HITACHI S-4500 SEM was used to analyze a thin section of Y-81020. To identify the minerals present, we performed ~200 spot EDS analyses of AOAs (one per $1-4 \ \mu m^2$). We also collected EBSP (electron back-scattering patterns) on each area. A crystal that has an EBSP showing a different orientation was defined as a different grain. Chemical compositions were measured using a JEOL JX-733 EPMA.

Results and Discussion: AOAs in Y-81020 are up to 700 μ m in size and are composed of olivine (Fo_{99,5–99,9}), Al-diopside, anorthite (An₁₀₀), and spinel (pure MgAl₂O₄). No perovskite or melilite were observed. The Al content in Al-diopside ranges from 1 to 17 wt%.

All AOAs in Y-81020 show compact textures. Forsterite grains are closely packed, and grain boundaries among adjacent grains are not distinctive. Although the grain boundaries of olivines in AOAs from other chondrites are determined by FeO-rich olivine that develop at forsterite grain boundaries [2], measuring the sizes of olivines in the AOAs from Y-81020 is difficult, because they are free of FeO-rich olivine.

Clear EBSPs were obtained from all minerals from AOAs, indicating they are crystalline. We have collected EBSPs from about 200 points from the desired region of an AOA in Y-81020 so far. Based on the EBSD study, we find that the grain size of forsterite is 1 to 9 μ m. Al-diopside occurs as thin (<10 μ m) rims around forsterite. EBSPs show that the individual grain size of Al-diopside is up to 5 μ m. Anorthite is present in a core region of a Ca, Alrich area. The grain size of anorthite is less than 8 μ m. Spinel is heterogeneously distributed in the anorthite region. Spinel nodules are composed of small spinel grains <8 μ m in size.

The textures and chemical compositions of AOAs in Y-81020 are similar to AOAs from other carbonaceous chondrites (e.g., [2, 3]). However, the sizes of AOAs in Y-81020 tend to be smaller than those from other types of chondrites. In addition, EBSD studies show that the grain sizes of forsterites are smaller. Because AOAs have never experienced extensive melting [2], the difference in grain sizes of the constituent minerals of AOAs may indicate a different thermal history of AOAs in Y-81020.

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HIGH SPECTRAL AND SPATIAL RESOLUTION ANALYSES OF MARTIAN METEORITE-LIKE COMPOSITIONS ON THE SURFACE OF MARS

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Objective: We are attempting to identify potential martian meteorite source regions on Mars using high spatial resolution thermal infrared imaging data from the Mars Odyssey Thermal Emission Imaging System (THEMIS) in conjunction with high spectral resolution data from the Mars Global Surveyor Thermal Emission Spectrometer (TES). Hamilton et al. [1] used TES data to identify regions of Mars with thermal infrared spectral signatures like those of some martian meteorites, and additional characterization of the mineralogy, geology, and cratering histories of these sites is required to determine if any of these areas can be linked definitively to the meteorites.

Introduction: Global deconvolutions of MGS TES data identify only small areas in martian dark regions with spectral signatures like those of Chassigny, ALHA77005, and/or ALH 84001 [1]. No signatures like those of basaltic shergottites were identified anywhere in the dark regions at the maximum scale (32 pixels/degree) of the study. Hamilton et al. [1] concluded that the martian meteorites are not representative of a large fraction of the martian crust, which does not appear to be Al-depleted. No candidate parent craters were proposed in any of the areas in which the meteorite-like compositions were identified, primarily because detailed correlations of the spectral signatures and commonly complex local geology are required.

This study: New visible and infrared imaging data from THEMIS show areas with martian meteorite-like spectral components in unprecedented spatial detail (~20 and ~100 m/pixel, respectively), allowing us to better correlate TES hyperspectral data with features on the martian surface. Decorrelation stretch images of THEMIS infrared data reveal details of the distribution of martian meteorite-like mineralogies with respect to local geology (Fig. 1). We have also used THEMIS multi-band infrared image data to identify new locations with meteorite-like compositions that were suspect in the initial TES data analysis because of their small spatial extent. New deconvolution analyses of the TES data improve upon the deconvolutions of [1] by using an end member library containing mineral spectra rather than meteorite and martian surface type spectra. These new deconvolutions place better constraints on the local variations in mineralogy and the solid solution compositions of major phases (e.g., olivine).



Fig. 1. THEMIS infrared image of crater in Nili Fossae showing olivine-bearing materials in green/bright. The image width is \sim 32 km.

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NATURE OF CHICXULUB IMPACTOR—EVIDENCE FROM THE MELT-RICH BRECCIAS INSIDE THE CRATER

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Synopsis: The nature of the bolide that excavated the Chicxulub crater in the Yucatan peninsula, Mexico is one of the remaining long-standing questions. We describe cm-sized pieces and mm-sized fragments recovered within the melt-rich breccia sequence of the Chicxulub crater that show a siderophile component.

Introduction: Impactor identification in large terrestrial craters where no bolide pieces survive the high-energy events remains a notoriously difficult problem. Modeling of large impact events points to impactor vaporization with low probabilities for survival of bolide pieces. In the absence of direct evidence, the nature of bolide is usually investigated from platinum group elements (PGEs); Cr, Ni, and Co abundances; and interelement ratios in melt rocks and ejecta layers. For the Cretaceous/ Tertiary (K/T) boundary event, characteristics of the global ejecta layer at various sections have been interpreted in terms of a chondritic signature. There are, however, sites not showing chondritic signatures, and discrepancies are ascribed to PGE remobilization in differing depositional environments and the high-energy vaporization and condensation process.

Results: The K/T boundary impact site has been traced to the buried Chicxulub crater located in the Yucatan carbonate platform of southeastern Mexico, which has since been extensively studied and interpreted in terms of a ~200 km diameter multiring structure with an age of 65 Ma. Among the major long-standing questions are those related to the nature of the bolide and dynamics of the impact event, which are, in general, difficult to document in the absence of surviving bolide fragments. Here we describe both cm-sized pieces and mm-sized fragments recovered within the melt-rich breccia sequence of the Chicxulub crater that show a siderophile component. Highresolution magnetic susceptibility measurements in the drill cores permit a detailed simple inventory of melt fragments and basement clasts. The fragments examined here present high iron contents and strong ferrimagnetic signal. Whole-sample X-ray fluorescence measurements give some 26-30 wt% iron and 45-53 wt% silica. Individual fragments show higher iron contents up to 60 wt%. Rock-magnetic data indicate low coercivity irontitanium oxide minerals. The fragments are relatively complex, mainly composed of iron and silica, and show evidence of partial melting and alteration. We present macroscopic descriptions of the material and results of the petrographic and geochemical analyses (including detailed microprobe, ICP-MS, X-ray fluorescence, X-ray diffraction measurements). PGE determinations show enrichment of Ir, Ru, Ph, Pd, and Pt, with higher values for Pd.

CUMULATE EUCRITES: MINERALOGICAL EVIDENCE FOR IMPACT EVENTS DURING SLOW COOLING

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Eucrites record the oldest planetary differentiation in the solar system, and probably form most of the outer crust of the asteroid 4 Vesta. Cumulate eucrites formed deep in the crust and cooled very slowly. Previous workers mainly studied pyroxene mineralogy to estimate the thermal history of cumulate eucrites (e.g., [1, 2]). In this study, we focused on the texture, occurrence, and chemistry of minor minerals in the unbrecciated cumulate eucrites Y-791195, Moore County, Serra de Magé, and Moama.

Most grains of pyroxene and plagioclase in these cumulate eucrites have sharp optical extinction, indicating that these eucrites did not experience a significant shock metamorphism after post-crystallization slow cooling. Thus, these cumulate eucrites probably escaped the latest impact bombardment.

Textures of Moama, Moore County, and Serra de Magé are undisturbed, displaying a coarse-grained texture [1]. In contrast, Y-791195 has a granular texture [2]. In this meteorite, we found recrystallized portions composed of finer-grained minerals (20–100 μ m) in a coarser-grained (~0.5 mm) granular portion. This indicates that Y-791195 was brecciated and recrystallized by subsequent slow cooling.

We found irregular chains of fine (<30 µm) chromite grains in pyroxene in Serra de Magé, Moore County, and Y-791195. Most of the chromites in Moore County and Y-791195 are enriched in TiO2 (6.1-18.3 and 7.3-15.9 wt%, respectively), similar to those found in basaltic eucrites [3]. Because the orientation of some chromite chains are not related to any crystallographic orientation of the host mineral, these chromites may have formed along healed fractures after mild brecciation [4]. In Moore County, some Ti-rich chromites are closely associated with ilmenite and minor Fe-metal and troilite. This assemblage could have been formed by decomposition of Crulvöspinel by changes of T-f(O2) [3]. In Moama and Moore County, there are fine grains (<2-3 µm) of troilite and/or minor Fe-metal that penetrate grains of silicate and oxides. Some troilite and Fe metal are in contact with tiny grains of silica minerals, indicating the reduction of silicate by S. The fine inclusions of troilite in tridymite and plagioclase could have been formed by shock injection, because these minerals do not contain a significant amount of FeO. Troilite grains are surrounded by host silicate minerals, suggesting the fractures were closed by subsequent annealing.

The presence of these annealed shock textures indicates that some cumulate eucrites may have experienced impact events during slow cooling after initial crystallization. These observations are consistent with incomplete inversion textures of pigeonites in Y-791195 and Moore County [1, 2] and with incomplete augite exsolution in orthopyroxene of Serra de Magé. The post-crystallization thermal history of cumulate eucrites is similar to that of equilibrated basaltic eucrites [5]. These facts suggest that the eucritic crust experienced multiple impact events shortly after or during volcanism.

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¹⁶O-RICH OLIVINE IN IGNEOUS RIM OF TYPE I CHONDRULE FROM CR2 CHONDRITE

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Introduction: Magnesian (type I) chondrules are the dominant chondrule type in the CR chondrite. The type I chondrule of porphyritic texture are commonly layered [1]. Several researchers argue the origin and formation process of the chondrules, Fe-Ni metal, and rim (e.g., [1–3]). In this study, we report oxygen isotope distributions of chondrule rim from CR2 chondrite and its implications.

Experimental: The sample used in this study is a polished thin section from the NWA 530 CR2 chondrite. Petrologic and mineralogical studies by scanning electron microscope (JEOL JSM-5310LV) equipped with energy dispersive X-ray spectroscopy (Oxford LINK ISIS) were made before and after the isotope analysis.

Oxygen isotopic analyses were performed by TiTech isotope microscope system (CAMECA IMS-1270 + SCAPS). In addition to conventional ion microprobe analyses with a primary beam of 3 μ m spot, an isotope mapping technique [4] for δ^{18} O was also applied. The size of a δ^{18} O map corresponds to 70 \times 70 μ m on the sample.

Results and Discussion: The chondrule NWA 530–1 has an MgO-rich (type I) porphyritic texture and a Fe-Ni metal layer and igneous rim. The size is about 2.6 mm in semimajor axis length and 2.2 mm in semiminor axis length. Phenocrysts in the core mainly consist of MgO-rich olivine (Fa₂₋₄) and low-Ca and Mg-rich pyroxene (Fs₃₋₁₀, Wo₀₋₆). Mesostasis in the core consists of Ca-rich pyroxene and plagioclase. The typical size of phenocrysts is 100–200 µm. The igneous rim is 100 µm thick. The rim crystals are mostly Mg-rich pyroxene (Fs₃₋₁₁, Wo₀₋₇). MgO-rich olivine (Fa₄₋₅), CaO- and FeO-rich pyroxene, and plagioclase also exist as minor phases. The crystals are 10–20 µm in size and enclosed by mesostasis of fine mineral aggregates with feldspathic composition. Fe-Ni metal blebs containing 5 wt% Ni scattered in the mesostasis of the rim.

Five maps of δ^{18} O in the igneous rim were obtained for investigation of oxygen isotopic distribution in the rim. The maps show that about 50% of olivine crystals in mapping areas have ¹⁸O-poor compositions and another 50% of olivine crystals have ¹⁸O-rich compositions. The other components in the rim also show ¹⁸O-rich compositions. The olivine crystal with ¹⁸O-poor compositions found in the δ^{18} O map was evaluated by 3 O isotopic measurements using an ion microprobe method, and show ¹⁶O-rich compositions ($\delta^{17}O_{SMOW} = -35\%$, $\delta^{18}O_{SMOW} = -33\%$). On the other hand, oxygen isotopic composition of ¹⁸O-rich grains in the rim and of phenocrysts and mesostasis in the core show ${}^{16}\text{O-poor}$ (-10 ${<}\delta^{17}\text{O}_{\text{SMOW}}$ <4, -8 $<\delta^{18}O_{SMOW}$ <8‰). ¹⁶O-rich components in the core were not found in this study. Based on ¹⁶O-rich and -poor olivine crystals in the igneous rim, we infer that materials produced at different places and/or different times were mixed in the nebula and accreted onto the pre-existing core of the chondrule. Olivine crystals in the rim did not experience complete melting at the rim formation and preserved original oxygen isotopic compositions. The xistence of 16O-rich olivine in the chondrule rim suggests that solar nebula dusts with ¹⁶O-rich compositions survived until the chondrule formation stage and might have existed universally.

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PROPOSAL FOR A FRENCH ANTARCTIC METEORITE RECOVERY PROGRAM

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Introduction: The French government's Antarctic program has the logistical capability to sustain a robust meteorite recovery program. Surface traverses could occur to potential meteorite blue ice places in Antarctica.

Body: The Japanese program uses surface traverses to go to potential meteorite blue ice locales. The United States uses airlift capability to go to meteorite recovery locales and to blue ice recovery meteorite places along the Trans-Antarctic mountains. Thousands of meteorites have been recovered by national scientific programs in the Antarctic. France's Antarctic program could, within its science program, implement an Antarctic meteorite recovery program that matches the scale of other nations' Antarctic meteorite recovery programs. Areas of search could be coordinated with existing Antarctic meteorite recovery programs.

Conclusion: The French Antarctic program could, within existing budgets, allocate financial resources to set up a meteorite recovery program.

TRAPPED NOBLE GAS COMPONENT AND THERMAL HISTORIES OF UNEQUILIBRATED ORDINARY CHONDRITES

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Introduction: Some UOCs and carbonaceous chondrites contain a trapped component with Ar/Xe ratio (~several hundreds) higher than "Q" (e.g., [1, 2]). Our previous studies found some remarkable features of the component: 1) the elemental composition is different from that of "Q," but isotopic compositions are similar to "Q" within analytical errors; 2) the released temperature is around 1100°C under stepwise heating in a vacuum; 3) it seems to be related to isotopically light nitrogen; and 4) it is mostly removed by etching with HCl [2, 3]. To examine if the component has been distributed widely into UOCs as well as to clarify its feature, origin, and evolution in further detail, we attempted additional analyses of noble gases with stepwise heating extraction.

Samples and Experiments: The samples measured in the present work are: Yamato-74024 (Y-74024) (L3.7) whole rock (hereafter WR) and HCl (etched with 1 M HCl for 3 hr), Allan Hills 83010 (ALH 83010) (LL3.3) WR and HCl (1 M for 3hr), ALH 77299 (H3.7) WR, ALH 77167 (L3.4) HCl-(C) (0.5 M for 1 h), and HCl-(d) (0.2 M for 5 min). ALH 77167 contains a large amount of the trapped noble gas component. We have reported noble gas data for WR and HCl-etched samples with different condition (1 M for 3 hr and 3 M for 3 hr) of the meteorite [3]. Noble gases were extracted from 8 temperature steps: 700, 900, 1000, 1100, 1200, 1300, 1500, and 1700°C.

Results and Discussion: The two whole rock samples, ALH 83010 and ALH 77299, show large releases of trapped Ar and higher Ar/Xe ratios at temperatures between 1000 and 1200°C. Y-74024 shows the high Ar/Xe ratios below 1000°C. The absolute concentrations of ³⁶Ar are similar among the three meteorites $(1.9 - 2.3 \times 10^{-7} \text{ cm}^3\text{STP/g})$, which are about one third of that in ALH 77167 WR. Although trapped noble gas contents are expected to correlate with petrologic types, ALH 83010 (LL 3.3) shows the ³⁶Ar concentration lower than those in some UOCs with higher petrologic types. The K-Ar age of ALH 83010 is obtained to be 1.1 Gyr assuming the average K content of 793 ppm for LL chondrites [4], indicating a large impact event took place about 1 Gyr ago, at which time, a part of trapped noble gases might have been released. As suggested by [5], complex histories, like thermal metamorphism, aqueous alteration, and shock events must have changed all or any of the petrology, TL sensitivities, and/or volatile contents.

Combined with the results of HCl-etched samples, the majority of trapped noble gases, particularly Ar, seems to be in a phase other than Q. The concentrations of Ar in the 1 M HCl-etched samples are 20-30% of the WR, and mass yields of the residues suggest that noble gases in phase Q are a minor component in these meteorites.

HCl-etching of 4 different conditions has been applied to ALH 77167. Etching with 1 M and 3 M HCl efficiently removed the trapped noble gases (only 3% and 6% of trapped ³⁶Ar is in residues, respectively). However, 0.5 M HCl removed slightly and 0.2 M for 5 min HCl did not remove noble gases significantly.

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ELECTRON BACKSCATTER DIFFRACTION (EBSD) ANALYSIS ON KAERSUTITE IN MARTIAN METEORITES

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Introduction: Kaersutites are reported as rare minerals in martian meteorites (e.g., Zagami and LEW 88516), and they are very small (10–20 μ m) [1, 2]. Identifications of crystalline materials have been determined by X-ray diffraction (XRD). However, for the above reasons, martian kaersutites are very difficult to identify with this technique. Electron backscatter diffraction (EBSD) pattern (Kikuchi diffraction pattern) analysis is used to provide crystallographic and phase information on crystalline materials [3]. Spatial resolution of EBSD analysis is about 0.5 μ m in combination with field emission scanning electron microscope (FE-SEM). EBSD analysis can display its ability when we analyze minute minerals such as martian kaersutites. In this abstract, we report identification of martian kaersutite by using EBSD analysis.

Analytical Method: Kaersutites in martian meteorites (Zagami and LEW 88516) were analyzed by EBSD using FE-SEM with a method similar to [4]. The accelerating voltage of the incident beam was 20 kV, and the beam current was 1-2 nA. The collection semiangle of the EBSD detector was $\sim 37.5^{\circ}$. The specimens were coated with amorphous carbon to maintain electrical conductivity. The specimens were tilted $\sim 70^{\circ}$ from the horizontal toward the phosphor screen (the detector) using a specimen mount.

Results and Discussions: EBSD patterns are successfully obtained from martian kaersutites, showing that martian kaersutites are crystalline material. Fig. 1 shows both observed and calculated EBSD patterns for kaersutite in LEW 88516. The calculated pattern for kaersutite shows good agreement with the observed EBSD pattern from the kaersutite. The identification of martian kaersutite has been reported by [5] through the use of Raman spectra. We show that EBSD analysis is a useful identification technique in a micro area as well as in Raman spectra. We are planning to employ EBSD analysis in order to detect high-pressure polymorphs in martian meteorites.



Fig. 1 Left: EBSD pattern from kaersutite in LEW 88516. Right: Calculated pattern for kaersutite.

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NOBLE GAS STUDIES OF DHOFAR 378 MARTIAN METEORITE

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Introduction: Dhofar 378 (Dho 378), weighing 15 g, was found in Oman (2000) and classified as basaltic shergottite. It was somewhat similar to Dhofar 019 and recovered from a near area, but they are not a pair [1].

Experimental Method: Dho 378 was analyzed by using a mass spectrometric system (modified-VG5400/MS-II). Before starting measurement, we put the Dho sample into the diluted HNO₃ solution with ultrasonic waves. Because it looked brittle and weathered, we needed to remove the weathering products of the hot desert before preheating for avoiding adsorption of terrestrial gases. Noble gases in Dho 378 were extracted by the total melting method (0.0165 g at 1800°C) and the stepwise heating method (0.0622 g at 400, 600, 800, 1000, 1300, and 1750°C).

Results and Discussion: The concentrations of the cosmogenic nuclides ³He, ²¹Ne, and ³⁸Ar (10^{-9} cm³STP/g) are: 1) SH-22.6, 5.39, 2.57; and 2) TM-19.7, 4.37, 2.80, respectively. The K-Ar ages and cosmic-ray exposure ages of Dho 378 are given in Table 1. Dho 378 has the typical ejection age of basaltic shergottites summarized in [2], while Dho 019 shows the oldest age among the SNC meteorites [3]. The K-Ar age is estimated by using ⁴⁰Ar concentrations and the average K concentrations of 830 ppm for Dho 378 [4]. The obtained age is about 0.79~1.19 Gyr, which is typical for basaltic shergottites.

Table 1. The cosmic-ray exposure ages and K-Ar ages.^a

				-
Dhofar 378	T ₃	T ₂₁	T ₃₈	K-Ar age
	Ma		Ga (K = 830 ppm [4])	
SH TM	1.35 1.20	3.64 2.99	1.68 1.82	$\begin{array}{c} 1.19 \pm 0.12 \\ 0.79 \pm 0.09 \end{array}$

^aSH: stepwise heating method; TM: total melting method.

Fig. 1 shows the heavy noble gas ratios of Dho 378 and Dho 019. The lower temperature data of Dho 378 (under 1000°C) plot toward Air, while the high temperature data have a tendency toward martian atmosphere, which suggests the presence of trapped martian atmospheric components. On the other hand, Dho 019 data plot between three components, Chassigny, Elementally Fractionated Air (EFA), and Air. Heavier noble gases, likely fractionated terrestrial atmosphere, may be trapped on the meteorites or weathering products produced in the hot desert [5].



Fig. 1. 84Kr/132Xe versus 129Xe/132Xe.

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OPTIMIZATION OF ISOTOPIC MASS FRACTIONATION MEASUREMENTS BY SIMS

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Isotopic mass fractionation is an important parameter to be determined in early solar system materials. High temperature processing through evaporation and condensation lead to changes in isotopic abundances, and obtaining high-precision and accurate data on different phases can lead to insights to formation conditions and the processes involved. Secondary Ion Mass Spectrometry (SIMS) has been used for measurement of such effects for some time, but it is generally acknowledged that a fundamental difficulty in this technique is the large correction that has to be applied for instrumentally induced fractionation and the problems associated with obtaining accurate and reproducible estimates of that fractionation. A better understanding will be important in analytical design where obtaining accurate mass fractionation is of primary importance. Such an example is the analysis of Genesis return samples where concentrations are low and concentrated in the top few hundred nanometers, characteristics that are well suited to SIMS analysis.

Most of the discussion has centered around the use of Cameca ion microscopes for measurements. It is evident that a number of machine parameters must be held as stable as possible during the course of analysis such as alignment of primary and secondary ion optical axes, bandwidth of secondary ion energy, and beam truncation at defining slits and apertures. If these parameters are controlled, data at the level of counting statistics or close to noise limits of electrometers can be obtained.

Various results indicate that the SHRIMP ion microprobes are less prone to isotopic variation that would be ascribed to changing geometric and ion optic conditions. In part, this appears to be due to the wider secondary-ion acceptance of the mass analyzer of the SHRIMP instruments. This allows less truncation of the beam, especially at the energy slit that is either not inserted or operated with a very large bandwidth (>100 eV). The SHRIMP ion microprobes themselves have different ion extraction geometries and beam transfer systems, so it is necessary to evaluate the different systems for optimal conditions for isotope mass fractionation measurements. The basic alignment of the SHRIMP systems is carried out as a consequence of obtaining focus in the shallow depth of field viewing optics.

In evaluating ion probe geometries, differences in the SHRIMP I versus SHRIMP II designs are of interest. Early Mg isotopic data from SHRIMP I suggested that instrumentally induced fractionation could be controlled to better than 0.2 ‰/amu with surprisingly little attention to analytical set up [1]. Measurements of Allende 4691 spinel at +4.74 ± 0.16‰ (2 σ) are in good agreement with TIMS analyses of [2]. SHRIMP I utilizes slit-einzel lenses whereas the SHRIMP II design uses a quadrupole lens extraction system, the modeling of which appears to suggest a larger potential for isotopic discrimination at the source slit, but which achieves higher transmission.

A better understanding of the relationship between the ion optical design and measurement stability should lead to better intrinsic fractionation measurements.

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A HYDRODYNAMIC MODEL OF REGMAGLYPT FORMATION ON A METEORITE FRONT FACE

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Introduction: According to general belief, regmaglypts are produced by erosive action of turbulent compressed and heated air masses passing a meteorite during its fall. However, little is known about real mechanisms of regmaglypt formation. Turbulent boundary layers (as was suggested in [1]) or hydrodynamic instabilities [2] produce small-scale waves in molten layers on the surface but cannot create regmaglypt depressions, which are typically one tenth of a meteorite size. The mechanism of heat transfer necessary for melting a significant mass of stony or iron bodies is also unclear. Numerous studies of the Sikhote-Alin meteorite fall show that a lot of fragments with regmaglypts must have been produced at low altitudes and velocities when both radiative and convective heat fluxes on fragment faces were small.

Physical Model: Stony or iron liquid droplets are known to be produced from thin (typically 0.1–1 mm), molten meteorite layers due to the Kelvin-Helmholtz and Rayleigh-Taylor instabilities. The droplets are assumed to be ejected from the meteorite front surface and move in the shock-compressed air layer at various subsonic velocities. They decelerate, are heated by thermal conductivity, partially vaporize, and partially return to the surface. Disturbances of hydrodynamic flow by droplets can generate large-scale instabilities of the bow shock wave and the whole flow around the meteoroid [3, 4]. In this unstable flow, the sizes of vortexes formed in the shock-compressed layer are about the bow shock wave stand-off distance, which is usually one tenth of a meteorite size.

Numerical Model: The numberical model includes the hydrodynamic equations with 2 components—air and vapor, radiation transfer, and spherical particles, which move through the gas and undergo drag forces and heat fluxes which are determined by viscosity and thermal conductivity of the air. Coefficients depend on Reynolds, Mach, and Nusselt numbers [5]. The amount of particles ejected from the meteorite surface depends on the heat flux on it, which includes the convective and radiation fluxes from the air and an energy flux from particles striking the surface. Particle sizes are from 10^{-3} to 10^{-2} cm [1, 2], and ejection velocities are determined by instability growth rates, which depend on the flow velocity, gas density, meteorite deceleration, surface tension, and viscosity of melted material.

Results: 2-D numerical simulations have been made for flat-faced cylindrical and bar-shaped bodies moving with deceleration in the atmosphere below 20 km at relatively low velocities. At some period of the fall, which depends on altitude, meteorite size, and speed, the ejected particles acquire sufficient velocity and are large enough to travel through the shock-compressed region, being only partially braked and vaporized. They strongly disturb the flow, which becomes nonstationary with large-scale vortexes. The particles are drawn into the vortical motion and then become another source of energy transferred to the surface. They get additional thermal and kinetic energy from the heated air and put this energy to the surface when they return to it. The places of their return, which are controlled by the vortex structure, vaporize faster and end up as depressions.

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THE ORGANIC COMPOSITION OF CARBONACEOUS CHONDRITES

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Introduction: The carbonaceous chondrite meteorites are fragments of asteroids that have remained relatively unprocessed since the formation of the solar system 4.55 Gyr ago. These carbon-rich objects contain a variety of extraterrestrial organic molecules that constitute a record of abiotic chemical evolution that occurred prior to the origin of life on Earth [1, 2]. Organic material can constitute up to 3 wt% of the meteorite; usually more than 80% of organic matter is insoluble in solvents.

Structural and stable isotopic characteristics suggest that a number of environments may have contributed to the organic inventory, including interstellar space, the solar nebula and the asteroidal meteorite parent body.

Insoluble Organic Matter (Macromolecular Material): In Murchison, the macromolecular material has an empirical formula $C_{100}H_{48}N_{1.8}O_{12}S_2$ based on pyrolytic release studies [3]. The macromolecular material is investigated by several techniques including solid state nuclear magnetic resonance (NMR) spectroscopy on demineralized meteorite samples [4, 5] and analytical pyrolysis [6, 7]. Analytical pyrolysis aided by the presence of water has revealed that the composition of macromolecular materials in different meteorites appears related to levels of parent body aqueous alteration [7], a process that also seems to be controlling the stable isotope composition of bulk carbonaceous chondrites [8].

Soluble Organic Compounds: A wide variety of organic compounds have been identified in several carbonaceous chondrite extracts [1, 2]. The amino acid composition varies systematically with the carbonaceous chondrite type [9], with the CI containing only two major amino acids [10]. Enantiomeric excesses of non-biological amino acids have been detected in the two CMs Murchison and Murray with quantitative differences, raising questions about the origin of this feature [11]. The resent discovery of dihydroxyacetone and other sugar-related compounds in Murchison [12] has added another component to the inventory of biologically relevant compounds in carbonaceous chondrites.

Summary: The various studies on the organic matter in carbonaceous chondrites indicate that the major biogenic compounds can be delivered to the earth's surface in both simple and moderately complex organic forms. It is conceivable that on the primitive earth, the delivery of these types of extraterrestrial molecules may have contributed to the building blocks from which life originated.

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CM?-U-TH-PB ISOTOPIC EVOLUTION OF THE D'ORBIGNY ANGRITE

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D'Orbigny is the sixth Angrite known and the largest of this rare meteorite class. High-precision Pb-Pb data exist for Angra dos Reis and LEW 86010 yielding an age of 4557.8 ± 0.5 Ma [1].Here, we report high-precision U-Th-Pb data on handpicked mineral phases from D'Orbigny. Two of the D'Orbigny separates are groundmass pyroxenes, while the other three are euhedral pyroxenes, which grew inside druses-like cavities. The latter are considered to be 100% pure while the former may contain some inclusions. Also, we analyzed one sample of anorthite, which had a Pb isotopic composition close to that of terrestrial Pb and may be dominated by terrestrial Pb. We also report U-Th-Pb data from one sample of carbonate and three samples of glass.

The Pb-Pb ages of the two matrix pyroxenes are 4549 ± 2 Ma and 4557 ± 2 Ma, respectively, but the U-Pb ages are distinctly discordant. The druse pyroxenes, however, gave Pb-Pb ages of 4555.4 ± 1.9 , 4556 ± 4 , and 4557 ± 1 Ma with 206 Pb/ 204 Pb ratios of 522, ~ 2000 , and ~ 40000 , respectively. Furthermore, the U-Pb ages for these pyroxenes are concordant within the uncertainties of the correction parameters, as is the Th-Pb age for the second analysis. Unfortunately, the relatively large error of its Pb-Pb age reflects the small amount of Pb available for analysis.

U-Th-Pb measurements were also carried out on accessory minerals such as carbonate and a glass. The carbonate contains radiogenic Pb and is consistent with the pyroxene age. The glass, however, yields a Pb-Pb "age" of 4700 Ma. Two of the three glasses analyzed have ²⁰⁷Pb/²⁰⁶Pb ratios of 0.6855 and 0.6956, respectively, causing this unreasonable age. However, with ²⁰⁶Pb/²⁰⁴Pb ratios of 826 and 145, respectively, the amounts of common or initial Pb in these glasses are too small to explain the high ²⁰⁷Pb/²⁰⁶Pb ratios. In their U-Th-Pb systematic, these glasses are discordant, indicating a young disturbance. Because we used a 235U-205Pb tracer for these samples, we could not determine the U isotopic composition. To check for a possible excess in ²³⁵U, we dissolved an additional glass sample and extracted the U. Special effort was put into avoiding cross contamination from our ²³⁵U tracer. We obtained a $^{238}\text{U}/^{235}\text{U}$ ratio of 134.39 ± 0.37 for this sample. Using the same instrument settings, we find a $^{238}U/^{235}U$ ratio of 137.88 ± 0.2 for natural U and 0.9954 ± 0.0005 for the U500 standard. Thus, the low ²³⁸U/²³⁵U ratio suggests that a contribution from extinct ^{247C}m to ²³⁵U may be a distinct possibility. We are fully aware of the importance of this finding and will make further measurements in an attempt to substantiate the existence of ²⁴⁷Cm in these glasses.

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IMPACTS OF HIGHLY DISRUPTED PROJECTILES AND THEIR POSSIBLE GEOLOGICAL RECORDS

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The remarkable Tunguska impact [1], which occured in June 1908, is the largest aerial burst recorded in human history. Good reasons exist to belive that similar and even much larger events continiously occured during geological history. Wasson and Moore [2] and Wasson and Boslough [3] suggested that radiation produced by the aerial bursts was capable of melting several mm of sand and rocks in desert-like regions and could be responsible for production of layered tektites in South East Asia and Libyan Desert Glass found in Western Egypt. The radiation generated by the Tunguska event was not high enough to produce any surface melting. However, Wasson and Boslough [3] and Svetsov [4] suggested that highly oblique impacts of larger meteoroids can produce thermal effects on the ground within large areas.

The model with radiation and ablation for the impact of Tunguska-like (several tens of meters in size) meteoroids, which penetrate the Earth's atmosphere below 40 km, has been elaborated by [5]. The model was used to study the impact of a 30 m radius cometary projectile. The results, in particular, show that at altitudes of about 15 km, the totally disrupted projectile transforms into debris jet and then, after total evaporation of solid fragments at an altitude of about 10 km, transforms into air-vapor jet. It is important that the jet velocity (and kinetic energy, consequently) is only slightly less than the pre-entry projectile velocity (and kinetic energy).

Based on these results, we propose a mechanism of origin of layered tektites due to surface impact of highly disrupted and evaporated projectile. In the case of Tunguska, the jet was formed at too high of an altitude (10-15 km) and did not reach the ground. If we increase a projectile size or strength several times, the jet will form near the ground and will strike the solid surface. Our numerical simulations show that such impacts are much more effective from the viewpoint of thermal effects on the ground than aerial bursts. In this impact (contrary to an aerial burst), only a minor amount of energy is released in the atmosphere during the projectile flight. Most of the kinetic energy is released at the surface. However, due to low air-vapor density in the jet, impact pressure does not exceed 10-100 MPa, which is considerably lower than the typical strength of rocks. Therefore, there is no crater and target material ejection. Instead of this, a hot plasma cloud arises over the ground. Its temperature (up to several tens kK) is higher than the temperature of a fireball created due to aerial burst. Radiation and thermal conductivity provide strong heating, melting, and even evaporation of the upper target layer over an area of about 10-100 km². This area will be much larger in the case of oblique impact of a larger projectile.

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NUMERICAL MODELING OF THE ELTANIN IMPACT

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Introduction: Eltanin [1] is the only presently known impact structure formed after the fall of a cosmic body into a deep (4–5 km) oceanic basin. According to the estimates made by Gersonde and Kyte [2], the impact structure of Eltanin was formed by the impact of an asteroid 0.5–2 km in size 2.2 Myr ago. No traces of an underwater crater have been discovered.

I used numerical simulations to calculate a probable impactor size, to elucidate the fate of a projectile, and to calculate an initial tsunami amplitude. To simulate the main stages of the impact, I used the SOVA multi-material, multi-dimensional hydrocode [3].

Impactor Size: In the first set of runs, vertical and oblique impacts were considered for different impactor sizes. The purpose was to determine the range of impactor sizes for which a bottom crater does not form. Numerical simulations show that the impactor diameter should have been no larger than 1 km for a vertical impact and no larger than about 1.5 km for a 45 degree oblique impact. Otherwise, an underwater crater could arise. On the other hand, projectiles with diameters less than 0.5 km do not produce water cavities reaching the ocean floor and do not produce strong erosion of sediments. The ocean depth was assumed to be 4 km. Impact velocity V was taken to be 15 and 20 km/s.

The Fate of the Projectile: In the second set of runs, the 1 km diameter projectile impacts the ocean at angles a = 30, 45, 60, and 90 degrees from the surface. The main result is that, contrary to land impacts, in all the cases under consideration, a considerable part of the projectile (from 100% for V = 15 km/s, $a = 30^{\circ}$ to 25% for V = 20 km/s, $a = 90^{\circ}$) remains unmelted. In particular, this means that some amino acids could survive the shock heating of asteroidal material during impacts into deep water basins.

Although the water transient cavity reaches the ocean floor (4 km), the projectile material decelerates at a depth of approximately 1.5 km. Later, a part of the impactor mass (both melted and unmelted) accelerates upward in an impact induced plume to velocities reaching 1–3 km/s. This high-velocity part of projectile ejecta could fly for a distance 100–1000 km and can be found at these distances. The other part of the impactor material is involved into water motion and displaces with the water before sedimentation.

Tsunami Generation: The numerical simulations show that the vertical impact of a 1 km diameter asteroid produces water waves with amplitudes of 1200, 800, 450, and 320 m at distances of 20, 30, 50, and 70 km from the impact site. These results are in a good agreement with empirical approximations derived from underwater nuclear tests [4]. The period of the tsunami waves is about 150 s, which correlates well with [5].

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REFLECTANCE SPECTRA FOR A EUCRITE HEATED WITH A SUDDEN OXYGEN-FUGACITY CHANGE

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Introduction: We have studied spectral changes of diffuse reflectance spectra (200–2500 nm) for the samples heated at different oxygen fugacities because bombardments on asteroidal surfaces by meteoroids could locally increase surface temperature and change oxygen fugacity by selective evaporation of projectiles and surface materials. The general trend of the spectral changes for the sample heated at different oxygen fugacities show lower spectral contrast, stronger reddening, and lower albedo that are similar to those produced by space weathering effects (e.g., [1]). Miyamoto et al. [2] also studied the spectral changes for olivine heated with sudden (large) oxygen-fugacity changes to the oxidized condition. Here, we report spectral changes for the Millbillilie eucrite heated with a sudden oxygen-fugacity change.

Sample and Experiments: A pellet was made by the powder sample (<100 μ m) of the Millbillillie eucrite weighing about 70 mg. The pellet, placed in Pt-foil, was heated at 800°C under one log unit below the iron-wüstite buffer for 1 hr. The charge was taken out of the furnace slowly for 20 s (20S cooling). The procedure of the sudden oxygen-fugacity change is the same as that in [2]. The measurement of biconical diffuse reflectance spectra is the same as those used in our previous studies.

Results and Discussion: Fig. 1 shows the spectra of the Millbillillie sample of 20S cooling and compares it with those of the unheated sample and Vesta. The 20S cooling sample shows a lower spectral contrast, stronger reddening and lower albedo compared with that of the unheated sample. The albedo at 560 nm of the 20S cooling sample (38%) is the same as that of Vesta. The degree of spectral changes for the Millbillillie eucrite heated with a sudden oxygen-fugacity change is smaller than that of the olivine samples heated with a similar oxygen-fugacity change [2]. This result suggests that the eucrite sample is resistant to heating with a sudden oxygen-fugacity change. Similar results are obtained for the Millbillillie samples heated at different oxygen fugacities [3]. These results may explain why the spectra of Vesta show a high contrast.

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Fig. 1. Diffuse reflectance spectra of the Millbillillie eucrite and Vesta (open circles). Numbers show the albedos at 560 nm.

THE STRUCTURE OF PLANETESIMALS IN THE SOLAR NEBULA J. Blum. Astrophysical Institute, Friedrich Schiller University Jena, 07745 Jena, Germany. E-mail: blum@astro.uni-jena.de

In the past years, considerable progress in the field of protoplanetary dust aggregation and the formation of planetesimals—the km-sized planetary precursors, has been made. It has become clear that—in the solar nebula, dust particles collide due to Brownian motion, differential drift, and gas turbulence [1]. Whenever two micron-sized dust grains collide at low velocity, they will stick together due to the mutual van der Waals attraction [2, 3]. As a consequence, fractal dust agglomerates with a quasi-monodisperse mass distribution form in the early solar nebula [4, 5, 6]. When the mean collision velocities reach a critical value for aggregate compaction [7, 8]—i.e., when the agglomerates are typically cm-sized—the growing dust agglomerates' morphologies change from fractal to non-fractal. For impact velocities >1 m/s, i.e., for agglomerate sizes of approximately >10 cm at 1 AU distance from the young Sun, mutual collisions lead to fragmentation [7, 8] which changes the mass distribution function considerably.

We have developed a model of how the growth of proto-planetesimals can still proceed in spite of fragmentation [9, 10]. A consequence of this aerodynamically driven growth process is that the proto-planetesimals are extremely porous (see Fig. 1). We have recently performed laboratory experiments on the formation and the mechanical properties of protoplanetesimal analogs. A result of these investigations with macroscopic highporosity dust agglomerates consisting of micron-sized grains of different materials and morphologies is that km-sized planetesimals have porosities of >65%.



Fig. 1. A small cubic sector from a numerical simulation of a protoplanetary dust agglomerate; the local porosity is ~85%.

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THE LARGEST METEORITES ON EARTH

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Introduction: Hoba is the largest known meteorite at $\sim 6.10^4$ kg. But it is not clear that this represents an upper mass limit for meteorites on Earth. To define that limit, it is necessary to model the interaction between small asteroids and the atmosphere. Artemieva et al. [1, 2] have developed a model that calculates motion, aerodynamic loading, and ablation for each particle in a disrupted impactor, providing a mass-velocity distribution for fragments at the surface. Here, we apply the separated fragments (SF) model to explore the upper mass limits for low velocity fragments (i.e., meteorites).

Results and Discussion: We use the SF model to calculate the final mass-velocity distribution of fragments from iron bolides with pre-entry masses of 107-1010 kg and low atmospheric entry angles (<15°): "strong" impactors that experience substantial deceleration. The model input parameters (density, strength, ablation) are standard for iron bodies and are taken from Sikhote-Alin (e.g., [1]). We find that the mass of the largest low velocity (<2 km/s) fragment on the surface depends on several factors. Varying pre-entry mass has a minimal effect: 10% increase in fragment size with a pre-entry mass increase of 2 orders of magnitude. Atmospheric entry velocity has a more substantial effect: for a 1010 kg pre-entry mass and a 10° entry angle, we find largest surviving fragment masses of 2×10^4 , 8×10^4 , and 3×10^5 kg for entry velocities of 18, 14, and 11km/s, respectively. But, the strongest determinant on final fragment mass is initial entry angle. For the lowest impact velocity of 11km/s, the increase is from 9×10^5 kg to 8×10^6 kg over the entry angle interval 8°-6.5°. Thus, for maximum surviving fragment mass we require a low entry velocity and a low entry angle. The lower limit for pre-atmospheric velocity is 11 km/s (Earth escape velocity), and the lowest entry angle (without ricochet off the atmosphere) is 6.5° (at 11 km/s) and 10° (at 18 km/s).

Encounters between the Earth and metallic asteroids with a low velocity and low entry angle are rare, but they will occur. In the extreme case of 11 km/s entry velocity and 6.5° entry angle, we find that bodies >10⁸ kg all produce fragments at the surface with mass >7 × 10⁶ kg (>12 m diameter). Iron bodies with a pre-entry mass of 10¹⁰ kg and the above entry conditions produce showers of large fragments: 30–40 objects, each with final masses >10⁷ kg (up to 2.6×10^7 kg) i.e., bodies 14–18 m in diameter. Impact velocity for these fragments is 2–2.5 km/s, and the final impact angle is 6–8° (total mass of <2.5 km/s fragments on the ground is ~10⁹ kg). Although these velocities are higher than for typical meteorite falls, impact experiments have shown that low angles favor projectile survival [3]. We are currently investigating the survivability of projectile material in these types of impacts using numerical techniques.

Conclusions: That meteorites $>6 \times 10^4$ kg have not been discovered at the Earth's surface is not surprising. Given impact rates for irons with preentry mass 10^{8} - 10^{10} kg [4] and the unusual entry conditions, low velocity fragments with mass $\sim 10^7$ kg will arrive only every ~ 10 Ma. But, it is interesting that ~ 15 m meteorites can occur. Whether they could be preserved and recovered is another issue.

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NWA 1560 (CK4/5) AND NWA 1563 (CK5)—A COMPARISON WITH HAH 280 (CK4) CHONDRITE

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Introduction: Two CK chondrites from Morocco, NWA 1560 (CK 4/5, Erfoud, 822 g) and NWA 1563 (CK 5, Hamara, 2950 g) were studied and are compared with the CK4 chondrite HaH 280 from Libya (Hammadah al Hamra, 26.5 kg) [1]. Large differences exist between CK3 chondrites (e.g., NWA 1559, [2]) and the more equilibrated types CK4–5 [3]. Here, we try to show some common and different features of some CK4–5 chondrites. The slices of both NWA meteorites were studied by SEM and EMP at the NHM in Vienna.

Results and Discussion: Both meteorites, NWA 1560 and NWA 1563, have well developed BO, PO, and BPO chondrules (diameters ranging from 0.5 to 2 mm, not elongated, but often with asymmetric rims), olivine crystals with various kinds of rims and fine-grained matrix (grain size 40-120 µm). Matrix constituents are predominantly olivine, minor low-Ca pyroxene, and plagioclase (up to 120 µm in NWA 1563, 50-100 µm in NWA 1560). Magnetite (with ilmenite exsolution lamellae) and rare sulfides-mainly pentlandite (no metal) are distributed irregularly but are often present in the rims around chondrules. The different types of inclusions include concentric layered olivine aggregates with plagioclase and minor fassaite; various olivine-plagioclase intergrowths of irregular shape; coarse-grained olivine objects consisting of large (up to 0.5 mm) single olivine crystals with finegrained mesostasis and fluffy plagioclase-diopside intergrowths. CAIs rich in hercynite were found in NWA 1560 [3] and HaH 280 [1]. An elongated amoeboid inclusion in NWA 1560, 450 \times 250 μ m in diameter, consists mainly of dark green hercynite, plagioclase, and diopside (constituting the center of the inclusion), and rare magnetite (with low Cr content) and ilmenite. One tiny grain of baddeleyite was also found. A well-developed rim consists of a plagioclase inner layer and diopside outer layer.

Olivines are homogeneous with mean values of Fa32.3 in NWA 1560, Fa30 in NWA 1563, and Fa32.3 for matrix olivine in HaH 280. The contents of NiO and CaO in olivine are in both NWA 1560 and 1563 in the range 0.4-0.5 wt% NiO and 0.1-0.5 wt% CaO. Pyroxene compositions are variable with a mean of Fs12W044 2 in NWA 156, Fs25-32W02-11 in NWA 1563 and Fs85-102W0472-48.9 in HaH 280. Plagioclase is heterogeneous: An_{77.6}Or_{3.5} in NWA 1560, An₄₉Or₆ and An₇₈Or₂ in NWA 1563). Magnetite-the dominant and characteristic opaque mineral in CK chondrites [4]-is Cr-rich (about 4 wt% Cr_2O_3) and was found in all of these meteorites. According to [5], the mean diameter of plagioclase grains, the absence of glass, chondrule delineation, and coarseness of groundmass grains were used to assign petrologic types 4/5 and 5 to NWA 1560 and NWA 1563, respectively. The homogeneity of olivines and inhomogeneity of pyroxenes and plagioclases, the presence of typical fluffy inclusions, and commonly layered hercynite-rich inclusions are main features in the two CK chondrites HaH 280 and NWA 1560. Therefore, we conclude that these meteorites are closely related in spite of the existence of some differences in grain size and delineation of chondrules.

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FE-MG COMPOSITION AND MODAL ABUNDANCE OF MARTIAN SILICATES BY MÖSSBAUER SPECTROSCOPY

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Introduction: Mössbauer spectrometers form part of the science payload on 3 upcoming Mars missions. Beagle 2 will land on Mars in late December 2003. The Mars Exploration Rovers (MERs), carrying the Athena Science Payload, will land later the following month. All three landers will carry Mössbauer spectrometers to investigate the Fe-bearing mineralogy of Martian soils and rocks. In this work, we explore how data from different instrument geometries correlate, and whether, in addition to valence state information, Mössbauer can provide data on the Fe-Mg composition of silicates and their modal abundance.

Mössbauer spectrometers on Mars will operate in backscatter mode [1]. Typically, 57Fe Mössbauer spectra are collected in transmission mode: a powdered sample is introduced between a vibrationally modulated ⁵⁷Co source and a detector. Operating in backscatter geometry dispenses with sample preparation. Mössbauer will provide data on the Fe valence state of Martian rocks and soils and identify Fe-bearing phases within those samples. If overall Fe wt% in a sample is also measured, and the phase is of known composition, then the intensity of a component in a Mössbauer spectrum may be used to estimate the modal abundance of that component in the rock (e.g., [2]). On Mars, Fe wt% in the bulk rock will be determined by alpha particle X-ray spectrometry or X-ray fluorescence spectrometry, but there is no method on any lander to determine the composition of individual phases. Thus, if (say) hematite is detected (a phase with distinctive Mössbauer parameters and simple chemistry), modal abundance could be estimated, but for phases with more variable chemistry (olivine, pyroxene, etc.), it could not

Methodology: Menzies et al. [3, 4] have recently shown that the Mössbauer parameter *quadrupole splitting* (QS) varies consistently with Fe-Mg over the olivine solid solution series. In addition to natural samples, a suite of synthetic olivine standards were made that help to define the trend over the whole compositional range. The linear relationship between QS and Fe-Mg in olivine allows Mg# to be determined to within ~10 molar units. A similar correlation appears to hold for En-Fs in pyroxene [4]. We are extending this study using natural and synthetic samples to more clearly define the relationship between QS and composition in both silicates. In addition, comparative backscatter/transmission Mössbauer studies will allow us to use our database of transmission Mössbauer parameters in interpreting backscatter Mössbauer from Mars.

Conclusions: The work of Menzies et al. [3, 4] has provided a means of determining Mg# in Martian ferromagnesian silicates. This compositional information will also allow modal abundance of those phases to be estimated. The data will be extremely valuable in interpreting the geological history of Martian materials.

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THE EFFECT OF AN EXTRACTION PROCEDURE ON THE SUR-FACE CHEMISTRY OF SYNTHETIC NANODIAMONDS

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Introduction: The surface species on presolar nanodiamonds extracted from meteorites may carry a signature of chemical processes in the interstellar medium. However, the chemical extraction procedures were shown to modify many of the surface IR-active chemical features [1–3]. To understand if there is a relation between the chemical properties of starting and extracted diamond grains, we have studied the effect of the same extraction procedure on the surface chemistry of synthetic analogs of meteoritic nanodiamonds.

Experimental: Four samples of ultradispersed detonation diamonds (UDD) with different surface chemistry were used as starting material [4]. All samples were treated by the same chemical procedure used to separate meteoritic diamonds including treatment by concentrated mineral-acids, oxidation in HClO₄, and washing in HCl. The surface chemistry of the samples both before and after chemical treatment was studied by means of thermodesorption mass spectrometry (TDMS) and IR spectroscopy [4].

Results and Discussion: TDMS study of the received samples showed release of H_2O (100–600°C), CO_2 (200–600°C), CO (400–1000°C), and H_2 (above 800°C) as main components. Different samples differed mainly in the temperature profiles of CO and CO_2 release caused by the decomposition of oxygen-containing surface groups. The main difference observed in the IR spectra of various samples was the shape of the 1800–1700 cm⁻¹ band related to the configuration of surface C=O bonds.

TDMS and IR data on treated samples indicated substantial chemical modification of the surface, but there was a clear "memory" of the initial surface properties. For all samples studied, the final state of surface oxidation depends on the initial one. Applying the constructed "calibration" curve, "starting versus final states," to the data on diamonds extracted by the same procedure from the different meteorites [3], we find that Allende and Murchison diamonds should have had different levels of initial oxidation as characterized by the IR bands at 1720 and 1740 cm⁻¹, respectively.

Another observation made by TDMS of treated samples concerns the presence of chlorine caused by chemical treatment and desorbed from the surface as HCl near 700°C. The abundance of this specie in different UDD varied two orders of magnitude. If this is also true in the case of meteoritic diamonds, it might open a way to separate the different types of meteoritic diamonds according to their surface properties using an appropriate titration technique.

In conclusion, our results indicate that the effect of the extraction procedure on the surface chemistry of UDD strongly depends on the starting properties of nanodiamond grains. We are under way to apply this approach to meteoritic diamonds.

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A CHEMICAL AND PETROLOGICAL STUDY OF CHONDRULES AND MICRO-OBJECTS IN SOME CM2, CR2, AND C3 CHON-DRITES

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Introduction: Individual chondrules, fragments and unclassified objects from the Ningqiang (C3, ungr.), Murray (CM2), Murchison (CM2), Nogoya (CM2), and Renazzo (CR2) chondrites have been studied with the aim to gain information concerning their formation. Twelve objects with diameters ranging from 1.5 mm to 60 µm were selected. SEM and EMPA where used for detailed petrological studies as well as for mineral and bulk major element analysis. Trace elements in bulk chondrules and individual phases were analyzed by Laser Ablation ICP-MS following the procedure of [1].

Results and Discussion: The objects have different textures which, occasionally, cannot easily be grouped into the common textural chondrule types. Barred olivine objects, granular objects, and porphyritic objects are frequent, with some transitions. The main silicate phases are olivine, low-Ca pyroxene, high Ca-pyroxene, glass/mesostasis, and phyllosilicates. Two objects contain additional Ti-pyroxene and one also contains Mg-Al spinel. Metal and sulfides are present in trace amounts within the objects and occasionally form rims around them. Major element contents vary strongly among the objects: 27-50 wt% SiO2, 0.3-24 wt% Al2O3, 1.9-36 wt% FeO, 15.5-47 wt% MgO, and 0.1-16 wt% CaO. The lithophile trace element abundances are also highly variable. Normalized values mostly range between 0.6 and $5 \times CI$, with some exceptions being more refractory (up to 10 × CI). Abundance anomalies are common, such as positive U and negative Ca and Sr anomalies. Four groups of abundance patterns can be distinguished (Fig. 1): 1) highly refractory patterns with depletion of the moderately volatile and volatile elements; 2) refractory and strongly fractionated patterns-similar to Group II CAI patterns [2, 3]; 3) patterns with roughly flat REE abundances between 0.6 and 1.5 × CI; and 4) patterns with slightly fractionated LREE relative to HREE elements (either depleted or enriched). Objects with abundance patterns (1) and (2) document vapor fractionation. Also, the flat trace element abundance patterns of group (3) make an origin by partial melting or fractional crystallization unlikely. These objects could, therefore, have originated as liquid condensates. Objects with the slightly fractionated REE abundances of group (4) apparently experienced some additional trace element fractionation and, therefore, indicate a more complicated genesis.



Fig. 1. CI-normalized trace element abundances of selected objects; CI abundances from [4]; NG: Ningqiang; NO: Nogoya; RZ: Renazzo.

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DETERMINING THE TIMING OF PHYLLOSILICATE FORMA-TION IN FINE-GRAINED CHONDRULE RIMS USING FOCUSED ION BEAM (FIB) TECHNIQUES

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Introduction: Most chondrules in the Murchison (CM2) meteorite are enclosed by \sim 100 µm thick fine-grained phyllosilicate-rich rims. The timing of formation of the phyllosilicates relative to accretion of the rim has been especially difficult to determine using standard SEM techniques. Some authors have suggested that the phyllosilicates formed prior to accretion of the rim on its host chondrule [1], while others have concluded that an originally anhydrous and mineralogically diverse rim was aqueously altered after accretion and incorporation into a parent body (e.g., [2]). We suggest that one simple way to distinguish between the two models is to image the chondrule-rim interface using high-resolution TEM. Interpenetration of rim phyllosilicates with chondrule minerals will be unequivocal evidence for aqueous alteration of an originally anhydrous rim following accretion.



Fig. 1. FIB image of the chondrule-rim interface.

Results: TEM images of the interface between chondrule and rim phyllosilicates show that the two differ considerably in both morphology and crystal size. The rim phyllosilicates are very finely crystalline, while the chondrule phyllosilicates are much coarser and lath-shaped. The two groups of phyllosilicates interpenetrate on the micron-scale, indicating that they formed at a similar time (i.e., after accretion into the Murchison parent body). The fluids that mediated alteration cannot have moved over distances of more than a few microns during alteration such that the chondrule and rim phyllosilicates have retained some of the chemical character of their different precursors (nebular dust versus chondrule glass).

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A REPORT ON THE PREFLIGHT TEST OF MUSES-C MULTIBAND IMAGING CAMERA (AMICA) AND ITS CURRENT STATUS

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About the Mission: Muses-C is the first Japanese asteroid mission and also a technology demonstration one to the S-type asteroid, 1998SF36. The new technological items to be proved in this mission are: 1) interplanetary ion-engine performance; 2) autonomous spacecraft control; 3) sampling at the low-gravity asteroid surface; and 4) high-speed Earth re-entry. From the scientific perspective, it is expected to collect surface materials of the target asteroid and obtain geological and geomorphological information by remotesensing instruments such as multiband camera, near infrared, and X-ray spectrometers.

Multiband Camera: The multiband imaging camera of Muses-C is a part of the spacecrafts' navigation cameras. The telescopic optical navigation camera (ONC-T) with seven bandpass filters (and one "wide"-band filter) and polarizers is called AMICA (Asteroid Multiband Imaging CAmera) when ONC-T is used for scientific observations [1]. ONC-T's field of view (FOV) and spatial resolution are 5.7×5.7 degrees and 20 arcsec, respectively. The AMICA's seven bandpass filters are nearly equivalent to the seven filters of the ECAS (Eight Color Asteroid Survey) system. Obtained spectroscopic data will be easily compared with previously obtained ECAS data. AMICA also has four polarizers, which are located on one edge of the CCD chip (covering 1.1×1.1 degrees each). Using the polarizers of AMICA, we can obtain polarimetric information of the target asteroid's surface.

Preflight Test: At the beginning of 2002, the subsystem test of the AMICA flight model (FM) started at the manufacture's laboratory, and we could obtain basic performance data of response, dark current, flat-field, distortion, poralizers, etc. During the Muses-C integration test (December 2001–March 2003), we intended to gain as much pre-flight data as possible. We planned to obtain in situ pre-flight flat-field images at function check events of the test. We built the small integration sphere and successfully obtained pre-flight flat-field images after the camera was mounted into the spacecraft on the latter half of the integration test. The dark current and the CCD linearity data were also obtained again at that time. No distinct change of performance between the subsystem- and integration-tests was found. Through the sequence of the test, we found that the distortion of the optics and the FWHM of the PSF were <1 pixel (<20 arcsec) and 2.0 (40 arcsec) pixels, respectively. In addition, we found, through the thermal vacuum test, that the response dispersion is within 3% for v-band.

Current Status: On March 2003, the integration test ended and the spacecraft moved from the ISAS Sagamihara campus to the Kagoshima Space Center (KSC) for the launch and a few spacecraft function checks in preparation for the launch. At KSC, we also tested AMICA, and the preflight dark current and flat-field data have been successfully obtained. The launch is scheduled for May 2003.

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BIOLOGICALLY-INDUCED ELEMENTAL VARIATIONS IN ANT-ARCTIC SANDSTONES: A POTENTIAL TEST FOR MARTIAN MICRO-ORGANISMS

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Introduction: Evidence from satellite observations suggests that the Martian surface is cold, dry, and wind-swept. The thin atmosphere also results in exposure of the surface soils and rocks to high u.v. fluxes. Any organisms able to survive in such an hostile environment must be welladapted and hardy. On Earth, an analogous habitat (although with lower surface u.v. flux) occurs in the Dry Valleys of Antarctica, and rather than being biologically barren, is home to microbial communities that colonize the rocks [1]. The stress tolerant nature of the microbes has resulted in the suggestion that a similar type of micro-organism could flourish at the Martian surface. The cryptoendoliths occur in the interstitial spaces of translucent sandstones [2, 3] and extend down to 10 mm below the rock surface. They primarily consist of symbiotic or free living lichen and cyanobacteria, and their presence is identified by 3 colored zones [4]. It is clear from these zones that the communities change their host rock. Utilizing ICP-AES and ICP-MS techniques, we are undertaking a major, minor, and trace element study of the different layers within the sandstones to establish how the microbes affect the chemical composition of the rocks.

Samples: Cryptoendolith-bearing rocks were collected by a British Antarctic Survey expedition to Terra Nova Bay from the Battleship Promontory (BP) region; non-endolithic sandstones were also collected at the same time from neighboring regions, for comparison. The sandstones are reddish in color, medium- to coarse-grained, dominantly quartz, with minor biotite and feldspar. Where endoliths are present, the color has been leached from the sandstone and the different layers of the colonies can readily be distinguished. Quartz grains from the different layers were hand-picked for elemental analysis.

Discussion: Our preliminary results show that the microorganisms have a significant effect on major and minor element contents, with concentrations depleted in the layers that host the micro-organisms [5]. If a characteristic suite of elemental or isotopic variations is detected, then the nature and extent of this effect would add value to the potential role of cryptoendolithic communities as biomarkers when considering future in situ analysis of Martian surface materials and Mars sample return rocks.

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MG, SI, AND FE FRACTIONATION OBSERVED IN ANTARCTIC SILICATE SPHERULES

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Introduction: Previously, we analyzed oxygen isotopic compositions of Antarctic silicate spherules with an ion probe [1]. Together with major element chemistry and the isotopic fractionation, we attempted to recover the chemical compositions and O-isotopic compositions of the precursors.

We performed Mg, Si, and Fe isotope analyses of four silicate spherules, whose oxygen isotopic compositions had been analyzed, with the ion probe CAMECA IMS 6F at the University of Tokyo. The analytical condition was basically the same as [2, 3]. The San Carlos olivine was set in the same holder with the samples and analyzed to compensate instrumental mass fractionations.

Results and Discussion: Mg, Si, and Fe isotopic fractionations of the silicate spherules relative to the San Carlos olivine are shown in Table 1. Errors are expressed in 2σ . The degree of isotopic fractionation observed in M23, GI3, and possibly MY240184 shows a trend of Fe > Mg > Si, while that in M10 shows a trend of Fe > Si > Mg, which is the same tendency observed in [4]. This indicates that the heating conditions for M10 were different from those of the others.

We assumed Rayleigh fractionations for the evaporation of the spherules during their atmospheric entry and calculated how much Mg, Si, and Fe were retained in the spherule from their original abundances. These elements should have evaporated with oxygen. Thus oxygen should have been lost at a ratio of 1:1 for Mg and Fe and 2:1 for Si. From the calculation, original oxygen isotopic compositions of the spherules were estimated.

The estimated original chemical compositions of M10 and GI3 are close to the CI abundance and not depleted in Ca, which is depleted in matrices of carbonaceous chondrites. This implies that they are different from the majority of unmelted micrometeorites, which are similar to the matrices of carbonaceous chondrites [5, 6]. Since the oxygen in M23 is enriched in ¹⁶O [1], the precursor, which is almost identical to forsterite, would be something similar to amoeboid olivine aggregates [7].

The estimated original oxygen isotopic compositions of M10, M23, and GI3 are isotopically heavy. For example, the analytical data of GI3 are +23‰ in δ^{17} O and +49‰ in δ^{18} O, while the estimated isotopic compositions of precursors are +17‰ and +38‰, respectively. The estimated value is isotopically heavier the isotopic fractionation of oxygen. A possible explanation for this is that oxygen coupled with cations other than Mg, Si, and Fe may have evaporated to contribute to the isotopic fractionation of oxygen.

Tab	le	1.	Isotop	ic	fracti	onat	ion	of	four	sil	licate	sp	herul	les

Sample no.	Φ_{Mg} (‰/AMU)	Φ_{Si} (%/AMU)	$\Phi_{\rm Fe}$ (%/AMU)
M10	0.9 ± 0.4	2.8 ± 0.7	8.3 ± 1.5
MY240184	21.0 ± 0.5	12.9 ± 0.9	-
M23	0.7 ± 0.4	-2.2 ± 0.7	10.4 ± 11.8
GI3	4.6 ± 0.4	3.5 ± 0.7	12.4 ± 1.8

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INFRARED SILICATE FEATURES FROM DUST: MODEL CALCU-LATIONS VERSUS ASTRONOMICAL OBSERVATIONS

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Introduction: Investigating the properties of interstellar dust, primitive cometary dust, and interplanetary dust is important for understanding the formation and evolution of our planetary system. Recently, the properties of solar system dust are not only compared to interstellar dust but also to observations in circumstellar debris disks, which are assumed to be a part of planetary systems in the early stages of evolution. Important tools to derive the dust properties from astronomical observations are studies of the spectral variation of the dust thermal emission, where the observation of emission features can be indicative of the mineralogical composition of the dust particles. Especially, the observation of different silicates and of amorphous and crystalline materials is often discussed. Model calculations to reproduce the observed thermal emission brightness are based on the knowledge of the optical properties and on models to describe the light scattering and thermal properties of a small particle of a certain material composition.

Optical Constants: The thermal properties of the particles depend on the optical constants of the material. Optical constants can be derived empirically from astronomical observations as was done for "astronomical silicate" [1] (also used in Fig. 1). A more detailed study of the dust mineral composition by astronomical observations requires the comparison to laboratory measurements where the reflection and transmission of minerals are measured for different wavelengths. The results, however, depend on the exact chemical composition of the mineral, the temperature, the orientation of the crystal relative to the incoming light, and whether the material is measured as a powder or a slab.

Light Scattering Models: Applying the Mie-theory to calculate the scattering properties of particles, the absorption efficiency Q_{abs} can be calculated for the optical constants. Using the Maxwell-Garnett theory, the optical constants can be calculated for porous grains. Aside from the structure of grains, their size also influences the thermal emission. The calculated spectrum for astronomical silicate [1] particles of 2 μ m size shows features while these disappear for bigger particles (Fig. 1). Hence, the absence of features of a certain material in an observed spectrum does not necessarily mean that there are no grains of this material.

We present model calculations of the infrared spectra for different materials where the refractive indices are already known and show the problems which can occur in the interpretation of astronomical observations.



Fig. 1. Calculated spectra of astronomical silicate for different sizes: 2 μ m, 5 μ m, 10 μ m.

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NUMERICAL SIMULATION OF NEUTRON-CAPTURE-PRODUCTION OF COSMOGENIC NUCLIDES IN STONY METEORITES

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Introduction: A purely physical model for the simulation of cosmicray-particle interactions with matter was used to investigate the effects of bulk composition on production of neutron-capture-produced cosmogenic nuclides in meteoroids.

Calculational Model: The numerical simulation of interactions of primary and secondary cosmic-ray particles was done with the LAHET Code System (LCS) [1], which uses MCNP [2] for transport of low-energy neutrons. The investigated objects were spheres with various radii that were divided into spherical layers. We used the spectrum of the galactic-cosmic-ray particles corresponding to the solar modulation parameter $\Phi = 650$ MeV. The statistical errors of the LCS calculated fluxes were ~3–5%. The production rates were calculated using the excitation functions from evaluated neutron data files ENDF/B-VI [3] and JEF-2.2 [4].

Results and Discussion: Significant differences exist between production rate depth profiles in ordinary chondrites and C-chondrites caused by the presence of hydrogen, which is a strong neutron moderator. We found that there are also differences between capture rates in individual subclasses of ordinary chondrites. Generally, higher iron and lower oxygen content results in lower fluxes of thermal neutrons and, therefore the lower capture rates and vice versa. The relative differences depend on the excitation function of the particular (n, γ) reaction. The capture rate of ³⁶Cl in LL chondrites relative to that in L chondrites is shown in Fig. 1. For meteorite sizes with radii greater than 50 cm, the ratio is constant with depth and radius for all investigated isotopes. The situation is similar for the H/L chondrite ratio when the difference in bulk densities is considered.

The mean GCR particle flux at 1 AU determined by comparing calculated depth profiles to measured 41 Ca data from the Apollo 15 drill core [3] was 2.86 cm⁻² s⁻¹, which is \approx 1.6 times less than the values obtained in model calculations of spallation production [5, 6].





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EXTINCT ²⁴⁴PU IN ANCIENT TERRESTRIAL ZIRCONS

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The initial Pu/U ratio of the solar system is an important parameter in models of nucleosynthesis, mantle evolution, and cosmochronology. Current estimates are based on analyses of the chondrite St. Severin and the achondrite Angra dos Reis and are poorly constrained, ranging from 0.004 to 0.008. On account of its short, 82 Ma half-life, ²⁴⁴Pu was essentially extinct 3900 Ma ago, and consequently, there exists no reliable measurement of Pu/ U for Earth. The discovery of zircons dating from the period when ²⁴⁴Pu was "live" offers an opportunity to measure the former terrestrial abundance of ²⁴⁴Pu directly by way of fissiogenic xenon isotopes. The expected levels of fission xenon in individual zircons, (1 to 4 µg, 100-200 ppm U), are comparable to the Xe blank levels (~10⁻¹⁵ ccSTP) typical of conventional noble gas mass spectrometers. To analyze these minute amounts of xenon, we have made use of laser resonance ionization using the RELAX mass spectrometer. We have carried out preliminary analyses of 3 individual 4150 Ma zircons and one 3600 Ma zircon from Western Australia and obtained 4 clear fission spectra. All were free from significant atmospheric blank (¹³⁰Xe was less than 4 \times 10⁻¹⁸ ccSTP, i.e., 100 atoms). The spectra of the older zircons clearly demonstrated the presence of varying proportions of ²⁴⁴Pu fission xenon.

The highest 131 Xe/ 136 Xe ratio, 0.134 ± 0.003, corresponds to an initial Pu/U ratio of 0.0035 ± 0.005. The variable ratios could result from loss of Xe after 4.0 Ga or represent U-Pu fractionation. We are currently analyzing older zircons and intend to search for correlations with REE patterns, oxygen isotopes, and the degree of U-Pb concordance, and to investigate the thermal release characteristics of the xenon. In addition to constraining the terrestrial Pu/U ratio, these investigations may allow us to characterize the geochemical behaviour of Pu in the earliest crust forming processes.





PHOTOLUMINESCENCE SPECTRA OF THE LAPPAJÄRVI IMPACT DIAMONDS

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Introduction: Impact diamonds derived from the Lappajärvi astrobleme, Finland [1, 2] were recently characterized in terms of their carbon isotope composition [3] and SEM-CL data on them were reported [4]. Now, we present the first photoluminescence (PHL) and Raman data for the diamonds, obtained by means of Ramanor U1000 Jobin Ivon microspectrometer with Ar-induced 514.5 nm laser radiation.

Results: The Lappajärvi diamonds exhibit a strong PHL, which often makes the detection of Raman bands impossible. The PHL spectra vary from grain to grain (Fig. 1). The pure PHL spectra are well approximated by Gaussians with peak positions at 558.9, 629.2 nm and at 542, 573, 600 nm for 2 light grains (curves 1 and 2 in Fig. 1., respectively), and at 561, 591.6 nm for less intensive spectrum of dark grain. After subtraction of PHL background, the Raman spectra of the grains show intensive broadening with a superposition of several lines. Three Lorentzian curves were required to fit 1 of the spectra. We observed a splitting of the Raman diamond line into 2 at 1327, 1334 cm⁻¹, and in another line at 1343 cm⁻¹, with line widths ~9 cm⁻¹ for one of the light grains.

Discussion: The yellow-green color of PHLs for the Lappajärvi diamonds is similar to those found for the natural endogenous diamonds, and it can be referred to impurities and defects of H_3 , H_4 , S_1 , and of S_2 types. PHL spectra of the Lappajärvi diamonds (curves 1 and 2 in Fig. 1) differ from spectra of the Popigai and Kara diamonds (curves 3 and 4, respectively). A strong PHL is also common for the Ries impact diamonds in spite of their coloration [6]. The high-frequent shift of the Raman peak at 1334 cm⁻¹ is possibly related to internal stress [7]. The low-frequent band at 1327 cm⁻¹ can possibly be referred to irregular distribution of stacking faults on {111} planes of diamond lattice [8]. On the other hand, it can be referred to a small size of the diamond crystallites [9]. In this case, there is a shift of the Raman diamond peak to lower frequencies. At this frequency the intensity decreases significantly.



Fig. 1. PHL-spectra of Lappajärvi (curves 1, 2; this study) as well as Popigai and Kara (curves 3 and 4, respectively, [5]) impact diamonds.

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NOBLE GAS COMPONENTS IN THE ZAG METEORITE: A BRECCIATED CHONDRITE WITH HALITE CRYSTALS

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Introduction: The Zag meteorite (H3–6), which fell in Morocco in 1988, has mm-sized halite crystals inside. The meteorite consists of two distinct phases, light and dark, and the halite crystals were only discovered in the dark phase until now [1]. The halite grains have excess ¹²⁹Xe, the beta-decay daughter of extinct ¹²⁹I, indicating that aqueous fluids existed on the H chondrite parent body in the early solar system [2].

Experimental: We had two cm-sized blocks of the Zag meteorite, named Block A and B. Block A contained a visible halite crystal in a dark phase. On the other hand, no halite grain was observed on the surface of Block B. The two blocks were broken into several pieces for separation between the light and dark phases. The dark phase containing the visible halite crystal was partly broken, keeping the halite from destruction for laser microprobe noble gas analysis planned in the future (cf. [3]). Some pieces composed of a single phase were selected for noble gas analysis.

Noble gas analysis was performed with a modified VG5400 mass spectrometer (MS-II) with total melting and stepwise heating methods. In the former method, several fragments of each phase, weighing about 60 mg, were melted in a furnace at 1800°C. In the latter, 100–200 mg of them were heated at 700, 900, 1100, 1300, 1500 and 1700°C (6 steps) for the dark and light phases of Block B or 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1500, and 1800°C (11 steps) for the dark phase of Block A successively, and released noble gases at each temperature were measured.

Results and Discussion: Neon from the light phase was dominated by a cosmogenic component, while solar wind and solar energetic particles (SEP) were detected at low temperatures in the dark phases. Noble gas elemental abundance patterns for the dark phases are also similar to those of solar gas-rich meteorites. This indicates that dark phases were exposed to solar wind on the surface of the parent body, which supports the idea that this chondrite is a regolith breccia. Exposure ages estimated for both phases are about 6 Myr, which is common in H chondrites.

In the dark phase of Block A, $4.2 \, {}^{129}$ Xe/ 132 Xe ratio was obtained at 1000°C. Halite grains probably occurred inside the sample fragments, because they were taken from the phase containing the visible halite grain. In the dark phase of Block B, the maximum 129 Xe/ 132 Xe ratio was 1.9 at 1100°C, though the concentration of trapped Xe was slightly lower than that of Block A. This might simply be attributed to the low halite content. However, we have actually found some apatites as another carrier of chlorine, possibly of iodine. Laser microprobe noble gas analysis will clarify whether the apatites have 129 Xe derived from 129 I.

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Introduction: Ever since original their discovery, buckminsterfullerene C60 and its siblings have raised much interest not only in material science, but also in astronomy [1]. Specifically, it was recognized early on that the cage structure offers the possibility for introduction of foreign atoms, even chemically inert ones such as the noble gases [2]. In meteoritics, it has been suggested that fullerenes may be an important carrier of trapped gases in primitive meteorites [3, 4]. Also, since experiments suggested incorporation of Xe to be much less efficient than that of the other noble gases [5], it was suggested that Earth's "missing Xe" problem-and that of Mars, for that matter- may be due to the fact that fullerenes were a primary vehicle for bringing volatiles to the terrestrial planets [6, 4]. Since trapping most likely occurred during formation from the gas phase [7], we decided to study the efficiency of noble gas trapping from ambient gas during fullerene synthesis

Experimental: Samples were prepared following standard methods for fullerene synthesis, including extraction of C_{60}/C_{70} with benzene [8], in atmospheres of He, Ne, Ar, Kr, and Xe, respectively at ambient pressures of 100 Torr (200 Torr in the case of Ne). Yields were highest for He, decreasing with mass. Noble gases were extracted by combustion at 300°C, 500°C, and several steps at 600°C.

Results and Discussion: Clear-cut results were obtained for He and Ne, where concentrations of 5850 and 2930×10^{-8} cm³ STP/g were observed in our samples, corresponding to trapping efficiencies of ~45000 and ~11000 $\times 10^{-8}$ cm³ STP/(g atm). Main release of He and Ne correlates with peak carbon combustion indicating that these gases are indeed trapped within the fullerene structure. The factor of 4 difference is intermediate between the order of magnitude difference observed for the incorporation efficiency into fullerenes heated to 600°C when exposed to 3 bar of ³He and Ne, respectively on one hand [2], and the about equal efficiency for He and Ne incorporation when exposed to >1000 bar pressure [5].

The case of the heavier noble gases is tricky. Among other things, they are strongly compromised by an adsorbed component. While this was mostly released at a low temperature, there was significant tailing to the temperature where main combustion occurs. Subtracting adsorbed Ar based on the release of Ar adsorbed in similar quantities on the fullerenes synthesized in He and Ne, we estimate a trapping efficiency for Ar of $\sim 3000 \times 10^{-8}$ cm³ STP/ (g atm), i.e., another factor of 4 lower than that for Ne. The behavior of decreasing trapping efficiency with the mass of noble gas is rather different from that of the meteoritic Q phase, for which orders of magnitude higher trapping efficiencies have been implied for the heavy noble gases (e.g., [9]). Therefore, trapping of noble gases by C₆₀/C₇₀ fullerenes during their formation seems an unlikely process by which planetary noble gases were acquired.

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THE BEHAVIOR OF FE, NI, AND PT IN SILICATE MELTS DURING IMPACT-SIMULATED HIGH-TEMPERATURE HEATING

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Introduction: Modification of silicates under hypervelocity impact processing is one of fundamental factors during the evolution of solid materials from interplanetary dust to planets. Of particular interest in such processing is the behavior of siderophile elements (SE), since their pattern in impactites is informative about colliding materials. Particularly, any enrichment of SE in impactites in terrestrial craters compared to SE concentration in target rocks is usually considered a result of contamination by meteoritic projectile material. This approach is supported by the fact that many SE (particularly highly siderophile elements) are refractory elements, and the resulting change in their concentration is expected only due to simple mixing of colliding materials. Nevertheless, there are mechanisms which provide sufficiently high mobility of highly refractory elements during an impact. One of the aims of present experiments is to investigate the behavior of Fe, Ni, and Pt at impact-related high-temperature conditions.

Experimental Technique and Results: Our experiments were performed using a laser pulse (LP) technique [1]. Composition of the vapor cloud was investigated by analysis of the composition and structure of the forming condensed film. Residual melt was collected both as melt sheet on the crater walls and as dispersed melt spherules. Chemical analysis of melt was performed using FESEM/EDS microprobe analysis. Chemical analysis of condensate was performed using X-ray photo-electron spectroscopy (XPS). We used olivine and augite as target samples for investigation of the behavior of Fe. The behavior of Ni was investigated using garnierite and kerolite. The behavior of Pt was investigated using a pellet of pressed powder of Murchison + Ti-basalt, which was doped by Pt.

In all cases, Fe, Ni, and Pt were efficiently removed from silicate melts and transported to the condensate. The observed enhanced "volatility" is the result of thermal reduction of these elements and formation of metallic nanoparticles with subsequent dispersion into the vapor cloud. Such "mechanical" volatility also provides transportation of other SE partitioned into metallic phase during its formation in the melt.

Implications for Natural Processes: Reduction of iron with formation of nanoscale particles is a regular process for impact-induced, high-temperature processing of silicates. This mechanism can be valuable for the consideration of formation of agglutinitic glasses on the Moon and formation of GEMS in IDRs. The formation and efficient loss of metallic iron particles is a possible mechanism which provides scavenging of SE from impact-induced silicate melts.

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A RE-EVALUATION OF THE SIZE OF THE ACRAMAN IMPACT STRUCTURE, AUSTRALIA

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Introduction: The Acraman structure, centred at 32°01'S, 135°27'E, is located on the Gawler Craton of South Australia. The structure was formed in the Mesoproterozoic age Gawler Range Volcanics, a suite of acid lavas and pyroclastic ash flows. The Yardea Dacite, a massive, porphoritic dacite to rhyodacite near the top of the volcanic sequence, is mapped at surface over most of the structure. The Gawler Range Volcanics are characterized by a red-brown coloration due to amorphous hematite and are commonly up to 1 km thick [1].

Past Work: The Acraman structure was identified from circular features in satellite imagery and its impact origin verified from the presence of shock metamorphic features (breccia, shatter cones, PDFs, and impact melt) [2]. Ejecta from Acraman, consisting of reddish volcanic rocks bearing abundant PDFs and anomalous Ir, have been found in the Adelaide Geosyncline, 300 km to the east [3], and the Officer Basin, 450 km northwest [4].

Previously suggested dimensions of the Acraman structure [2] include: 1) a central uplift of 20 km defined by a subdued magnetic response; 2) a transient cavity ranging from 30 km (from topography) to 40 km (determined by scaling the extent of disrupted target rock); 3) and a final crater diameter of 85–90 km, correlating with an outer "ring" feature identified from magnetic data. Based on their own field observations, [6] Shoemaker and Shoemaker suggest that disruption and shock effects within the target rock do not occur beyond a diameter of 19–20 km, and the final crater was little more than 35–40 km in diameter.

A Re-Evaluation: The diameter of the transient cavity was later estimated to be 34 km by scaling of the thickness of the ejecta layer at distances of 300 and 450 km from the center of the crater [6]. Relationships between the size of the transient cavity and the final crater diameter, summarized in [7], suggest the original diameter of the structure was probably between 55 and 64 km.

Reinterpretation of the magnetic data suggests a central uplift diameter of 18 km, correlating with a circular zone of low magnetic response due to structural thinning of the Gawler Range Volcanics. Lobes of lowered magnetic susceptibility, out to a diameter of 30 km, are possibly the result of shock demagnetization of the target rock within the transient cavity. A set of regional northeast and northwest magnetic lineaments form the 85–90 km outer "ring" defined by [2]. While possible fault reactivation occurred along these trends as a result of the Acraman event, they are considered to lie well outside the crater.

The morphometric relationships of [8] suggest a crater with an 18 km central uplift will have a final diameter of around 55 km. This diameter correlates with perturbations in the regional gravity field, which are interpreted to reflect the extent of deformation due to the impact.

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NOBLE GASES AND COSMIC-RAY EXPOSURE HISTORY OF WILLARD(B) H CHONDRITE: A BRECCIA WITH CARBONACEOUS CHONDRITIC INCLUSIONS

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Introduction: Willard(b) weighing 12.7 kg was found in New Mexico, USA in 1934, and classified as H3.5–3.6. Its unique feature is a brecciated texture with small, dark clasts [1, 2]. Noble gases were measured for both the dark clast and the host rocks of the brecciated lithology. The results show clear differences of noble gas concentrations and cosmic-ray exposure ages between the two phases.

Experimental Method: Samples of dark material were collected from the dark clast by scratching with a needle. Small chips were taken from the brecciated portion hosting the dark clast. Noble gases were extracted from the host rocks by stepwise heating from 400 to 1750°C (10 steps), while three temperature steps were employed for the clast sample due to its small sample size (2.4 mg).

Results and Discussion: Isotopic ratios of He and Ne from the host samples are dominated by solar wind or SEP components. Concentrations of trapped noble gases are in the range for the gas-rich meteorites Kapoeta and Pesyanoe. In contrast to the host samples, noble gases of solar origin were not observed for the dark material, and its noble gas concentrations and isotopic ratios are similar to those of the CI chondrite Orgueil. Cosmic-ray exposure ages calculated for the host and the clast samples assuming 4π -geometry are presented in Table 1. The exposure age for clast (2 Myr) is much shorter than those for the host samples (93-13 Myr). The difference between the exposure ages may be explained by an impact of a CI-like meteoroide on an H chondrite parent body at the final stage of brecciation and solar-gas implantation. Maximum transit time from the parent asteroide to the Earth should be 2 Myr. In this case, the fragments from the CI-like meteoroide were rapidly mixed with surface materials and buried in a relatively deeper part, enough to be shielded from galactic cosmic-rays. The host materials had been exposed to galactic cosmic-rays more than about 20 Myr, considering 2π irradiation on the surface of the parent body. We did not detect clear excess in ¹³¹Xe, which would have been produced by secondary neutron capture on Ba during the cosmic-ray irradiation. Hence, a heavy shielding condition for the host materials was unlikely. K-Ar ages for the host samples are calculated as 3.9 and 3.7 Gyr, adopting average K concentration for H chondrites. The brecciation might have occurred at around 4 Gyr ago. The production rates $(10^{-9} \text{ cm}^3 \text{ STP/g/Myr})$ are: P₂₁ = 3.1 and 2.2 and P₃₈ = 0.50 and 0.34 for the host (H chondrite) and the clast (CI chondrite), respectively [3].

Table 1. Cosmogenic ²¹Ne and ³⁸Ar concentrations and cosmic-ray

exposure ages (4π-geometry). ^a								
Sample	²¹ Ne _{cos}	$^{38}\mathrm{Ar_{cos}}$	T ₂₁	T ₃₈	Taverage			
	10 ⁻⁹ cm ³	STP/g	Myr					
Host1	28	4.3	9.0	8.6	18.8			
Host2	40	6.2	13	12	12.5			
Clast	4.8	0.61	2.2	1.8	12.0			

^aProduction rates $(10^{-9} \text{ cm}^3 \text{ STP/g/Myr})$: P₂₁ = 3.1 and 2.2, and P₃₈ = 0.50 and 0.34 for the host (H chondrite) and the clast (CI chondrite), respectively [3].

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MANGANESE-CHROMIUM CHRONOLOGY OF OLIVINES IN L CHONDRITES

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The parent bodies of ordinary chondrites (OCs) accreted within a very short time scale in the early stage of the formation of the solar system. After accretion, parent bodies might have been internally heated by sources such as the decay of short-lived radionuclides (e.g., ${}^{26}Al$ [1]). In such cases, parent bodies should initially have had onion-shell structures, in which metamorphism increased with burial depth. Hence, the time scale of thermal metamorphism should have correlated with petrologic types. If a parent body of ~100 km was heated by the decay of ${}^{26}Al$, the time scale of thermal metamorphism would have been ~10 Myr for type 3–5 chondrites and ~100 Myr for type 6 chondrites [2]. The Pb-Pb and ${}^{40}Ar$ - ${}^{39}Ar$ ages and ${}^{244}Pu$ fission-track thermochronology of some H chondrites are consistent with the onion-shell model [3, 4].

However, if there is any disturbance of the structure of a parent body, cooling histories of OCs could have been different from those predicted by the onion-shell model. In fact, the Pb-Pb ages of L and LL chondrites have no correlation with petrologic types [3], and there is no clear relationship between petrologic types and cooling rates estimated from the chemical zoning in Fe-Ni metal [5]. The OC parent bodies, especially those of L and LL chondrites, could have experienced disruptive collisions during thermal metamorphism. In this case, some source materials of OCs could have been excavated from the hot interior and cooled rapidly.

If the 53 Mn- 53 Cr (t_{1/2} = 3.7 Myr) system is applicable to OCs, we can constrain the duration of thermal metamorphism of these meteoritic materials [6, 7]. Because many chondrites are brecciated, in situ analysis by ion-microprobe is useful for comparison of the isotopic and petrographic characteristics. We performed isotopic analyses of 52 Cr, 53 Cr, and 55 Mn in olivines in equilibrated L chondrites with the SHRIMP II. For the precise determination of the 53 Mn- 53 Cr ages, we selected olivines with very low Cr contents using electron probe microanalyzer. We found that some of them have very high Mn/Cr of up to several hundreds by SHRIMP analysis. The 53 Mn- 53 Cr ages of meteoritic materials suggest that the formation of OC chondrules predated LEW 86010 formation by 10 Myr [7]. If this was the case, the 53 Cr excess would be detectable only when the thermal metamorphism occurred at a very early stage in the solar system or when the parent body experienced a disruptive collision.

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TOF-SIMS ANALYSIS OF ISOTOPICALLY ANOMALOUS PHASES IN RENAZZO MATRIX

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Introduction: Deuterium and ¹⁵N enrichments are often observed in primitive solar system material like carbonaceous chondrites and IDPs [1]. However, the actual carrier phases of these anomalies are unknown. The purpose of the present study is to identify these carriers in matrix material of the CR chondrite Renazzo by using time-of-flight secondary ion mass spectrometry (TOF-SIMS).

Samples and Analytical Techniques: Samples of Renazzo matrix material were heated for two hours at temperatures between 200 and 1000°C in steps of 100°C in two series, under vacuum and in air, respectively [2]. These samples, as well as an unheated sample for comparison, were pressed in Au and analyzed in a previous study, which showed the loss of D and ¹⁵N anomalies with increasing temperature [2, 3]. Samples heated at 1000°C in air and unheated material were selected for our first TOF-SIMS analyses.

Three different regions $(150 \times 150 \ \mu\text{m}^2 - 200 \times 200 \ \mu\text{m}^2)$ of heated and unheated samples containing several grains each were sputter-cleaned with a 3 keV Ar⁺ ion beam prior to the TOF-SIMS investigation to remove surface contamination from previous sample handling. TOF-SIMS analyses [4] were performed at high lateral resolution (~0.3 $\ \mu\text{m}$) and high mass resolution (m/ Δ m up to 10000 at FWHM). Positive as well as negative secondary ions were analyzed in sequential measurements.

Results and Discussion: Comparing the two Renazzo samples, we note a loss of H, C, S, Pb, and the halogens during heating. Other elements, such as Li, Sc, V, Cr, and Cu, show higher ion signals relative to Si in the heated samples. In particular, we note an increase in the major element Mg. The ion signals correspond to Mg contents of \sim 3 wt% for the unheated and \sim 8 wt% for the heated samples. The latter value comes close to the average value for Renazzo matrix of 9.67 wt% reported in the literature [5], while the former value seems to be too low. This behavior may be explained by a loss of hydrocarbons in the immediate neighborhood of an Mg-rich phase during heating [6].

Intensities of low-mass hydrocarbons relative to Si decrease during heating but to various degrees. For example, CN^- decreases by a factor of ~2.2 while C⁻, CH⁻, CH₂⁻, C₂⁻, and C₂H⁻ decrease by factors of 2.5–4. For some N-bearing secondary ions like N⁺, NH⁻, NH₂⁺, NH₃⁺, NH₄⁺, and NO⁺, we observe almost identical abundances for heated and unheated samples or even a slight increase after heating. Polycyclic aromatic hydrocarbons (PAHs) also show higher intensities in the heated samples.

These results suggest that at least two different N-containing phases are present, a 15 N-enriched low-temperature organic phase that accounts for ~50% of the CN⁻ signal, and that is associated with Mg-rich material, and an isotopically normal high-temperature phase. Further analyses of the lateral distributions of isotopic anomalies, elements, and molecules will be performed in the future.

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COMPREHENSIVE STUDY OF COSMOGENIC NUCLIDES IN MARTIAN METEORITES

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Introduction: The irradiation history of meteorites can be deciphered by measuring the concentrations of cosmogenic radionuclides via Accelerator Mass Spectrometry (AMS) and application of physical model calculations. For a comprehensive discussion of the irradiation histories, the size of the meteoroides and the position of the analysed samples inside them, the radionuclides ¹⁰Be, ²⁶Al, and ⁵³Mn were determined in same sample aliquots of 10 Martian meteorites.

Aim of the Study: Integrated studies of different cosmic ray products such as radionuclides in same sample aliquots of a meteorite are essential to a realistic understanding of their production in meteoroides. Additionally, the application of physical models not only allows the discussion of the irradiation history, the size of a meteoroid and the position of a sample in it, but also an understanding of the basic nuclear interactions between cosmic ray particles and meteoroid matter. This knowledge leads to a physical understanding of the cosmic ray induced production of nuclides in general. For accurate and realistic results, same sample measurements of ²⁶A1, ¹⁰Be, and ⁵³Mn were performed in this work.

Experimental: We obtained samples of 10 Martian meteorites from the Museum für Naturkunde, Berlin. The mass of each sample was around 100 mg. The chemical analysis was done using the method of [1] employing ion exchange chromatography. The isotopic ratios in those samples were measured via AMS at the ETH Zürich (¹⁰Be and ²⁶Al) and TU-München (⁵³Mn). The physical modelling was performed using the model of [2]. Results: The results obtained so far are summarized in Table 1..

Table 1. Measured cosmogenic radionuclides in Martian meteorites.^a

Meteorite	¹⁰ Be [dpm/kg]	²⁶ Al [dpm/kg]	⁵³ Mn (dpm/kg Fe)
ALH 77005	_	_	206.3 ± 13.2
ALH 84001	23.1 ± 0.7	72.6 ± 2.3	270.7 ± 23.0
Chassigny	22.7 ± 0.7	50.5 ± 1.6	265.1 ± 15.1
EETA 79001A	5.3 ± 0.2	42.0 ± 2.2	42.8 ± 3.1
Gov. Valadares	23.9 ± 0.8	86.8 ± 2.8	543.7 ± 45.1
Lafayette	21.0 ± 0.7	83.0 ± 2.5	330.6 ± 24.1
Nakhla	24.7 ± 0.8	90.0 ± 2.9	399.6 ± 27.2
SaU 005	13.5 ± 0.4	48.5 ± 1.7	78.6 ± 6.1
Shergotty	16.6 ± 0.5	82.2 ± 2.7	166.7 ± 10.5
Zagami	-	-	212.3 ± 18.3

^aErrors denote the AMS error only.

Some data are given here for the first time. Other data of Table 1 agree with already published data (cf. e.g., [3, 4]). These data are used for discussion on the irradiation history (simple versus complex), the determination of the terrestrial and the cosmic ray exposure age, and the reconstruction of the meteoroid size.

References: [1] Michel R. et al. 1996. Nuclear Instruments and Methods in Physics Research 113:434. [2] Leya I. et al. 2000. Meteoritics & Planetary Science 35:259. [3] Schnabel C. et al. 2001. Abstract #1353. 32nd Lunar and Planetary Science Conference. CD-ROM. [4] Nishiizumi K. 1987. Nuclear Tracks and Radiation Measurements 13:209.

IMPLICATION FOR THE SLOW LINEAR COOLING ORIGIN OF VITROPHYRIC TEXTURES IN BASALTIC ROCKS

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Introduction: Porphyritic textures are commonly seen in many kinds of achondrites, lunar samples, martian meteorites, and terrestrial rocks. Some of such porphyritic textures are composed of large porphyritic grains set in a very fine-grained mesostasis of micro-lath minerals and called as "vitrophyre" in particular. Such a vitrophyric texture has been extensively studied on Apollo 12 and 15 samples (e.g., [1]), and its formation was explained by either 1) two stage cooling, which is slow cooling followed by rapid cooling; or 2) rapid linear cooling (>2°C/hr). We found that such a texture could be produced in linear cooling experiments at slower cooling rates than that estimated for lunar samples using the analogue meteorite composition.

Results and Discussions: The run product from our linear 0.5°C/hr cooling experiments with the bulk composition of QUE 94201 basaltic shergottite [2] has a porphyritic texture composed of large euhedral pyroxene grains set in a very fine-grained lathy pyroxene and plagioclase mesostasis similar to lunar "vitrophyre" (Fig. 1). Porphyritic pyroxene grains are roughly divided into two groups. One is a large grain (\sim 500 µm) and the other is a medium-size grain (<100 µm) showing a swallow-tailed shape. Microprobe analysis indicates that Ti-rich oxide is also present in the mesostasis. The core composition of the porphyritic pyroxene is more Ca- and Al-rich than that of pyroxene in equilibrium with the melt, although the Fe/Mg ratio is similar [2]. These pyroxene grains are extensively zoned. Fe, Ca, and Al contents increase from core to rim. Medium-grained pyroxene has a more Fe-rich composition than that of large pyroxene and has a variation in Ca contents. It is likely that the crystallization of plagioclase was suppressed in the early stage, and then the mesostasis was formed from the undercooled residual melt as referenced in [3].

The vitrophyric textures are seen in some achondrites recently found (e.g., [4]) and are often interpreted as the results of two-stage cooling. However, our experimental results show that such a texture could be produced by a relatively slow linear cooling history. Hence, we need to be careful when we consider cooling history of vitrophyric textures.



Fig. 1. BSE image of the QUE run product from 0.5°C/hr cooling.

References: [1] Grove T. and Walker D. 1977. Proceedings, 8th Lunar and Planetary Science Conference. pp. 1501–1520. [2] Koizumi E. et al. 2001. *Meteoritics & Planetary Science* 36:A102. [3] Grove T. and Raudsepp M. 1978. Proceedings, 9th Lunar and Planetary Science Conference. pp. 585– 599 [4] Fagan T. et al. 2002. *Meteoritics & Planetary Science* 37:371–394.

MINERALOGICAL DESCRIPTION OF PRE 95404: A RUMURUTI CHONDRITE THAT INCLUDES A LARGE UNEQUILIBRATED CLAST

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Introduction: Rumuruti chondrites (R chondrites) are characterized by highly oxidized olivines (e.g., [1-3]). However, R chondrites are distinguished from CK chondrites, which are also oxidized chondrites, because there are no magnetites in R chondrites. Since the number of Rumuruti chondrites is limited, the understanding of the petrogenesis of these materials is limited (e.g., formation in an oxidized nebula or parent body oxidation). A limited number of unequilibrated R chondrites or clasts have been previously reported [3]. In the present study, we describe the mineralogy and petrology of a new Antarctic unequilibrated R chondrite, PRE 95404.

Experiments and Results: We used an optical microscope and JXA-8800 EPMA for the present study. A polished thin section (PTS) of PRE 95404 indicates that it is a breccia consisting of two lithologies: unequilibrated (3) and equilibrated (>4).

We obtained the chondrule size distribution (range: 110~900 µm) and the volumetric chondrule/matrix ratio from the PTS. The average chondrule diameter is ~300 µm and it is larger than that of CO3 and smaller than that of ordinary chondrites [4]. The abundance of chondrules (chondrule/matrix ratio) for R chondrites is lowest among chondrites. Fa composition of olivines in chondrules in the R3 clast ranges from Fa₅ to Fa₄₀. On the other hand, that in the R >4 clast is nearly homogeneous, Fa₃₈₋₄₀. Olivines include variable proportions of NiO 0~0.3 (wt%). Low-Ca pyroxenes and high-Ca pyroxenes are both present. Sulfides consist of pyrrhotite (Fe_{1–8}S; δ = 0.01~0.10) and pentlandite, and mainly occur as opaque chondrules. No metals are present in the PTS.

Discussions: The fact that no metals can be found and both Fa and Fs contents are higher in the rims of individual mineral grains than those in ordinary chondrites suggests that PRE 95404 experienced higher oxygen fugacity than the ordinary chondrites. Where did these materials experience higher oxygen fugacities: in the nebula, on the parent body, or in both locations? On the parent body, oxidation may occur just in the lithification processes in order to form breccia. Alternatively, the existence of the unequilibrated R chondrites may suggest a high oxygen fugacity in the nebula. No evidence exists for reduction following oxidation on the parent body. We suggest that the oxidized condition was attained in both locations. In the oxidized solar nebula, Fe(-Ni) sulfides may directly condense from the nebula. Kozasa and Hasegawa [5] showed the possibility of direct condensation of FeS instead of Fe from the solar nebula gas using the time dependent homogeneous nucleation theory in a rapidly cooling solar nebula. The low abundance of chondrule may suggest that the formation region of R chondrites had a larger heliocentric distance compared with ordinary chondrites [2]. It seems that these are qualitatively consistent with each other.

References: [1] Schultze H. et al. 1994. *Meteoritics* 29:275–286. [2] Kallemeyn G. W. et al. 1996. *Geochimica et Cosmochimica Acta* 60:2243–2256. [3] Bischoff A. 2000. *Meteoritics & Planetary Science* 35:699–706. [4] Dodd R. T. 1981. *Meteorites*. Cambridge University Press. 368 p. [5] Kozasa T. and Hasegawa H. 1988. *Icarus* 73:180–190.

ACAPULCOITE-LODRANITE CLAN ACHONDRITES—HOW MANY PARENT BODIES?

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Introduction: Acapulcoite and lodranite meteorites form the prototypical primitive achondrite clan. Some members are metamorphosed chondritic materials, some have lost or gained metal-sulfide system melts, and some have lost basaltic melts. It is generally believed that all acapulcoite-lodranite clan meteorites formed on a single parent body. Thus, their petrological and chemical characteristics ought to make sense in some petrogenetic context. Note that O-isotope data show that the parent materials of the acapulcoite-lodranite clan meteorites were not uniform. I will discuss the petrologic and chemical characteristics of acapulcoite-lodranite clan meteorites relative to their petrogenesis based on my data and the literature data [1]. I will define lodranites as those clan members that have lost basaltic melts; those that have not lost basaltic melts are acapulcoites.

Discussion: After anatexis, restites ought to be more magnesian than their parent materials. This simple model is not evident among the acapulcoite-lodranite clan meteorites. Acapulcoite orthopyroxenes have Mg#s in the range of 89-94, while lodranites form two distinct groups. Gibson, Y-75274, and Y-8002-magnesian lodranites-have orthopyroxenes with Mg#s of 94-96, consistent with a restite origin. All other lodranitesferroan lodranites- have orthopyroxenes with mg#s in the range of 86-88more ferroan than the presumed parent rocks. The different lodranites cannot be explained by later redox reactions having altered their Mg#s, as orthopyroxene Mn/Mg ratios show the same pattern-most lodranites have mafic silicates with Mn/Mg ratios as high as or higher than those of acapulcoites. Thus, most lodranites are not restites from parent materials identical to known acapulcoites. Again, only the magnesian have Mn/Mg ratios consistent with a restite origin. Gibson orthopyroxenes and clinopyroxenes have lower Ti contents than do acapulcoite pyroxenes, consistent with a restite origin. Orthopyroxenes in Y-8002 have Ti contents within the range observed for acapulcoite orthopyroxenes, while its clinopyroxenes have Ti contents above the range for acapulcoites. Y-75274 orthopyroxenes and clinopyroxenes have higher Ti contents than those of any acapulcoite. These two lodranites are inconsistent with an origin as restites from acapulcoite parent materials based on pyroxene Ti contents.

There are relatively few geochemical data on the magnesian lodranites for comparative purposes. However, lithophile element ratios show Gibson is less depleted in a basaltic component than ferroan lodranites, and the REE contents of Y-8002 are higher than for ferroan lodranites. Magnesian lodranites tend to have lower δ^{17} O, but their Δ^{17} O fall within the range of ferroan lodranites and acapulcoites. The trapped ³⁶Ar content of Gibson is within the range observed for ferroan lodranites and less than that found in acapulcoites. All acapulcoite-lodranite clan meteorites have cosmic-ray exposure ages within a narrow range irrespective of petrologic type. Thus, there are no clear-cut distinctions that strongly suggest separate parent bodies for magnesian and ferroan lodranites are from sources more ferroan than any acapulcoites, and thus, may have originated on a separate parent body.

References: [1] Due to circumstances beyond my control, I wrote this abstract far from suitable library facilities and was unable to provide detailed references.

OXYGEN ISOTOPE EVIDENCE FOR THE ORIGIN OF HEDS AND ANGRITES

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Introduction: HEDs and angrites represent distinct suites of mafic igneous rocks formed early in the history of the solar system [1]. Despite their mineralogical and chemical differences, both groups have similar O-isotope compositions [2]. To examine the origin of HEDS and angrites, we have undertaken a high-precision study of their O-isotope systematics.

Experimental Techniques: Oxygen isotope analyses were undertaken by infrared laser-assisted fluorination [3]. Samples were fused prior to fluorination. O₂ was analyzed using a Micromass Prism III dual inlet mass spectrometer. Precision is $\pm 0.04\%$ for δ^{17} O, $\pm 0.08\%$ for δ^{18} O, and $\pm 0.025\%$ for Δ^{17} O [3]. The meteorites studied are: *Diogenites*: Bilanga (4), Johnstown (4), Shalka (2), Tatahouine (2); *Eucrites*: Pasamonte (5), Juvinas (2), Padvarnika (2), Sioux County (2), Stannern (2), Moore County (2); *Howardites*: Kapoeta (2), Pavlovka (2), Molteno (2); *Angrites*: Angra dos Ries (4), LEW 86010^{*}(2), D'Orbigny^{*}(2), NWA 1296^{*} (2). (All falls except as indicated by an asterisk; number of replicate analyses in brackets.)

Results: Angrites and HEDs plot as distinct groups (Fig. 1) and define single mass fractionation lines ($\Delta^{17}O = -0.056 \pm 0.007$ for angrites and -0.220 ± 0.012 for HEDs). Previous studies have indicated that Angra dos Reis has an O-isotope composition indistinguishable from HEDs [2]. Using two distinct sub-samples, we have found it to have a $\Delta^{17}O$ value of -0.065 ± 0.009 and plots in the angrite field (Fig. 1). Eucrites and diogenites plot at either end of the HED array (Fig. 1), while howardites occupy a more central position. The large error bars for $\delta^{18}O$ reflect the inhomogeneous, coarse-grained nature of HEDs, with diogenites having grain sizes in excess of 5 cm [1].

Discussion: Experimental work indicates that either an angritic or eucritic melt can be produced from a chondritic parent simply by partial melting under differing conditions of oxygen fugacity [1]. Thus, a single asteroid might be capable of producing both the HEDs and angrites. However, O-isotope data indicates that this is highly unlikely and that both suites must come from distinct parent bodies. Furthermore, as both fall on well-defined mass fractionation lines, only a single parent body per group is required. Finally, in contrast to recent suggestions [4], O-isotope data presented here clearly demonstrates that Angra dos Ries is an angrite.



Fig. 1.

References: [1] Mittlefehldt D. W. et al. 1998. *Planetary materials*, edited by Papike J. J. [2] Clayton R. N. and Mayeda T. K. 1996. *Geochimica et Cosmochimica Acta* 60:1999–2017. [3] Miller M. F. et al. 1999. *Rapid Communications in Mass Spectrometry* 13:1211–1217. [4] Mittlefehldt et al. 2002. *Meteoritics & Planetary Science* 37:345–369.

ARE CK CHONDRITES REALLY A DISTINCT GROUP OR JUST EQUILIBRATED CVS?

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Introduction: The CK group, as presently defined [1, 2], is dominated by equilibrated meteorites, while all other carbonaceous chondrites groups contain only unequilibrated material [3]. This is in marked contrast to ordinary chondrites, in which equilibrated and unequilibrated meteorites form a continuum within each of the main groups (H, L, LL). As part of a classification exercise on newly-recovered CK-like material, it became apparent to us that the distinction between the CK and CV groups is far from clear-cut and that the relationship between them may need to be re-evaluated.

Experimental Techniques: Backscattered electron imagery, X-ray mapping, and mineral analyses were performed on a JEOL 840 scanning electron microscope with an Oxford Instruments exL energy dispersive spectrometer (20 kV accelerating voltage, 2 nA probe current). Oxygen isotope analyses were undertaken by infrared laser-assisted fluorination [4]. The samples studied are: Karoonda (CK4 fall), Dar al Gani 250 (CK4/5), Dar al Gani 275 (CK4/5), recently-recovered CK6-like chondrite.

Results and Discussion: CK chondrites are highly oxidized meteorites having high modal abundances of magnetite and trace amounts of Fe, Nimetal [1, 2]. The main classification criteria used to define the group are: 1) low chondrule to matrix ratio; 2) chondrule size intermediate between the CO and CV groups; 3) absence of coarse-grained rims around chondrules; 4) low abundance of refractory inclusions compared to CO and CV groups; 5) low C content; 6) refractory lithophile abundances intermediate between CO and CV groups; and 7) O-isotope compositions overlapping those of the CO and CV groups.

While we do not dispute the validity of most of these features, our own observations suggest that they are mainly a reflection of the higher metamorphic grade of most CKs compared to other carbonaceous chondrites. Thus, the apparently low content of refractory inclusions, is most likely, a product of alteration and subsequent metamorphism, as shown by the similarity between the bulk refractory lithophile abundances in CKs and the CAI-rich CV group [1]. Chondrule abundance, or perhaps more correctly, apparent chondrule abundance, will also decrease with increasing grade. Coarse-grained chondrule rims are present in at least some CKs (e.g., DAG 250), but due to recrystallization are far less obvious than in the lower grade CV3 chondrites.

A number of meteorites have been classified as being CK3 (Camel Donga 003, Watson 002, DAG 431, Dhofar 015). Note that these meteorites do not generally show typical features of the CK group, often having abundant chondrules and/or refractory inclusions and oxygen isotope compositions that plot away from other equilibrated members of the CK group. In many respects, these meteorites resemble CV3 chondrites of the oxidized subgroup.

Conclusions: The distinction between CK and CV3 (oxidized subgroup) chondrites may be more apparent than real and may reflect varying metamorphic conditions rather than more fundamental compositional differences.

References: [1] Kallemeyn G. W. et al. 1991. *Geochimica et Cosmochimica Acta* 55:881–892. [2] Geiger T. and Bischoff A. 1995. *Planetary and Space Science* 43:485–495. [3] Brearley A. J. and Jones R. H. 1998. *Planetary materials*, edited by Papike J. J. [4] Miller M. F. et al. 1999. *Rapid Communications in Mass Spectrometry* 13:1211–1217.

PETROGRAPHY, COMPOSITION, SHOCK METAMORPHISM, AND GEOLOGY OF THE IMPACT FORMATIONS OF THE ICDP DRILL CORE YAX-1, CHICXULUB CRATER, MEXICO

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Introduction: The drilling of Yaxcopoil-1, ~60 km off the impact center [1], exposes 1510 m of lithologies affected by the Chicxulub impact. 795 m of tertiary sediments are underlain by 100 m of allochthonous suevite-like, very melt-rich breccias resting on an obviously displaced megablock unit dissected by impact dike breccias.

Stratigraphy, Petrography, and Classification of Rocks: We distinguish between layered suevite-like breccias, dike breccias, and variable deformed units of Cretaceous carbonates with anhydrite intercalations. The suevitic sequence is composed of six units: 1) Upper sorted suevite; 2) lower sorted suevite; 3) upper suevite; 4) middle suevite; 5) brecciated melt rock; and 6) lower suevite. Suevitic dike breccias occur near to the top of the megablock unit, one melt rock dike and several polymict clastic matrix dikes below 1300 m.

Deformation and Shock Metamorphism: The Cretaceous megablock unit displays variable degrees of impact-induced brittle and ductile deformations and post-impact brittle deformation, as well as zones enriched in kerogen and oil. The kerogen is of pre-impact origin and got mobilized by impact-induced thermal effects which also induced K-metasomatism in the whole core section below 795 m. Different degrees of tilting of the bedding planes in different sections (10°–50°) indicate 4 subunits of the carbonateanhydrite strata. The full range of progressive stages of shock metamorphism is observed in crystalline basement clasts of all suevitic layers, in particular, PDFs in quartz, recrystallized quartz and feldspar glass, checkerboard plagioclase, and abundant whole rock melt particles.

Lithological Composition and Chemistry of the Polymict Impactites: The suevite units, as a whole, are mixtures of silicate rocks and carbonates as the melt particles in the suevite are, as indicated by their modal and chemical composition. Exsolved carbonate melts in silicate melt bodies are common, and carbonate melt bodies occur in the bottom section. All melt components are crystallized. The silicate melts are composed of minor primary plagioclase and pyroxene and abundant sheet silicates as they are affected by hydrothermal alteration and K-metasomatism. The primarily clastic matrix of the suevitic breccias is also altered by this process and by secondary calcite. PGE contents in the suevite layers are extremely low and show non-chondritic element patterns indicating the lack of any detectable contamination by the impactor.

Interpretation: The source material of the upper suevite section is from the deepest excavation zone and was incorporated into the ejecta plume at a late stage when the bulk of the high rising plume and the main mass of the vaporized projectile had disappeared from the impact site and were distributed globally. Only these upper 4 suevite units represent ballistic "fallout" material from the ejecta plume. The lower suevite (unit 6) was not airborne but ground surged material deposited as the first layer and then covered with laterally moving and brecciated material (unit 5) from a tongue of coherent melt deposited on the transient cavity wall and quenched during the collapse of the cavity. The fine-grain size and the sorting of units 1 and 2 may be due to the combined effects of the atmosphere re-entering the crater region and minor aquatic sedimentation.

Reference: [1] Dressler B. O. et al. 2003. EOS Transactions 84:125.

PLATINUM-GROUP ELEMENTS FROM THE PURBECK CINDER BED OF ENGLAND AND BOULONNAIS OF FRANCE: IMPLICATIONS FOR AN IMPACT EVENT AT THE JURASSIC-CRETACEOUS BOUNDARY

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Introduction: The Jurassic-Cretaceous boundary is coeval with three known impact events, Morokweng, Gosses Bluff, and Mjølnir. In the Jurassic-Cretaceous Purbeckian facies of northern France and southern England, a conglomeratic unit associated with an accumulation of wood fragments and a marine incursion into non-marine limestones have been hypothesised as a tsunami deposit, associated with the Mjølnir impact [1].

Analytical Method: Samples were collected from sections across the Cinder bed at Durlston Bay, Dorset and the conglomeratic unit of Pointe aux Oies, in northern France. Platinum-group element (PGE) concentrations were determined using a nickel fire assay collection procedure followed by ICP-MS [2].

Results and Implications: In the northern hemisphere, Iridium anomalies have previously been reported from the Jurassic-Cretaceous boundary of northern Siberia [3]. PGE analysis of the Boulonnais conglomeratic unit and Cinder bed show no evidence of anomalous, elevated Ir abundances. Slight elevations in Ir concentrations within shale units (>50 ppt) underlying and overlying the Cinder bed and the Boulonnais conglomerate (<10 ppt) represent fractionated crustal material (Fig. 1). No evidence of shocked quartz was found in any thin sections from samples across the Cinder bed section. From the PGE analysis and lack of other indicators, such as shocked quartz associated with the Pointe aux Oies conglomerate and Cinder bed, direct evidence to link these beds with an impact event such as Mjølnir in the Barents Sea seems unlikely.



Fig. 1. Fractionated PGE patterns from shales underlying and overlying the Cinder bed.

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ATOMIC FORCE AND SCANNING ELECTRON MICROSCOPE INVESTIGATIONS OF NANOCOMPOSITE ANALOGUES OF INTERSTELLAR AMORPHOUS SILICATES

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The scanning probe microscopy (SPM) consists of a family of microscopy methods where a very sharp needle (hereafter called tip) is scanned across a specified surface. With this method, it is possible to measure and monitor the interactive forces between the tip and the sample surface. One primary form of SPM is the atomic force microscope (AFM) [1]. The material of the sample as well as the matter of the tip are responsible for the distinct forces, which can be determined in different submodes. One further development of the AFM is the magnetic force microscope (MFM). With this technique, we are able to analyze the topography and the magnetic features of the sample surface at the same time [2].

In our study, we generate a database for the MIDAS experiment on the Rosetta mission, which will start, in the near future, to investigate the environmental dust of a comet [3]. Complementary to the MIDAS experiment, we use a conventional AFM for our analyses. The total number of AFM tips that are onboard the MIDAS experiment is 16, including four magnetic tips. To interpret the upcoming AFM and MFM images from MIDAS, we assemble mineralogical data of cometary analogue material made with different methods.

One possible analogue material is a designer polysiloxane with variable kinds of substituents, in our case, metallocenes [4]. Thermal treatment at 500°C of this material led to an assemblage of silicon oxide matrix with nanophase Fe-metal. TEM investigations shows a nearly homogeneous distribution of smaller than 100 nm Fe-metal spherules in the silica matrix. Infrared spectra of dust in interstellar molecular cloud environments have almost the same features as those obtained by Fourier transform infrared spectroscopic measurements of this material in the laboratory [5].

In this work, we analyze this analogue material with an AFM. In particular, we want to investigate the Fe-metal spherules with the MFM technique. MFM investigations of the CV chondrite Vigarano showed that different magnetic signals from different Fe-containing materials can be obtained [6]. These authors demonstrated that it is indeed possible to get a weak signal from an Fe-metal phase. Further element mapping with a scanning electron microscope from the same area should prove the occurrence of Fe-metal.

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FRONTIER MOUNTAIN 93001: AN IGNEOUS-TEXTURED MEM-BER OF THE ACAPULCO-LODRAN CLAN

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Introduction: Frontier Mountain (FRO) 93001 is a $\sim 16 \times 13 \times 12$ mm, $\sim 20\%$ fusion-crusted stony fragment of 4.86 g, initially classified as a Lodranite [1]. During a survey of the acapulcoites and lodranites present in the collection of the Museo Nazionale dell'Antartide in Siena, we observed that FRO 93001 is unlike any other known lodranite, and that it resembles the igneous regions described in the LEW 86220 acapulcoite [2]. Given the importance that such lithologies may have for understanding the igneous processes on the Acapulco-Lodran parent body [2–5], we report on our petrographic and electron microprobe study of FRO 93001.

Petrography and Mineral Chemistry: We have analyzed two polished thin sections with maximum dimensions of $\sim 13 \times 11$ mm from the largest side of the FRO 93001 specimen. FRO 93001 has a medium- to coarsegrained granular texture. It mainly consists of orthopyroxene, augite, and plagioclase poikilitic crystals up to 1 cm across, enclosing numerous grains of olivine, metal and trolite, often associated with accessory chromite, phosphate and schreibersite. Orthopyroxene and augite are typically equant anhedral; they are exsolved on [100], with nearly homogeneous bulk composition, $Fs_{13.1}Wo_{2.3}$ and $Fs_{5.8}Wo_{43.6},$ respectively, which yield equilibrium crystallization temperatures of $1100 \pm 15^{\circ}$ C. Plagioclase is characteristically interstitial, with variable composition, and An_{16.3±3.7}Or_{3.2±0.9}. Olivine grains have an average grain size of 600 µm, are often isolated with rounded-shapes, although, in places, they may form clusters of several individuals characterized by 120° triple junctions. The olivine composition is $Fa_{9.8 \pm 0.7}$, with a chondritic [Mn/Mg] = 0.006. Metal and troilite form irregular crystals with embayed contours or rounded clots up to several hundred micrometers across. The mineral mode (vol %) is orthopyroxene 52, olivine 14, metal 11, plagioclase 9, augite 6, troilite 7, and others 1.

Shock Stage: FRO 93001 shows petrographic features diagnostic of unshocked meteorites, i.e., shock stage S1 after [6], such as sharp optical extinction in olivine and other silicates.

Weathering Grade: Oxide haloes affect very few metal grains, indicating minor weathering, i.e., grade W1 according to [7].

Discussion and Conclusions: Mineralogical data confirms that FRO 93001 is a sample of the Acapulco-Lodran parent body. Contrary to known acapulcoites and lodranites, however, FRO 93001 resulted from the crystallization of coalescent gabbroic and Fe, Ni-FeS melts. Olivine with relics of granoblastic textures are interpreted as unmelted residues of the source rock; based on the olivine grain-size, the source must have been a lodranite-like material. The presence of abundant relics of the source rock, together with equilibrium temperatures similar to lodranites, suggest an in situ (or nearly so) origin for the FRO 93001 melts. The lack of fractionation between the gabbroic and the Fe, Ni-FeS melts, in spite of their different liquidus temperatures (i.e., >1100°C and ~980°C, respectively) and density contrast (~3.5 versus 5 g cm⁻³), is difficult to reconcile with a magmatic origin as proposed for the similar lithology in LEW 86220 [2], but rather, suggests a relatively rapid, localized melting process, likely associated with cosmic impacts.

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CHONDRULE RECYCLING EXPERIMENTS

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Introduction: The exact conditions under which chondrules formed are of great interest to those who seek to determine what major heating mechanism operated in the early solar system. We have shown that, with a single rapid heating, very fine-grained starting material analogous to nebular condensates do not normally generate the porphyritic textures characteristic of chondrules [1]. We explore here the consequences of reheating such synthetic chondrules.

Experimental Techniques: We prepared 8 charges by heating a <20 µm mix for 1 minute at 1537°C in 1 atm CO/CO2 and cooling on a curve starting at 2400°C/hr and ending at 360°C/hr, as in [1]. The products (MPO, NGS 32 µm) were reheated for one minute at temperatures between 1540 and 1640°C and then cooled as before. We made additional runs with a first peak temperature of 1600°C which were reheated at various temperatures down to 1466°C.



Fig. 1. a) Left, heated once; b) right, heated twice.

Results: The grain size of charges first heated to 1537°C increases directly with reheating temperature, until total melting. A charge heated twice (Fig. 1b) is much coarser than one heated once to the same temperature (Fig. 1a). There is no textural evidence of reheating in Fig. 1b. Some relict grains survived in runs reheated at the lower temperatures, but fewer than in charges heated only once to those temperatures. Heating once to 1600°C produced BO, and reheating to very low temperatures preserved the BO texture. Similarly, reheating at low temperature does not appreciably coarsen fine-grained charges [2].

Discussion and Conclusions: Reheating a charge to the same temperature makes little difference, because the same grains grow back. With higher temperatures, the smallest grains are dissolved and the survivors can grow bigger. Fine-grained condensate precursors could be converted to PO chondrules by repeated heating, but only to the extent that reheating is to successively higher temperatures. Normally, it should be impossible to tell from textures whether a chondrule has been heated once or more than once. Relicts are destroyed by recycling, and indicate polymict precursors (nebular or asteroidal debris) rather than reheating of chondrules.

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SEARCH FOR IN SITU PRESOLAR OXYGEN-RICH DUST IN METEORITES

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Introduction: Presolar oxides found in acid-resistant residues of primitive meteorites have revealed important astrophysical information [1]. The most abundant mineral among presolar O-rich dust is spinel (1 ppm) followed by corundum (200 ppb) [2]. This contrasts with ISO observations, which revealed that silicates are the major oxide phases around young stars and in outflows from evolved red giant stars [3]. Although recently identified in IDPs [4], no presolar silicates have been found in meteorites so far. The search for presolar silicates in meteorites is complicated by the fact that silicates are destroyed by most of the chemical treatments used to prepare meteoritic residues. But, even gentler treatments of meteoritic matter failed to identify presolar silicates and it was argued that they might have been destroyed in the meteorite parent bodies and/or might be too small (<100 nm) to be detected. Here, we report on an in situ NanoSIMS search for presolar Orich dust (oxides and silicates) in meteorites, avoiding the harsh chemical treatments and making use of the high spatial resolution of the NanoSIMS.

Experimental: PTSs from Semarkona (LL3.0) and Bishunpur (LL3.1) were searched for presolar O-rich dust in the matrix using the NanoSIMS ion microprobe at the MPI for Chemistry. A focussed Cs⁺ ion beam (<100 nm) of ≈ 0.5 pA was rastered over areas of 5×5 to $10 \times 10 \ \mu\text{m}^2$. Negative secondary ions of the three O-isotopes and ²⁸Si were simultaneously measured in multicollection and 256 \times 256 pixel image sequences (total integration time of ~1 hour per image set) were acquired on different locations.

Results and Discussion: Matrix areas of 2200 µm² and 388 µm² were scanned in Semarkona and Bishunpur, respectively. Selection criteria for considering a grain as a presolar candidate were: 1) an anomaly in at least one O-isotopic ratio of $>3\sigma$ extending over at least 4 pixels; and 2) presence in at least two subsequent images of the same area. In Semarkona, one presolar Orich candidate grain, about 100 nm in size, was found with $\delta^{17}O = 396 \pm$ 126‰ and $\delta^{18}O = -153 \pm 41$ ‰. An attempt to raster 2 × 2 µm images around this grain was unsuccessful as it sputtered away quickly. Another O-rich presolar candidate grain was found in Bishunpur, ~200 nm in size (arrow in the Fig. 1) with $\delta^{17}O = 477 \pm 78\%$ and $\delta^{18}O = -70 \pm 25\%$. Both presolar candidate grains represent typical group 1 presolar oxide grains [1]. While the O⁻/Si⁻ ratios of both grains are roughly within the olivine/pyroxene range, a SEM-EDX investigation of the presolar candidate grain in Bishunpur was not conclusive with respect to mineralogy. The two presolar O-rich candidate grains in Semarkona and Bishunpur represent an abundance of about 20 ppm in these two meteorites, which is higher by one order of magnitude compared to the abundance given by [2] for presolar oxides in CM meteorites but clearly lower than the abundance of 5500 ppm reported for presolar silicates in IDPs [4].





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EVAPORATION OF CMAS-LIQUIDS UNDER REDUCING CONDITIONS: CONSTRAINTS ON THE FORMATION OF THE MELILITE MANTLE OF TYPE B1 CAIS

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Introduction: We have argued that the melilite mantles of Type B1 CAIs could have formed by preferential crystallization in the outer parts of partially molten droplets due to rapid evaporative depletion of Mg and Si [1, 2]. If, however, the rate of evaporation is sufficiently slow for diffusion to maintain chemical homogeneity, there would be no distinction between the inner and outer parts of the molten droplet, and a much more uniform distribution of melilite, like that of the Type B2 CAIs, would result. Here, we present the results of new evaporation experiments aimed at further refining the conditions determining the textures of the Type B CAIs.

Experimental: The evaporation experiments were conducted at 1425° and 1475°C using partially molten droplets of DT1 composition [2]. A Deltech 1 atm gas-mixing furnace operated with H₂-CO₂ gas mixtures with log fO₂ from IW-4 to ~IW-10 (nominally pure H₂) flowing at 0.8 to 5 cm s⁻¹ was used. The rate of evaporation is controlled by gas saturated in the evaporating species (which is a function of fO₂) being continuously removed at a prescribed flow rate. The samples were quenched in air after 0.5–50 hr of exposure. Run products were examined by SEM and analyzed by EDX.

Results and Discussion: Type B2-like textures were observed at log fO₂ >IW-4, independent of both cooling rate and gas flow rate. This suggests that the evaporation rates of Mg and Si were slow compared to their diffusion rates, thus maintaining a chemically homogeneous droplet. This was confirmed by SEM analyses of quenched samples run for up to 2 hours at temperatures above the crystallization temperature of melilite, which showed no chemical gradients. Type B1-like textures with relatively thick melilite rims were observed in experiments when samples were exposed to H₂ for more than ~2 hr. Long exposure to H₂ also often results in formation of hibonite and nonstoichiometric spinel (0.25 \leq (Mg/Al)_{atom} \leq 0.50) at the extreme edges of charges. These phases are only found in contact with melilite, not with glass. When similar samples were quenched after exposure to H₂ for 0.5–1 hr, but before crystallization of melilite, the outer parts of the charges were found to be depleted in Mg and Si compared to the interior, with profiles similar to those calculated [3]. This suggests that under more reducing conditions, the evaporation rate is too fast for diffusion to maintain chemical homogeneity and that the depletion of Mg and Si in the outer parts of the charges causes the formation of the melilite rim. Droplets exposed to gas with solar fO₂ (log fO₂ ~ IW-6) showed both B1- and B2-like textures depending on the evaporation rate (which is proportional to the flow rate of the gas). Under high (5 cm s⁻¹) flow rates, with high removal rates of the evaporating species, B1-like textures were observed, while under low flow rates (0.8 cm s⁻¹), B2-like textures were formed. The experimental results provide a generalized estimate of the critical value of the evaporation rate relative to the chemical diffusion rate required to produce chemical gradients sufficient for the preferential crystallization of melilite in the vicinity of the evaporating surface. This critical evaporation rate is then used to characterize the conditions that led some Type B CAIs to have distinctive melilite mantles (B1) versus others with more uniformly distributed melilite (B2).

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A ROCK FABRIC IN CHONDRITE MATRIX

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Introduction: The description and interpretation of petrofabrics is a fundamental aspect of geology. Chondritic meteorites are the most primitive rocks available to us, recording a range of nebula and asteroidal processes. But, due to the abundance of fine-grained matrix, these samples have largely resisted traditional fabric analysis. Magnetic susceptibility, natural remanent magnetisation, and X-ray pole figure goniometry studies of bulk meteorites [1–3] have revealed that many chondrites contain petrofabrics. But the fabrics themselves are only observed in situ in the preferred orientation of large (>100s μ m) components, e.g., non-spherical chondrules [1, 4–7], lithic fragments [8], and large isolated grains [9].

Here, we present a preliminary study of Allende matrix using orientation contrast imaging (OCI) and electron backscatter diffraction (EBSD) to provide crystallographic orientation data. OCI combined with electron backscatter diffraction patterns (EBSP) separates grains based on crystallographic orientation (<1° for misorientations). We previously used OCI to study textures in chondritic metal grains [10]. Applied to chondrite matrix, the technique allows the orientation of all grains down to ~50 nm to be determined, enabling matrix fabrics in primitive meteorites to be analyzed and imaged, in addition to providing a size-frequency distribution of matrix grains.

Results: Areas of Allende matrix were mapped using a FEG-SEM equipped with forescatter detectors and a phosphor screen to collect EBSPs. The figure shows an EBSD map of grain orientation in matrix adjacent to a chondrule (right) together with a pole figure (inset). The data suggest that Allende matrix possesses a fabric, defined by preferred orientations in grains 50 nm to a few μ ms in size, which is coherent over large regions of the sample.



Fig. 1.

Conclusions: EBSD and OCI allow petrofabrics in chondrite matrix to be visualized. We are currently extending our analysis to investigate chondrule-rim/matrix relationships and whether fabrics in fine-grained dark inclusions match those in the host matrix.

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FIRST EVIDENCE OF CHICXULUB-IMPACT BOLIDE PROJECTILE AT THE YAXCOPOIL-I DRILL

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Two small pieces of Yaxcopoil-I Chicxulub impact brecccia (suevite) (10 mm in diameter) have been analyzed by optical microscopy, X-ray diffraction and microprobe analysis (CAMECA 50, at 20 kV). The samples represent loose, rusty, intensely altered material containing small dark nodules (chondrules ?) up to 1-2 mm in diameter as well as micronodules of 0.2-0.05 mm. The main components are a Chlorite-Smectite mixed layer, Saponite, Illite, Glauconite, Calcite, Goethite and Hematite, Cl-Apatite, K-Feldspar, Strontiobaryte, Halite, Anhydrite and Gypsum, and Jarosite. Other minor components are Plagioclase (48-66% An), Pyroxene, Rutile, Ilmenite, Spinels, and other opaque minerals. Graphite, identified by both microprobe and microscopically, is partly subidiomorphic-lamellar or presents infillings. Sporadic micro-cryptocrystalline spheres (50-190 µm), with lower birefringence have been identified and likely represent devitrification products of microspherules. Well-preserved (fresh) brown-green arcuated glass shards with a refractive index of about 1.524 (±0.002) are occasionally present; they contain small pores but no visible crystals. Fresh brown-green shards are interpreted as microtektites or impact glasses. Microprobe investigations allow insights regarding the nature and origin of different spinels. Homogenous-idiomorph or porous-xenomorph grains of spinels show a large variation of compositions (e.g., with high Fe, Cr, Al, Ti, and Mg, respectively) and point to different target rocks. A special observation is the occasional presence of unusual Fe-Cr-Ni clusters of tiny blebs containing Au, Ag, Cr, Fe, and Cu, as well as metallic Cu dispersed within the matrix or associated with spinels. A possible link between these metals and meteoritic material, possibly a carbonaceous chondrite, is underlined by high Ir, Pd, Pt, Ru, and Rh values. Our analyses, including PGE and Os/Os isotopes, and the metallic Fe-Cr-Ni clusters give evidence that relict material of the bolide appears to be present in the Chicxulub suevite.

MEASUREMENTS OF NICKEL VAPOR PRESSURE AT HIGH TEM-PERATURE

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Introduction: High temperature processes (near 2000 K) played a large role in the inner regions of the early solar nebula. Unfortunately, much, if not all, of the data for the vapor pressures of refractory metals such as Ni or Fe does not cover the desired temperature range. As a result, extrapolations are needed for the higher temperatures of interest to meteoriticists. These extrapolations can be complex due to contributing factors such as oxygen fugacity or the presence of hydrogen gas [1]. Following the work by [2], we will measure the nickel vapor pressure at temperatures from 1200 to approximately 2000 K in a vacuum. Previously, the highest temperature at which this pressure was measured did not exceed 1600 K. Fig. 1 shows published data for nickel vapor pressure [3]. We will measure the nickel vapor pressure at these results at this meeting.

Experiments: We measure vapor pressure by using a commercial Thermo-Cahn Thermogravimetric system capable of vacuum operation to 1975 K. It is capable of measuring mass loss with microgram accuracy provided that the sample plus cell is 100 g or smaller. We will determine the mass loss rate of pure nickel metal under vacuum from 1100 to 1975 K. The metal will be placed in a simple effusion cell (constructed of alumina) that contains a small hole for vapor escape. The temperature and mass loss are recorded simultaneously. Experimental details are given in Ferguson et al. (2003) [4].



Fig. 1. Published nickel vapor pressure data [3]. The symbols represent different experiments dating from 1914 to 1960. We will extend the nickel vapor pressure data set to higher temperatures near 2000 K.

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ORIGIN OF SILICATE INCLUSIONS IN THE MILES (IIE) IRON: MINIMAL PARTIAL MELTING, MAXIMAL FRACTIONAL CRYSTALLIZATION

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Introduction: Twelve silicate inclusions in the Miles IIE iron meteorite were studied using SEM, EMP, and LA-ICPMS techniques to show their petrogenesis. Previous workers suggested that silicates in Miles formed by the partial melting of a precursor with H chondrite affinity [1–4], either as a result of impact shock on an undifferentiated parent body [2–3], or by the injection of molten iron into the crust of an already differentiated body [4].

Petrology: The main phases in the inclusions are clinopyroxene (Cpx, $Wo_{39-42}En_{46-50}$), orthopyroxene (Opx, $Wo_{2-4}En_{73-79}$), and plagioclase (Plag, $Ab_{85-96}An_{12-1}$). Pyroxene is often euhedral or glomerocrystic. Plag generally encloses pyroxene grains, implying that it usually crystallized after pyroxene. Silica polymorph and K-feldspar are accessory phases often intergrown with one another in late-crystallizing mesostases. Cl-apatite, merrillite, schreibersite, Si-polymorph, and iron-poor pyroxene are found at inclusion margins, suggestive of redox reactions occurring between the silicate and metal [2, 5]. At inclusion edges, metal often fills spaces between pyroxene grains, implying that the metallic host was liquid.

Although major-element abundances in pyroxene are relatively uniform within and between inclusions, Cpx grains have Ti-rich, Al-poor margins. This implies behavior of Ti and Al as incompatible and compatible elements, respectively, during cotectic fractional crystallization of Cpx and Plag [2]. Divalent cations (Ca, Fe, Mg, and Mn) in Opx and Cpx are not appreciably zoned, unlike other cations (Na, Cr, Al, and Ti), which can be explained by preferential diffusive re-equilibration of divalent cations.

Trace-element data provide evidence that partial melting and closedsystem fractional crystallization played important roles in the evolution of the inclusions. Abundances of incompatible elements show large variations compared to slightly compatible elements. In Cpx, for example, CInormalized abundances range from ~1–6 for La and ~5–26 for Yb, but only from ~3–5 for Cr and ~5–7 for V. Moreover, Cpx shows a large negative Eu anomaly, which deepens with increased REE abundances. This suggests that Plag co-crystallized with Cpx, in agreement with the EMP Al data. For Plag, CI-normalized REE abundances are generally low (~.01–1), except for positive Eu anomalies (~.8–13).

Trace-Element Model: We have modeled trace-element abundances assuming equilibrium partial melting of an H chondrite precursor followed by fractional crystallization of the resulting silicate liquid. Our results suggest that the degree of partial melting was low (\sim 7%), much less than the 25% inferred by [1, 2, 3], and less than the 10% estimated by [4]. Subsequent fractional crystallization must have been extensive to account for the large variations in abundances of incompatible elements. The melt compositions in equilibrium with the analyzed Plag are not the same as those calculated for the pyroxenes. This can be explained by the breakdown of an earlier generation of more calcic Plag to form albitic Plag and phosphate during the last stages of crystallization, consistent with the redox reactions proposed by [2] and [5].

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Following a description of the probable occurrence of cosmic spherules [1], Deutsch, et al. [2] have reported the discovery of micrometeorites (MM) in the approximately 1.3 Gyr old (Jotnian) Satakunta Sandstone, SW Finland. More than 100 MM were hand-picked from 286.9 g of the 63-250 µm grain size fractions, which have been prepared by crushing, sieving, and using heavy liquid and magnetic techniques from highly siliceous, red sandstones. The material was sampled in the fall of 1996 mostly at the locality of Murronmäki (61°5'36.4"N, 22°17'18.8"E). Mineralogical-petrographic [2, 3], Cr/Fe, Co/Fe, Ni/Fe, Ir/Fe [4], and δ^{18} O data [5] provided evidence for the cosmic origin of these spherules; although, one published olivine analysis [2] later turned out to be from a micrometeorite of a different collection [6]. To better constrain the "occurrence of fossil MMs," we collected more than 700 kg sandstones in the 1998/9 field campaign, followed by mineral separation and sedimentological studies of the Satakunta sandstone [3]. Yet, not a single additional MM was found in the ≈14,000 g of the 63-250 µm fractions, which included all remnants of samples used by [2]. The total mass of processed sandstone exceeded one metric ton [3]. Re-analysis of the original Satakunta samples [1] showed that these spherules are not of extraterrestrial origin but probably of industrial origin [3]. We state that the "Satakunta MMs" recovered from grain size fractions and published by [2] were NOT an integral part of the sandstone samples, and in the commonly used sense, they are not a contamination either (for details, see [3, 7]).

Outlook: This result prompted a detailed investigation [3] of other localities, either claimed to contain cosmic spherules or discussed as potential host material for fossil MM (e.g., Devonian limestones, Triassic evaporates, Jurassic schists, and radiolarites). Except for sands from the Lybian Desert, all sediments turned out to be barren of cosmic spherules [3]. Based on this result, we suggest re-evaluation of all published occurrences of "fossil MM."

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BULK CHEMISTRY OF NEUSCHWANSTEIN (EL6)

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Introduction: Neuschwanstein (EL6) fell in Bavaria in April 2002. Its fall was recorded by the European Fireball Network (EN), which led to its recovery 3 months later. The calculated orbit for Neuschwanstein is identical to that of Pribram (H5), which led to speculations about the existence of meteorite streams [1]. However, a common origin for both meteorites can be excluded based on their distinct classification. Neuschwanstein is a typical EL6 chondrite [2, 3] that shows only minor effects of weathering. Preliminary data of its bulk composition were published in [3]. Here, we present new data for S, C, and halogenes.

Bulk Chemistry: Previously, we showed [3] results for lithophile and siderophile element abundances in Neuschwanstein compared to average EH and EL chondrite compositions, which are mainly based on falls [4]. Lithophile element abundances clearly follow the element abundance trend typical of EL chondrites. As for other EL chondrites, Neuschwanstein has a bulk composition characterized by a lower La abundance if compared to other refractory element abundances, by minor depletions in K and Na, and by a low Mn/Mg ratio. EL chondrite falls show a wide range in Mn/Mg ratios, indicating successive loss of moderately volatile Mn. In addition, Neuschwanstein has a very low Zn concentration (<12 ppm) which is a characteristic feature for all EL chondrites. Average EH chondrites are Fericher and contain more metal than EL chondrites, as reflected by high abundances of siderophile elements. Neuschwanstein has moderately volatile siderophile element abundances which are higher than in average EL chondrites, reflecting an unusually high metal content.

Sulfur and Carbon: S and C concentrations in EH chondrites are higher than in EL chondrites [4]. Neuschwanstein has high S concentrations of 4.4 wt% and high C concentrations of 0.46 wt%. These concentrations are a factor of 1.3 higher than in average EL chondrites, reflecting the high sulfide and graphite contents in this meteorite.

Halogenes: Silicon and CI normalized abundances of halogenes (Li, F, Cl, Br, and I) are by factors of 1.5 to 4 higher in EH than in EL chondrites, and decrease from Li >Cl >Br >I. Flourine abundances in both average EL and EH chondrites are strongly enriched relative to the other halogenes [4]. Such an enrichment of F is absent in our Neuschwanstein data set and in other enstatite chondrites analyzed in Mainz. Abundances of Cl, Br, and I are like those in average EL chondrites, reflecting the pristine nature of this meteorite.

Implications: Neuschwanstein is a typical member of the EL subgroup based on its bulk chemical composition. Minor differences between Neuschwanstein and averge EL chondrites include a low Mn/Mg ratio and a somewhat higher metal, sulfide, and graphite content than typical EL chondrites. Relative abundances of moderately volatile lithophile and siderophile elements support the interpretation that they are not purely volatility controlled. Abundances of halogenes show no evidence that Neuschwanstein's bulk chemistry was affected by weathering, despite the fact that it was recovered only 3 months after its fall.

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CLASSIFICATION OF A NEW CHONDRITE FROM LAGO DI VALSCURA, ITALY

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Introduction: In August 1995, a mountain excursionist, Mr. Francesco Felice, was walking near a moraine along the shore of the upper Lago di Valscura (coordinates: 44°11′30′′N 7°12′01″E) in the Argentera mountain group, near the Terme di Valdieri municipality (Cuneo). He saw a small stone and picked it up because it was the only black stone among a lot of white stones. The man wrote to Mr. Matteo Chinellato, an Italian collector, and sent him the main mass. Mr. Chinellato realized that it was a meteorite and purchased it.

Description: The original total mass of the meteorite was 200 g. Mr. Chinellato owns the main mass weighing 77.4 g. It has a pyramidal shape and shows a fusion crust covering 90% of the specimen, with traces of shock fractures. Its dimensions are $6 \times 5.2 \times 4.5$ cm. The main mass has been cut on one side to provide a sample for analysis. On this side, its chondritic texture can be easily seen, with metal grains scattered in a gray-brown silicate matrix.

Electron microprobe analyses indicate an iron content of olivine and pyroxene consistent with an H chondrite (Fa = 18.95 mol%, Fs = 16.43 mol%, Wo = 1.43 mol%) [1]. Olivine and pyroxene compositions are homogeneous either inside and outside chondrules, pointing to a rather equilibrated petrologic type.

Metal grains have a kamacitic composition and sulphide grains are composed mostly of troilite. Some relict chondrules show a barred texture, with an intergrowth of olivine crystals and of feldspar. Minor crystals of hydroxylapatite and of chlorapatite have been found inside chondrules (Fig. 1).



Fig. 1. SEM-BSE image of a relict barred chondrule consisting of feldspar (black) and olivine crystals (dark grey); metal grains (white) show narrow rims of oxides (light grey); in the center a small grain of chlorapatite (light gray).

Textural features (presence of poorly delineated chondrules, absence of glass inside the chondrules) confirm the analytical data, suggesting a high petrologic type. Moderate oxidation (20–60% of the metal being affected) indicates a rather low weathering grade (W2) [2]; undulose extinction and microfractures of olivine crystals point to a rather high (S4) shock stage [3].

Conclusions: Based on mineralogical and chemical data, the meteorite is classified as an H5 chondrite. We propose to name it "Lago Valscura," after the location in which it was found. Further investigation will clarify the exact date and time of the find.

This meteorite constitutes the 32nd meteorite found in Italy, the 22nd chondrite, and the 5th of the H5 type.

The type specimen weighing 22.1 g is deposited in the Museo di Scienze Planetarie della Provincia di Prato (MSP), Prato, Italy.

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PLUTONIUM-XENON SYSTEMATICS OF ANGRITES

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Introduction: Angrites are igneous meteorites that crystallized very early in the solar system, ~10 Myr after CAIs, as also implied by the presence of now extinct short-lived radionuclides such as 53 Mn, 146 Sm, and 244 Pu [1]. Fission Xe was used to calculate 244 Pu- 136 Xe-retention ages of eucrites relative to that of Angra dos Reis (AdoR) [2]. AdoR has an absolute Pb-Pb age of 4557.8 Myr (see [1]). Most eucrites, being as old as angrites, experienced various parent body processes leading to ages ranging from ~20 Myr before to ~100 Myr after AdoR [2]. Angrites, however, remained largely unaltered after differentiation. Here, we examine whether Xe isotopic characteristics allows us to determine an age sequence for angrites.

Experiment: We measured the Xe isotopic composition for the recent finds Sahara 99555 and D'Orbigny (details in [3]) and re-examined data for other angrites [4–8]. Two methods are used to obtain Pu-Xe-ages. Method 1 assumes ²⁴⁴Pu/¹⁵⁰Nd to be constant in the early solar system [9]. However, LEW 86010 implied some variations [5]. Thus, we also applied method 2 using spallogenic ¹²⁶Xe as a proxy for Nd, thus, reducing distribution effects of Nd [2].



Fig. 1.

Results: Results from both methods are shown in Fig. 1. Within large uncertainties (1 σ), both methods yield generally similar retention ages, scattering around the reference age of AdoR. However, Sahara 99555 and D'Orbigny show significantly older ages, apparently ~85 Myr prior to CAI formation. This might indicate problems with the assumed [Ba]/[REE] ratios, variations in the initial ²⁴⁴Pu/¹⁵⁰Nd, a varying production of ¹²⁶Xe from Nd relative to all REE, an unusually high ²³⁸U content in the respective sample, or fission Xe contributions from an unknown precursor.

The discovery of 2% excess on ²³⁵U in D'Orbigny glass, associated with an apparent Pb-Pb age of 4.7 Gyr [10], possibly originating from the decay of ²⁴⁷Cm ($T_{1/2} = 15.6$ Myr), might indicate that angrites could, indeed, contain remnants of an unknown radionuclide. The ongoing analysis of fission Xe in the D'Orbigny glass will address this issue.

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COMPARISON OF THE SOLAR SYSTEM DUST CLOUD TO DUST IN CIRCUMSTELLAR SYSTEMS

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Introduction: Infrared observations from satellite have revealed signals of circumstellar dust for a high percentage of nearby stars. The dust particles are not a remnant of the star formation but, rather, are produced by planetesimals in these systems, which are referred to a circumstellar debris disks. The existence of planets is observed or assumed for at least some of these systems. The sources of these particles, their dynamical and collisional evolution, and the evolution of their material properties are studied in comparison to the solar system dust cloud.

Dynamical and Collisonal Evolution: The dust is continuously replenished either by collisions between asteroidal objects or by the activity of comet-like bodies. The major effects to determine the overall distribution of dust in circumstellar systems are stellar gravity and radiation pressure, including the Poynting-Robertson effect and dust fragmentation by mutual collisions. The size distributions are influenced by collision fragmentation and radiation pressure force that ejects small particles from the disks, the latter depending on size, structure, and material composition of the grains. Based on model calculations for the radiation pressure force [1] for particles of different structure and composition, we estimate the size spectrum of dust particles and the Poynting-Robertson lifetime for selected cases of circumstellar disks. While the lifetime for small dust particles in the solar system is limited by the Poyting-Robertson effect, we show that, for the studied systems, collisions yield the major limitation.

Particle Properties Material **Evolution:** and Astronomical observations reveal the spectral variation of the dust thermal emission. These emission features depend, among other effects discussed in a different presentation [2], on the mineralogical composition of the dust particles and, especially, the identification of amorphous and crystalline materials reveals the thermal history of the dust particles. But, the lack of spatially resolved data prevents us from directly measuring the evolution of the dust material within a given system. Observations also suggest the existence of a gaseous disk around these stars. Processes to influence the gas component are the activity of planetesimals, sublimation of dust grains, and dust surface reactions. These are discussed in comparison to the dust properties.

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UNDERSTANDING THE I-XE SYSTEMATICS OF THE MARTIAN MANTLE

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Introduction: The presence of ¹²⁹I-produced xenon in the martian atmosphere and its absence in the mantle (Chassigny, [1]) is explained by invoking "early removal" of iodine from the martian interior and "large" initial xenon concentration for Mars [2].

I-Xe Systematics: Iodine being a volatile element, it is not easy to assess the initial concentration for a growing planet, which controls the evolution of 129 Xe/ 132 Xe. Dreibus and Wänke [3] derive an initial I concentration of 32 ppb using the correlation with La (a refractory lithophile element) and assuming a CI chondritic La concentration for Mars. This (La) is up to a factor of 1.3 lower than those required by precursors predicted by other models of Mars [4].

Planetary differentiation $(13 \pm 2 \text{ Myr after the solar system, [5]})$ on Mars, which formed core, mantle and perhaps the crust, may be linked with the 'early removal' of I from the interior. If this event efficiently flushed the martian mantle of its I so that subsequent I-decay did not significantly affect its ¹²⁹Xe/¹³²Xe ratio, then the present Chassigny-like signature [1] should be a result of the I-decay until this time $(13 \pm 2 \text{ Myr})$. Fig. 1 presents the amount of ¹³²Xe required (by this decay) to maintain a Chassigny-like ¹²⁹Xe/¹³²Xe ratio (the hatched region) in the mantle. An initial I concentration of 32 ppb [3] requires the mantle to have $\sim 2 \times 10^{-8}$ ccSTP/g of ¹³²Xe. Although consistent with the typical concentrations of 4×10^{-8} for CI and 2×10^{-8} for enstatite chondrites (e.g., [6]), this concentration is a few orders of magnitude higher than the highest ¹³²Xe measured in any martian meteorite [1]. Similarly, the initial I concentration is from 3 to 16 times lower than the expected concentrations in the predicted chondritic precursors of Mars [4]. Loss during accretion is difficult to accommodate with a near retention of xenon (more mobile than I) and the K isotopic data [7].



Fig. 1. Evolution of 129 Xe/ 132 Xe as a function of the concentrations of 132 Xe and I in the martian mantle until 13 ± 2 Myr.

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LATE I-XE AGES OF SILICATE CLASTS (CHONDRULES) FROM

GUJBA AND HAH237

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Introduction: Gujba and Hammadah al Hamra 237 (HaH 237) are both members of the metal-rich carbonaceous chondrite CR clan [1, 2] and have been grouped together as CB chondrites [2, 3]. Differences in petrography, such as the size of chondrules, led to the designation of Gujba as CB_a and HaH 237 as CB_b [2, 3, 7]. It has been suggested that zoned FeNi metal grains in HaH 237 formed by direct condensation from a hot gas (1–50 × solar dust/ gas ratio) in the nebula, as did metal-free chondrules [4] (the chondrules formed before condensation of the metal). On the other hand, an impact origin has been suggested for metal grains in Gujba (and CB_a members Weatherford and Bencubbin) to account for the necessary metal-rich vapour [5, 6]; the impact may have been into a metal-rich parent body with composition similar to the CB_b group.

Although impact processing may have occurred over a long time-scale, the nebula is generally thought to have existed for less than 10 Myr, and thus, radiometric dating may distinguish between these scenarios and shed light on whether the components in the CB_a meteorites could be derived from CB_b meteorites.

Experimental: Fragments of several chondrules were separated from small slices of both Gujba (Eric Twelker, www.meteoritemarket.com) and HaH 237 (Natural History Museum, London) and neutron was irradiated for I-Xe dating. Fragments from the same chondrules were mounted and polished for use with an electron microscope. Xenon isotopic analyses were carried out on the RELAX instrument at Manchester University using laser stepped heating; metal-free enstatite from Shallowater was used as an I-Xe reference.

Results: There was no evidence for iodine-derived ¹²⁹Xe in chondrules from either meteorite, but iodine-derived ¹²⁸Xe was observed even in high temperature releases.

Interpretation: Either 1) the I-Xe system was reset during the formation of the chondrules after the substantial decay of ¹²⁹I; 2) there was never any significant iodine in the chondrule, and the observed high-temperature ¹²⁸Xe (¹²⁷I) release is the result of terrestrial or parent body weathering; or 3) the I-Xe system was reset by thermal annealing on the parent body after decay of ¹²⁹I.

Observations of glass in barred olivine chondrules and sharp contrasts in nickel concentrations between adjacent metal grains in Gujba argue against significant thermal metamorphism [7]. There is no textural evidence of terrestrial alteration in the chondrules we analyzed, and thus, no obvious host that might trap terrestrial iodine derived xenon until high temperatures. Accordingly, we favor interpretation (1); that the I-Xe system reflects the high temperature formation of the chondrules and that this must have happened some 100 Myr after the origins of the solar system, strongly favoring an impact origin over nebula condensation.

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POROSITY OF BASALTIC MATERIALS: TERRESTRIAL AND METEORITIC SAMPLES

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In our studies to learn how meteorites are lithified, evolve with time, and are transported the Earth, we have used meteorite porosity to constrain the internal structure of asteroid parent bodies. We have been using a computerized point-counting system to measure void spaces visible in SEM images of ordinary chondrite meteorite thin sections, which are then compared with reported hand-sample porosity measurements [1].

We have found that the amount and type of porosity varies with meteorite type, but across a much narrower range than might be anticipated [2]. For ordinary chondrites, we have found that thin section and hand specimen porosities are usually equivalent, and we can conclude that most of the porosity found in ordinary chondrite hand samples can be accounted for by the microcracks seen in the thin sections and is probably not an artifact of the process of making the thin section [3].

Questions concerning the emplacement of the microcracks remain. Are shock-induced microcracks emplaced during the event that ejects the meteorite from the parent body or during the impact of the meteorite with the Earth (either with its atmosphere, or upon hitting the ground)? How does the porosity in meteorites on Earth compare with that of the material while it is still in its parent body? The answer to the first question could be addressed by measuring the microcrack porosity of a material similar in nature to meteoritic material that has not experienced ejection, transport, atmospheric entry, and impact on the surface of the earth. The natural material on which to make these measurements would be a basalt. Preliminary information for a basalt shows a porosity in a range similar to that observed for basaltic meteorites (Table 1).

To answer the second question, samples from the same location that have been collected in situ and have also experienced ejection, transport, entry, and impact need to be compared. The type of sample that would fit this category unequivocally are lunar materials. Materials exist that have been collected directly from the Moon that can be compared to materials that have experienced transport. Preliminary work has been done, but this question needs to be more extensively studied with a broader range of samples.

Meteorite	Туре	Microcrack Porosity
Juvinas	Eucrite	3.3%
Bishopville	Aubrite	8.2%
Norton County	Aubrite	4.9%
Dar al Gani 400	Lunite	3.6%
Dar al Gani 476	Shergottite	2.9%
Terrestrial Basalt	-	2.5%
61181	Agglutinate	2.1%

Table 1. Porosity measurements in basaltic samples.

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POSSIBLE ORIGINS OF TRAPPED NOBLE GASES IN CHONDRULES

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Introduction: Chondrules have a simpler history than planetary bodies, and an understanding of the origin of noble gases and other volatile elements trapped within chondrules may allow a better understanding of planetary volatile inventories. The data available for chondrules from ordinary chondrites (e.g., [1, 2]) suggest that the trapped gas is much heavier than solar and is more similar to the Q component. High abundances of "subsolar" gases in chondrules from the enstatite chondrite Y-791790 have been suggested to have arisen from implantation of solar gases into chondrule precursors, followed by partial diffusive loss [3], but may also, simply, be due to mixing between solar, Q, and air [4].

We have started a program to measure noble gases in individual chondrules, and to provide a framework to interpret our results, have been exploring simple physical models that might connect known reservoirs (e.g., solar, Q) to the observed gas in chondrules.

Modelling: Equilibration of molten chondrules with a transient atmosphere cannot explain the concentrations observed in chondrules unless rather high partial pressures of the noble gases are assumed (corresponding to total pressures of ~10 atm for solar composition). Cryo-adsorption of noble gases onto fine-grained precursors can provide high specific concentrations and will also favor the heavy noble gases. Accordingly, we have made calculations for a model of adsorption onto dust followed by very rapid melting and then diffusive loss as chondrules cool. The, initial results show that this can produce elemental ratios similar to those observed in ordinary chondrite chondrules, but we have not yet found a good match for the "subsolar" composition. However, even within this simplistic model there is a wide parameter space exists to explore (e.g., adsorption temperature, material, grain size, cooling rate, external partial pressures), and the appropriate coefficients (solubility, adsorption coefficient, diffusion coefficient) are poorly known.



Fig. 1. Effects of adsorption by dust at 190 K followed by diffusive equilibration of a molten chondrule with a solar gas at 10^{-3} atm. Different lines reflect different initially adsorbed concentrations (e.g., due to grain size).

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LARGE PLATES OF ANORTHITE-OLIVINE INTERGROWTHS IN THE D'ORBIGNY ANGRITE

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Introduction: The shape, structure, and texture of D'Orbigny and its mineral and bulk chemical compositions indicate an unusual genesis under changing redox conditions [1–3]. Empty shells, large plates, very high porosity, druses with augite and abundant glasses are outstanding peculiarities of this rock. Here ,we report on a study of a huge plate consisting of anorthite-olivine intergrowths.

Results and Discussion: The anorthite-olivine plate, 12 mm long and 200-800 µm thick, crosscuts the dense lithology of the investigated sample D'Orbigny G (PTS, NHM, Vienna). The center of the plate consists of large anorthites that are intimately intergrown with mostly anhedral olivines (up to 100 µm), commonly in a graphic way, and rare euhedral Al-Mg-Fe spinel. At the surface of the plate, subhedral to euhedral anorthite and anhedral olivine crystals (both >300 µm in size) form abundant off-springs of short branches. The interstitial space outside the plate contains large augite-hedenbergite and olivine-kirschsteinite with sulfides and ulvöspinel. Anorthite is chemically pure, olivine in the plates is mostly ~Fa₃₅La₁—rarely metasomatized to Fa₈₀La₁₉ as is common outside the plate, and spinel is Cr₂O₃-poor (7.5 wt%) but rich in FeO (22 wt%). Trace element (TE) contents of all phases are high and variable. In particular, olivines have highly variable TE contents (Fig. 1) with olivines inside the plate being much poorer in TEs than those outside [4]. The trapped olivines indicate an origin from a system that was enriched to about 10 \times CI in Sc, Sr, Nd, and Eu, about 20–50 \times CI in the HREE and >100 × CI in La, Ce, and Nb (partition coefficients from [5]). The latter two groups of elements are far out of equilibrium between olivine and angrite bulk. The first group seems to be in equilibrium as are the elements V, Mn, Cr, and Co. TEs have high (2-3 × CI) abundances in late olivines, except Sr, and are far out of equilibrium with the bulk rock, except for V, Mn, Cr, and Co. This situation leaves us with the following scenario: anorthite-olivine intergrowths precipitated from a fluid, covered spheres of an unknown, now vanished mineral, and formed large freely floating plates. A change in redox conditions caused the phase constituting the spheres to decompose, ultimately leaving hollow shells. This process liberated large amounts of TEs and Ca, and consequently, late olivines and augites, kirschsteinite, and hedenbergite grew from an environment very rich in TEs and Ca. Therefore, it is possible that CaS, a major host phase of TEs under reducing conditions [6], was constituting the spheres. The unfractionated pattern, similar to that of some olivines of carbonaceous chondrites [7-9], suggests a reservoir with chondritic relative TE abundances.





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MINERALOGY AND NOBLE GAS SIGNATURES OF VIGARANO METEORITE: EVOLUTION OF PLANETARY SURFACE MATERIAL ON CV PARENT BODY

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Introduction: The Vigarano CV3 chondrite is a breccia and contains clasts that suffered aqueous alteration [1, 2, 3]. In this study, we performed mineralogical and noble gas studies on the Vigarano meteorite to elucidate the evolution of the surface material of its parent body.

Results and Discussion: Texturally and mineralogically, there are two types of lithology in the matrix: porous matrix that includes abundant lathshaped olivine crystals and compact matrix that consists of fragmental materials with interstices filled by sub-µm particles. There are sharp boundaries between the two types of matrices. However, it is interesting that there are also places where these two types of matrices merge into each other. These two types of matrices are basically anhydrous with minor amounts of ferrihydrite and phyllosilicate [4]. On the other hand, dark rims around chondrules and dark clasts in the matrix contain abundant phyllosilicates. Most of them have about 1.0 nm lattice fringes, which indicates that saponite is dominant [3]. Synchrotron radiation X-ray diffraction patterns of these phyllosilicate-rich materials do not show obvious (001) peaks of saponite although the (001) fringes can be observed by TEM. This suggests the low crystallinity of saponite. The mesostases of chondrules enclosed by the dark rims contains interlayered mixtures of phyllosilicates with about 1.0 nm and 1.4-1.5 nm lattice fringes. Their chemical compositions suggest that they are a mixture of Na-bearing phlogopite and chlorite.

Laser-microprobe noble-gas analysis [5] was performed on thin Vigarano slices. The results clearly indicate that the noble gas compositions reflect textural differences: the porous matrix contains primordial noble gases but lacks solar gases, while the compact matrix contains both solar and primordial noble gases. Ne isotopic ratios of the porous matrix are plotted along the Ne-A and Ne-cosmogenic mixing line, while those of the compact matrix are plotted close to the Ne-SEP and Ne-cosmogenic mixing line. ²⁰Ne and ⁴He concentrations in the compact matrix are higher than those in the porous matrix due to the presence of solar gases, but the concentrations are much lower than those in other chondrite regolith breccias (e.g., [5]). The low abundance of solar gases implies: 1) short-duration exposure to solar wind; 2) dilution of solar-gas concentrations by the addition of materials depleted in solar gases; and 3) loss of solar gas due to later thermal metamorphism and/or aqueous alteration. Although it is indicated that the compact matrix once existed on the surface of the parent body, processes other than simple mechanical gardening in the regolith must be considered to explain the gradual textural change between the porous and the compact matrix, and the low solar-gas abundance in the compact matrix.

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COMPARISON OF THE HYDROGEN ISOTOPIC COMPOSITIONS OF ANTARCTIC MICROMETEORITES FROM THE FRENCH AND JAPANESE COLLECTIONS

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Introduction: The flux of modern extraterrestrial matter on Earth is dominated by the accretion of small objects, in the size range of micrometeorites (~200 µm). In the past, micrometeorites could have significantly contributed to the budget of volatiles on the early Earth (e.g., [1, 2, 3]). The isotopic composition of water hydrogen in Antarctic micrometeorites (AMMs) extracted by our team from Cap-Prudhomme (CP) blue ice fields shows an average value of D/H = 154×10^{-6} , which matches well with that of terrestrial oceans [4]. We report new measurements of D/H ratios of Antarctic micrometeorites collected by the 39th Japanese Antarctic Research Expedition in Kuwagata Nunataks (hereafter abbreviated as Kuwa-AMMs).

Results and Discussion: The D/H ratios of this new set of AMMs were measured with the CRPG (Nancy) Cameca ims3f ion microprobe following the procedure previously used for CP-AMMs [4, 5]. The precision of the analyses is ~40‰. The D/H ratios range from 47×10^{-6} to 178×10^{-6} with an average value of D/H = 140×10^{6} (Fig. 1). The distribution of D/H ratios in Kuwa-AMMs is slightly displaced toward lower values with regard to that of CP-AMMs (Fig. 1). The average D/H values of the two populations seem to be significantly different, but we cannot disregard a possible statistical effect.



Fig. 1. Frequency distribution of D/H ratios in two collections of Antarctic micrometeorites (AMMs): Cap Prudhomme AMMs [4] and micrometeorites collected by the JARE 39 consortium in Kuwagata Nunataks #3 (Kuwa AMMs, see [6]). The distribution for Kuwa AMMs was split depending on the textural type of micrometeorite: fine-grained (Fg) or scoriaceous (Sc).

Acknowledgements: We thank NIPR and especially Dr. H. Kojima for kindly allocating an unprocessed sample (Kuwagata #3) of the JARE 39 collection to us.

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SPACE WEATHERING BY HIGHLY CHARGED HEAVY IONS IN THE SOLAR WIND

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Introduction: Interaction between the solar wind and surface regolith is the most importent phenomenon of "space weathering" on asteroids. The ability to understand the nature and magnitude of physical and chemical changes induced by these interactions is hampered by the variability and complex nature of the solar wind.

Sputtering: Kinetic energies of solar wind ions are, on average, ~1 keV/amu (440 km/s), which is in the range of the highest sputtering efficiency. Sputtering by H⁺, which accounts for ~85% of the total kinetic energy ($E_{k, tot}$), is relatively inefficient. Thus, it is usually assumed that He²⁺ (~13% of $E_{k, tot}$) accounts for most of the observed space weathering effects. Only about 2% of $E_{k, tot}$ is carried by heavy ions ($Z \ge 6$), but spacecraft measurements have shown [1] that these also carry ~1 keV each in potential (ionization) energy. For targets with high electron conductivity (metals and semiconductors), the charge state of the impinging ion does not affect the sputtering efficiency. However, for insulating targets, considerable additional mass reduction due to "potential sputtering" [2] is observed. Experiments with Ar^{q+} (q = 1, 3, 8, 9) and Xe^{q+} (q = 9, 14, 19, 25) ions on SiO₂, Al₂O₃, and MgO targets have shown that at least 2 different mechanisms are involved [3]. These mechanisms are termed "defect-mediated desorption" and "kinetically assisted potential sputtering."

Implications for Asteroid Surfaces: Potential sputtering has mostly been studied at kinetic energies lower than those of solar wind heavy ions. In this regime, ionic charges typical of solar wind ions considerably increase the sputtering efficiency over +1 ions. A rough estimate can be obtained by expressing the sputtering yield as a fraction of the dissociation energy of the target (typically, 4–6 eV/atom). In potential sputtering, several percent of the total (potential + kinetic) energy of the incident ion are converted to target dissociation, while for kinetic sputtering alone, the fraction is closer to 0.1–1%. This makes it likely that heavy ions in the solar wind make a higher contribution to space weathering effects than previously thought. Also, potential sputtering of oxide phases preferentially removes oxygen, which could be a factor in the production of nanophase metallic Fe on the surface of regolith particles.

Some caveats to applying experimental results to the asteroid environment are: 1) experiments have so far been limited to a few simple oxides and have not been carried out at solar wind kinetic energies; and 2) oxide surfaces prepared in a laboratory tend to be O-enriched, which changes their sputtering characteristics compared to asteroid regoliths exposed to a space vacuum.

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TRAPPED NEON IN THE MARTIAN METEORITE SAU 005 R. K. Mohapatra,¹ S. P. Schwenzer, and U. Ott. Max-Planck-Institut für Chemie, Postfach 3050 Mainz-55020, Germany. ¹Present address: Department of Earth Sciences, University of Manchester, M13 9PL, Manchester, UK

Introduction: Neon data for martian meteorites apparently show a two-component mixture of cosmogenic Ne and a trapped component [1]. But the ²⁰Ne/²²Ne of this trapped end-member is not well constrained. Viking missions were unable to measure the neon isotopic ratios, while data from martian meteorites point to all possible values ranging from "planetary" to "solar." The dominance of cosmogenic neon and the presence of terrestrial contamination are two major problems, which may be minimized by using stepped heating data on selected phases.

Trapped ²⁰Ne/²²Ne in SaU 005: We have analyzed various samples of SaU 005 (the martian meteorite from Oman) for their nitrogen and noble gases as part of an ongoing study of martian meteorites [2]. The stepped temperature neon data for these samples provide a chance to investigate the nature of the trapped neon in martian meteorites. On a neon three-isotope plot (Fig. 1), they define a trend that passes through the cosmogenic Ne and a trapped end-member apparently different from air.

Trapped 12 Surface Interior GL-1 \wedge GL-2 ÷ Air 9 ²⁰Ne/²²Ne glass data only 6 3 0 0.25 0.50 0.75 0.00

Fig. 1. Plot between ²¹Ne/²²Ne and ²⁰Ne/²²Ne for the stepped heating data from SaU 005. The shaded region represents the uncertainties in the regression parameters obtained from the glass (GL) data.

A linear regression [3] on the stepped heating data for the glass (GL 1 and 2) samples yields an intercept of 11.3 ± 0.2 and a slope of -13.0 ± 0.3 , while the corresponding values obtained for the bulk data do not distinguish the trapped component from air. This may be explained by the presence of larger air contamination (in the form of secondary phases) and/or possible Na-spallation [4]. Using a ²¹Ne/²²Ne ratio of 0.03, we derive a trapped ²⁰Ne/ 22 Ne of 11.0 ± 0.3 from the glass data.

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CADMIUM ISOTOPE FRACTIONATION IN ENSTATITE AND **CARBONACEOUS CHONDRITES**

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Introduction: Large inorganic mass-dependent Cd isotope fractionations appear to result only from evaporation/condensation processes [1]. Cadmium isotope fractionations in unequilibrated ordinary chondrites [1, 2, 3] probably resulted from evaporation and condensation of Cd on the parent bodies, likely due to thermal metamorphism [1]. Here, we report Cd isotope fractionations in enstatite and carbonaceous chondrites and in refractory materials from Allende.

Methods: A NuPlasma MC-ICPMS in Zürich was used for the analyses. The external reproducibility is $\pm 1.1 \text{ }\varepsilon$ Cd/amu (2 standard deviation; [1]). The notation denotes the deviation of the sample Cd isotope composition from the in-house standard in parts per 10,000 per atomic mass unit (amu). Positive values denote heavy isotope compositions.

Results and Discussion: Two unequilibrated EH3 and two strongly metamorphosed enstatite (EL6 and E7) chondrites display heavy Cd isotope compositions (+8.4 to +39.2 cCd/amu) with respect to the standard and the Earth (Cd/amu $\sim 0 \pm 1$). However, isotope fractionations are not observed in the volatile, element-rich EH4 chondrites. Aqueously altered carbonaceous chondrites (CI, CM2, CR2, C2 ungr.) and the Allende CV3 chondrite show no Cd isotope fractionations. One CV3 (Leoville) and two CO3 chondrites, however, display ¿Cd/amu values between +3.1 and +11.1. Three CK chondrites of type 3 to 5 show small but resolvable variations from -2.4 to +1.1 εCd/amu.

It is likely that the part of the solar nebula from which bodies in the inner solar system accreted initially had a homogeneous Cd isotope composition, because most carbonaceous chondrites, EH4 chondrites, and the Earth display identical Cd isotope compositions within uncertainty. The heavy Cd isotope compositions of most enstatite and some carbonaceous chondrites suggests later local Cd volatilization. The Cd isotope fractionations in CO3 chondrites may be due to their mild thermal metamorphism. The CK chondrites form a metamorphic series, but the depletion of Cd and Cd isotope fractionation is less obvious than for CO3 chondrites. The depletion and redistribution due to volatilization of Cd varies between carbonaceous and enstatite chondrite classes and ordinary chondrites. This could be due to physical and mineralogical differences in the parent bodies (e.g., porosity and host mineralogy).

Separated Allende matrix shows no Cd isotope fractionations, but two chondrule separates and a refractory inclusion show light isotope compositions with up to -9.6 cCd/amu. This result is consistent with the light Zn isotope compositions reported for an Allende CAI [4]. The light Cd isotope composition of the refractory inclusion probably resulted from its preaccretionary evaporation/condensation history (see, e.g., [5]). This suggests that the refractory inclusion is an evaporation residue from a volatile-rich precursor material. Cadmium may have survived the evaporation process, because it was locked up in refractory phases (possibly spinel).

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Regression for the Spall. 1.00 ²¹Ne/²²Ne

RE-EXAMINING THE IGNITION REQUIREMENTS FOR POST-IMPACT WILDFIRES AND THE THRESHOLD FOR SIGNIFICANT ENVIRONMENTAL CONSEQUENCES

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Introduction: Local fires can be generated around an impact site by direct radiation from a fireball (e.g., [1]) and over larger (perhaps global) regions by atmospheric heating caused by a reaccreting high-energy, vaporrich plume [2] and possibly extended sheets or rays of lower-energy ejecta. In the case of the 1908 Tunguska blast, which detonated 6–10 km above a Siberian taiga, fires were ignited by a thermal radiation pulse over a 200–500 km² area (e.g., [3]). In the case of the Chicxulub impact event at the K/T boundary, fires may have been generated over a much larger region, generating a globally distributed layer of soot (e.g., [4]) and, possibly, localized deposits of charcoal and related residues in North America (e.g., [5]; cf., [6]). Recent calculations suggest the Chicxulub fires may have been ignited in some areas of the world and not others, because sufficient mass for the atmospheric heating needed for ignition may not have reaccreted above all areas around the globe [7].

Implications: This suggests that the Chicxulub impact event may be near the threshold size event needed to generate globally distributed fires. If so, then the distribution of fires will depend on projectile trajectories (different for each impact event), the position of the impact relative to the geographic distribution of forested continents (also different for each impact), and the mass incorporated into ejected plumes of material (values that are currently based on model simulations, but still uncertain).

It also implies that other parameters affecting the ignition of fires need to be scrutinized in more detail. Spontaneous ignition of wood is typically produced with $40-70 \text{ kW/m}^2$, depending on the species of tree, its moisture content, and the time it is exposed to heat. If there is an ignition source (e.g., lightening), then only 12 kW/m² may be needed. Forest litter (e.g., pine needles) may be easier to spontaneously ignite than wood when temperatures are in excess of 300° C, but not necessarily at lower temperatures. Variations in these parameters can have a dramatic effect on the extent of wildfires generated by reaccreting ejecta.

Among relatively small impact events, ignition from the fireball may be more important than ignition from a hot atmosphere created by ejecta. However, the intensity of irradiation energy needed to ignite vegetation is far greater for a fireball source, because the period of radiation exposure is far shorter. Measurements of luminous irradiation effects around nuclear test blasts suggest a factor of 4 to more than an order of magnitude more irradiation energy may be needed, depending on the size of the impact.

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DUST ASTRONOMY

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Dust particles, like photons, are born at remote sites in space and time, and carry information that may not be accessible to direct investigation.

In stellar winds of evolved stars, new dust is formed and is injected into interstellar space. Young stardust is mixed with old heavily-processed diffuse interstellar dust, and is subject to passing supernova shocks and ultraviolet radiation. Dusty clouds emerge. The protostar environment is a fertile ground for solids on all size scales to form—from dust grains to planets. Star formation in cool molecular clouds becomes both a sink of old dust and a source of new dust. Dust in a planetary system is the most processed of the different populations of cosmic dust. Interplanetary dust is permanently replenished by dust ejected from cometary nuclei, the most pristine bodies in the inner planetary system, and released from collisions in the asteroid and Kuiper belts. In our solar system, interplanetary dust exists alongside interstellar dust, which is flowing through the solar system, offering a physical link between our planetary system and the stars.

The dynamics of dust particles is affected by gravitational and magnetic fields. Dust trajectories trace out their radiation, gas, plasma, and dust environments. With accurate dust trajectory measurements, we can derive their place of origin: comets, asteroids, or even interstellar space. From the particles' bulk properties and their chemical composition, we are able to infer properties of the environments out of which the particles were formed and in which they were subsequently altered. The combination of trajectory determination and chemical analyses on the same dust particle is called dust astronomy. Recent developments of in situ dust detectors allow us to combine sensors of these capabilities into a single dust telescope that is carried by a dust observatory satellite in space.

A state-of-the-art dust telescope is capable of providing mass, velocity, physical, and chemical information of individual dust grains in space. Dust particles' trajectories are determined by the measurement of the electric signals that are induced when a charged grain flies through a position sensitive electrode system. High-resolution dust mass analyzers that provide chemical composition of dust particles have been flown on the Halley missions and are currently flying on the Stardust mission. The dust telescope chemical analyzer will have a sufficient mass resolution in order to resolve ions with atomic mass number up to >100 amu. The impact area of the mass analyzer will be 0.1 m^2 .

Targets for a dust telescope are dust from the local interstellar medium, meteor stream dust, cometary, asteroidal, and dust emitted from planets and their satellites.

IDENTIFICATION OF NANOPHASE IRON IN AN H CHONDRITE IMPACT MELT

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Introduction: One of the perplexing questions in planetary science is why there are so few asteroids that spectrally "match" meteorites. For example, many asteroids have interpreted mineralogies consistent with ordinary chondrites. However, the asteroids tend to have reflectance spectra with steeper spectral slopes (redder spectra) than measured meteorites in the visible and near-infrared. This slope difference is believed to be due to the production of nanophase iron in asteroidal regoliths. Nanophase iron particles are formed [1] by the reduction of FeO to metallic iron during impact heating and during implantation of hydrogen by the solar wind.

We have used transmission and analytical electron microscopy (TEM-AEM) to identify nanophase iron particles in an H chondrite impact melt (Dar al Gani 896 or DaG 896). We have also obtained a reflectance and a Mössbauer spectrum of this meteorite. We believe this meteorite has important implications for petrologic and spectroscopic studies of asteroids.

Petrology: DaG 896 has a microporphyritic texture with abundant (~64 vol%) olivine (Fo_{82.5 ± 2.5}) crystals set in a groundmass consisting mainly of Si-rich glass plus quench microlites of pigeonite ($En_{59 \pm 5}Wo_{9 \pm 3}$). There are blebs of opaque phases disseminated within the glass. Chondritic relics (~10 vol%) are spread throughout the igneous groundmass. DaG 896 is interpreted to have formed as the result of whole-rock melting of H chondrite material, nearly complete loss of the metal plus sulfide component, and crystallization without significant igneous fractionation.

Opaque Phases: TEM-AEM investigations allow us to identify and characterize the submicron-sized opaque phases. These opaque phases consist mainly of metal (kamacite, 1.5% Ni) and troilite blebs. Metal blebs are typically found in contact with pyroxene microlites. The metal particles are 150 to 350 nm in size and have an occurrence frequency of ~ 1 per μ m². Troilite particles typically free-float within the glass, are usually a few tens of microns in size, and have an occurrence frequency of ~ 10 per μ m². The metal and sulfide blebs are interpreted as residues from the removal of FeNi-FeS melt from the silicate melt.

Spectroscopy: A reflectance spectrum (0.32–25 μ m) for a sample of DaG 896 was obtained at the NASA/Keck RELAB facility. Its reflectance spectrum in the visible and near-infrared is significantly reddened compared to ordinary chondrites. The analysis of a room-temperature Mössbauer spectrum of the sample finds no detectable Fe³⁺, arguing that its reddened reflectance spectrum is not due to terrestrial weathering.

Conclusions: Dar al Gani 896 appears to be evidence that the formation of impact melts on the surfaces of asteroids can produce nanophase iron particles that can redden the reflectance spectra of asteroids. Studies of impact melts may give us the best insight on the processes that are occurring in asteroidal regoliths.

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¹⁸²HF-¹⁸²W CONSTRAINTS ON THE EARLY EVOLUTION OF THE MARTIAN MANTLE

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Introduction: The extinct 182 Hf- 182 W chronometer (half-life = 9 Myr) is well suited to constrain the timescales of planetary accretion, core formation, and early mantle differentiation. Here, we focus on the ¹⁸²W constraints for the early evolution of Mars and present new W isotope data for the basaltic shergottites DAG 476 and SAU 051. The W isotopes of these two meteorites were analyzed because they display pronounced ¹⁴²Nd anomalies of about 0.8 ɛ units [1], indicating very early silicate mantle differentiation on Mars. Osmium isotope data furthermore indicate that DAG 476 may be derived from a reservoir distinct from the sources of all other Martian meteorites [2]. The ¹⁸²W anomalies reported so far for Martian meteorites correlate with 142Nd anomalies. These meteorites define two distinct groups, one with ϵ^{142} Nd values of 0.25 to 0.9 and ϵ_W values between 2 and 3, and another with chondritic $\epsilon^{142}Nd$ and ϵ_W of about. 0.4 [3, 4]. The latter group represents the primitive Martian mantle, and the ¹⁸²W excess of this group relative to the chondritic ε_W of -1.9 [5, 6] can solely be attributed to Hf/W fractionation during core formation.

Results and Discussion: The ε_W values obtained in this study are -0.3 \pm 0.6 for DAG 476 and 0.8 \pm 0.5 for SAU 051. Despite their pronounced 142 Nd anomalies of about 0.8 ϵ units, these two meteorites have no 182 W excess relative to the primitive Martian mantle. Consequently, these two meteorites represent a third early formed mantle reservoir on Mars. This mantle reservoir must have formed after all ¹⁸²Hf had decayed, but before ¹⁴⁶Sm became extinct. Combined ¹⁸²W and ¹⁴²Nd data, therefore, reveal three stages in the early differentiation of Mars. These stages include core formation at 12 ± 2 Myr and two subsequent mantle differentiation events. To further constrain the timing of these differentiation events, a time integrated partial melting model following the approach of [7] was calculated. The quantitative model constrains the extent of the Sm/Nd and Hf/W fractionations in the Martian mantle and shows that the coupled ¹⁴²Nd and ¹⁸²W excesses of Chassigny, EETA 79001, Lafayette, and Nakhla are best accounted for if their source(s) separated from the primitive Martian mantle between ~12 and ~20 Myr after the start of the solar system. The source(s) of DAG 476 and SAU 051, in contrast, must have formed later, most likely between 50 and 150 Myr after CAI condensation.

The preservation of these early formed mantle heterogeneities suggests that convective mixing in the Martian mantle was limited, and that during the accretion of Mars, there were no late giant impacts later than ~ 15 Myr after the start of the solar system. This is in contrast to the Earth-Moon system that formed at ~ 30 Myr after CAI condensation [5]. The termination of Martian accretion was most likely caused by the growth of Jupiter that probably reached its present mass within less than 10 Myr [8].

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MINERALOGICAL AND MORPHOLOGICAL PROPERTIES OF DUST IN THE LOCAL INTERSTELLAR CLOUD

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Introduction: The solar system is currently immersed in a parsec-scale cloud, which is referred to as the Local Interstellar Cloud (LIC) [1]. While the majority of the LIC is partially ionized hydrogen atoms, the dust comprises 1% of the total mass of the LIC [2]. The mineralogical and morphological properties of the LIC dust can be constrained by considering the elemental abundances of LIC dust and its dynamics in the solar system. In this paper, we summarize our best knowledge of the dust properties.

Elemental Abundance Arguments: The gas-phase abundances of major dust-forming elements are calculated from their column densities through the LIC measured by Hubble Space Telescope. Once the total LIC composition is assumed to be solar, the dust-phase elemental abundances can be derived from the gas-phase abundances and the solar photospheric abundances [2].

Dynamical Arguments: In situ data on the mass and velocity of LIC dust in the solar system measured by Ulysses are used to estimate the ratio β of solar radiation pressure to solar gravity acting on the dust. Numerical calculations of the β ratio give insight into the properties of LIC dust [3].

Summary: Because of the similarity between Mg-normalized elemental abundances of LIC dust and those of solar system dust, we may infer the composition of dust in the LIC from available information on the composition of solar system dust. We suggest a model of LIC dust to consist of magnesium-rich pyroxenes, iron-sulfides, metals, spinels, and organic refractory. Then, the mass ratio of organic refractory to silicate is approximately equal. The β ratio of LIC dust is consistent with an aggregate of submicron-sized grains that have a structure of a silicate core and an organic refractory mantle.

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CONSTRAINTS ON THE AGE OF THE MOON FROM ¹⁸²W

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The decay of ¹⁸²Hf to ¹⁸²W (t_{1/2} = 9 Myr) has been applied successfully as a chronometer to date accretion and subsequent chemical differentiation of planetary bodies (e.g., [1–6]). The recently determined W isotope composition of chondrites [4–6] provides new constraints on the age and origin of the Moon. As a result of early core formation, Earth's mantle (BSE) shows a ¹⁸²W abundance of 1.9 ε units above the chondritic value [4–6]. For lunar samples, strongly positive ε_W values have been reported [1], which, in part, are of cosmogenic origin [3]. For mare basalt 15555, the ¹⁸²W effects from neutron-flux are negligible and the ε_W of 1.3 \pm 0.4 may, therefore, be interpreted to have chronological significance [3]. This sample has a chondritic ¹⁴²Nd¹⁴⁴Nd [7], indicating the absence of early mantle differentiation in its source. The ε_W of 1.3, therefore, can be considered as the W isotope composition of the bulk lunar mantle.

The excess of ¹⁸²W in the lunar mantle can be due to ¹⁸²Hf decay within the Moon or may be inherited from the impactor. In the first case, the 1.3 ε_{W} excess indicates that the Moon formed at 27 ± 3 Myr and, thus, prior to Earth's core formation at 33 ± 2 Myr (using the same Hf/W for the lunar mantle and BSE [8]). This interpretation requires that the lunar and terrestrial mantles started off with identical ¹⁸²W/¹⁸⁴W ratios after the Moon-forming impact. In this case, the BSE value is lower, because radiogenic W was extracted into the Earth's core after formation of the Moon. Identical initial ¹⁸²W/¹⁸⁴W ratios might have been set by effective mixing of proto-Earth and impactor material. This, however, is unlikely given that many of the chemical differences between Earth and the Moon seem to be inherited from the impactor [8]. Alternatively, the ¹⁸²W/¹⁸⁴W of the impactor mantle and BSE might have been similar. Since giant impacts can effectively homogenize the W isotopes [2], the ¹⁸²W/¹⁸⁴W ratio of the BSE was chondritic after formation of the Moon. Identical initial 182W/184W ratios, therefore, are only possible if the impactor mantle had a chondritic W isotope composition prior to its collision with proto-Earth, thus, requiring a giant impact on the impactor just prior to that which produced the Moon itself [2].

If the ^{182}W excess of the lunar mantle is inherited from the impactor, the 1.3 ϵ_W of the lunar mantle can be used to estimate the $^{182}W/^{184}W$ ratio of the impactor's mantle. A contribution of 70–30% from the impactor (e.g., [8, 9]) to the Moon implies $^{182}W/^{184}W$ ratios of the impactor mantle between 2 and 4 ϵ_W . Assuming that the Hf/W of the impactor mantle is similar to that of the lunar and terrestrial mantles, core formation ages of ~25 to ~18 Myr can be calculated.

In summary, W isotopes provide firm constraints that the Moon formed between 24 and 35 Myr. Formation of the Moon at 27 \pm 3 Myr, thus, before core formation in Earth at 33 \pm 2 Myr, requires a giant impact on the impactor just prior to its collision with proto-Earth. If the Moon formation, however, is coeval with the final core-mantle equilibration in Earth, then core formation in the impactor can be constrained to 18–25 Myr. This age is similar to the core formation age on Mars [4], the size of which is similar to that of the proposed impactor [9].

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DATING DIFFERENTIATION PROCESSES IN THE EARLY SOLAR SYSTEM

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The formation of planets from the solar nebula was a multistage process associated with different chemical and physical processes that led to relative enrichment and depletion of elements. Important differentiation processes in the early solar system include: 1) solid matter condensation from the solar nebula; 2) evaporation and recondensation of volatile elements; 3) core formation; and 4) silicate mantle differentiation in planetary bodies. The time, duration, and extent of these processes can be studied using stable and radiogenic isotopes combined with data on element abundances.

The fractionation of the stable isotopes of the heavy and volatile element Cd and the comparison of the isotope effects with Cd/Zn ratios provides evidence for the redistribution of material by evaporation and recondensation processes prior and during the formation of planetesimals.

Analyses of radioactive parent-daughter systems can provide absolute time constraints on fractionation processes. To obtain chronologic information with a time resolution close to 1 Myr, it is helpful to employ systems where: 1) parent and daughter display large fractionation effects; 2) the parent is abundant; 3) the rate of decay is high; and 4) precise measurements of the daughter isotopes are possible. These conditions are best met by short-lived isotope systems. The only long-lived system that can provide such a high time resolution is the paired decay of ²³⁸U and ²³⁵U to ²⁰⁶Pb and ²⁰⁷Pb. This system is only useful if undisturbed and separable phases are available. In this case, it can also be used to calibrate extinct nuclide systems, which provide only relative age information [1–3].

Depending on their geochemical and cosmochemical behavior, the short-lived isotope systems can provide time constraints on specific differentiation processes. One example is the decay of 182 Hf to 182 W (t_{1/2} = 9 Ma). Since Hf is lithophile and W is siderophile, this pair is particularly suitable to date metal-silicate segregation. ¹⁸²Hf-¹⁸²W systematics indicate that the final silicate-metal equilibration occurred on Vesta ~4 Myr, on Mars ~12 Myr, and on Earth ~33 Myr after CAI condensation [2, 3]. Hf and W can be further fractioned by silicate differentiation. If this process occurred in the first 50 Myr, it should result in detectable ¹⁸²W variations in the silicate mantles of planets. Such 182W variations have been detected in samples from Mars [4, 5] and possibly from the Moon [6], but have not yet been found on Earth. Silicate fractionation also modifies the ratios of the two lithophile elements Sm and Nd. If this process occurred in the first few 100 Myr, it should be indicated by 142Nd anomalies. Combined 182W-142Nd data indicate that silicate fractionation on Mars occurred between ~12 and ~20 Myr and most likely between ~50 and ~150 Myr after CAI condensation [4]. The absence of 182W variations in Earth's mantle is consistent with 142Nd data for Archean samples that constrain the oldest preserved silicate differentiation to ~4.46 Ga [7-8]. At this time, ¹⁸²Hf was effectively extinct.

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HIGH PRECISION MEASUREMENTS OF NB/TA AND ZR/HF IN CHONDRITES: IMPLICATIONS FOR THE MASS BALANCE OF NB-TA IN SOLID PLANETS

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Introduction: Mass balance calculations of the major and trace element inventory in solid planets hinge on the precise knowledge of the chondritic compositions as reference values. Recent measurements of Nb/Ta and Zr/Hf in a variety of terrestrial and extraterrestrial materials indicate that Nb is depleted in the silicate Earth, where all major silicate reservoirs have subchondritic Nb/Ta [1, 2]. In stark contrast to Earth, the Nb/Ta of the silicate mantles of Mars and the HED parent body appear to be close to the chondritic value [2]. The chondritic Nb/Ta and Zr/Hf values were long assumed to be ~17.6 and ~36.5, respectively [3]. Here, we report revised chondritic values for Nb/Ta and Zr/Hf based on the analyses of 17 ordinary, enstatite, and carbonaceous chondrites.

Analytical Methods and Results: Nb/Ta and Zr/Hf were analyzed by MC-ICPMS using a mixed ¹⁸⁰Ta-¹⁸⁰Hf-⁹⁴Zr tracer. Niobium was analyzed as Zr/Nb relative to a 99.9% AMES metal solution. External reproducibilities are ±4% for Nb/Ta and ±0.6% for Zr/Hf (all 2 σ). Nb/Ta and Zr/Hf in all analyzed ordinary and enstatite, and most carbonaceous chondrites, yield well defined average values of 19.8 ± 0.6 and 34.2 ± 0.3, respectively. In contrast to all other analyzed groups of carbonaceous chondrites (CI, CM, CK), 4 CV3 chondrites (Allende, Bali, Arch, Axtell) have significantly lower Nb/Ta between 16 and 18. However, Zr/Hf in these CV3 chondrites overlaps with those of the other chondrite groups.

Discussion: The new data indicate that the distribution of Nb-Ta and Zr-Hf in all major chondrite groups (except CV3) is homogeneous to within $\pm 5\%$. While the variations in Nb/Ta are nearly within analytical error, the variations in Zr/Hf are clearly outside analytical error, possibly reflecting sample heterogeneities. The lower Nb/Ta in the CV3 chondrites are most likely caused by an enrichment of refractory components in this group, as suggested by the higher abundance of other highly refractory elements [4]. Nb is probably more volatile than Ta, Zr, and Hf, consistent with experimental evidence [5]. Since CV chondrites are clearly more depleted in moderately volatile elements than Earth and Mars, this meteorite group can be ruled out as a major component in these 2 planets. Based on the results for the other chondrite groups, there is clear evidence that the bulk Earth and Mars have a Nb/Ta of ~20 and a Zr/Hf of ~34. The Nb deficit in the silicate Earth can therefore be ascribed to slighly siderophile properties of Nb at high pressures (>20 GPa) that prevailed in the magma ocean when Earth's core formed. In the silicate portion of Mars, Nb is not depleted due to lower core formation pressures (~1 GPa). The Nb/Ta of the Moon (17.0 \pm 0.8) lies between the values of the bulk silicate Earth and chondrites and can, therefore, be used to estimate the mass fraction of the material in the Moon that is derived from the Mars-sized impactor (chondritic Nb/Ta). Depending on the Nb/Ta of the silicate proto-Earth, the mass fraction of impactor material in the Moon can be constrained to ~50%.

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CHARACTERIZATION OF CARBONACEOUS MATTER IN CARBONACEOUS CHONDRITES FROM THE VIEWPOINT OF THIOPHENIC ABSORPTION OF SULFUR K-EDGE NEXAFS SPECTRA

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Introduction: Various techniques have been applied to the characterization of carbonaceous matter in carbonaceous chondrites.

Some researchers have begun to use X-ray absorption fine structure (XAFS) spectra for the characterization of some extraterrestrial carbonaceous materials, and an aromatic structure was indicated [1, 2, 3]. In this investigation, we observed, however, sulfur, not carbon K-shell excitation XAFS spectra. The carbonaceous matter contains sulfur heterocycles [4], and we intended to evaluate the thermal history of meteorites from the viewpoint of thiophenic absorption.

Samples: 11 CM chondrites (various degrees of aqueous alteration and thermal metamorphism) and Allende (CV3) were studied. 10 CMs and Allende have also been studied by pyrolysis-GC [5]. The samples were powdered and pressed onto stainless plates. The plates were set in the chamber at beamline BL-11B at The High Energy Accelerator Research Organization (KEK), and sulfur K-edge NEXAFS (near edge X-ray absorption fine structure) spectra were observed.

Results and Discussion: NEXAFS spectra of CM chondrites showed sulfidic and sulfate absorption. Thiophenic absorptions with various intensities were also observed. Allende showed sulfidic absorption, however, thiophenic and sulfate absorptions were not observed. Based on the intensity of thiophenic absorption, the samples can be classified into the following four groups: 1) weak absorption: Y-82054, Y-86789, Y-86695, B 7904, and Y-793321; 2) comparable to the sulfidic absorption: Y-791198, Murray, Cold Bokkeveld, and Murchison; 3) depleted in sulfur: A 881458 and A 881334; and 4) Allende. Although group 3 does not correspond to the degree of aqueous alteration or thermal metamorphism, group 1 corresponds to strongly heated chondrites in their parent bodies [5]. Group 2 corresponds to unheated chondrites [5], suggesting that the thiophenic structure of the carbonaceous matter in CM chondrites has been gradually lost during thermal metamorphism. Cold Bokkeveld, which suffered strong aqueous alteration, showed the strongest thiophenic absorption. These observations suggest that sulfur K-edge NEXAFS is a useful tool for evaluating thermal history of chondrites.

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CARBONACEOUS CHONDRITE CLASTS IN THE HALITE-BEARING H5 CHONDRITE ZAG

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Introduction: Zag is one of only two meteorites (both H5) that are known to contain water-bearing halite crystals. This water is the only sample we have of asteroidal fluid and is, thus, of critical importance for examinations of the evolution of water in the solar system and the delivery of volatiles to evolving small bodies as well as Earth itself [1, 2]. Given that these two halite-bearing meteorites are both metamorphosed, it is probable that the halite was contributed by some foreign material. Here, we report foreign clasts within Zag, one of which may be the source of the halite and water.

Zag Clasts—Mineralogy and Petrography: O. R. Norton discovered the clasts on a sawn surface; the two clasts appeared as one measuring 4 mm across. No others have been located. We performed microprobe analyses on grains from both types of clasts.

Clast A: Clast A consists of predominantly fine-grained matrix, consisting of a mixture of serpentine, saponite, magnetite, and pyrrhotite. Set within the matrix are small aggregates of magnetite, pyrrhotite, phyllosilicate and, notably, Ca-Mn-Mg-Na carbonates. The carbonates have very interesting zoning: Mn-rich cores, mantled with Ca-carbonate, and very thin Na-Mg-rich rims.

Clast B: Clast B appears to be an impact melt consisting of thin and skeletal laths of plagioclase floating in a mesostasis with a pyroxene composition. A few fine-grained aggregates float within this clast, and may be residual unmelted material.

Oxygen Isotopic Composition: Samples of each of the clasts yielded these compositions:

-	delta-18	delta-17	DELTA-1
А	23.68	+13.71	+1.41
В	+5.90	+2.74	-0.33

Clast A plots among the CI chondrites, though with a record high DELTA-17 value. Clast B plots closest to CR chondrites.

Conclusions: The oxygen compositions preclude a relation between Clast A and B. Clast A appears to be CI1, though with some unusual carbonate aggregates worthy of future examination. There appear to be Naenrichments associated with these carbonates, which suggests a link between this clast and the halite in Zag.

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Fig.1. BSE image of Zag Clast A; view measures 2 mm across. The largest aggregate (grey) is carbonate.

CATHODOLUMINESCENCE AND RAMAN STUDIES OF IMPACT GLASSES

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Introduction: Impact glasses have been studied in the past with a variety of physical and chemical methods, but it seems that there are few, if any, cathodoluminescence (CL) studies so far. To attempt a first study of the CL properties of impact glasses (including CL imaging and CL spectroscopy), we selected three samples: an Aouelloul impact glass, a Libyan Desert Glass, and a Muong Nong-type indochinite (tektite). The CL studies are supplemented by micro-Raman spectroscopy and infrared reflectance spectrometry, as well as compositional studies using electron microbeam techniques.

Results: The back-scattered electron (BSE) and CL images of the Muong Nong-type tektite are relatively featureless and show little variation (apart from a few BSE-bright inclusions, which also appear in the CL image). Also, the BSE image of the Libyan Desert Glass shows only limited brightness contrasts. For the Aouelloul glass, both BSE and CL images show distinct brightness contrast, and the CL images for the Libyan Desert Glass show spectacular flow textures that are not visible in any other microscopic method. All three glass types show an inverse relationship between BSE and CL intensities, which seems to be related to the presence of activators such as Al, Li, Na, and Fe, which might cause quenching of the CL signal. The Energy-Dispersive X-ray (EDX) compositional data show that the SiO₂ composition is relatively higher and the Al2O3 content is lower in the CLbright areas than in the CL-dark regions. The CL images seem to preserve remnants of the texture of the target rock that was melted to produce the impact glass. The tektite has a homogeneous appearance in both BSE and CL images, indicating that it was subjected to a high temperature. The Aouelloul impact glass preserves remnants of a texture in both BSE and CL images, indicating a relatively low formation temperature. And, the Libyan Desert Glass preserves a flow texture that is only visible in the CL images, indicating a medium temperature.

Broad bands at 491 and 821 cm⁻¹ in the Raman spectra in all samples might be associated with remnants of diaplectic glass, indicating early shock amorphization followed by thermal amorphization. The observed 2 broad bands at 332 (3.73 eV), 390 (3.17 eV), and around 440 (2.79 eV) nm in the cathodoluminescence spectra of the impact glass samples might be related to the presence of defect centers in the slightly distorted SiO₄ tetrahedra. This multi-technique approach, including BSE and CL imaging, combined with IR, CL, and Raman spectroscopy, has the potential to be a powerful tool that can be used to characterize the internal heterogeneities and structure of impact glasses. In particular, the CL images of Libyan Desert Glass show a variety of structure that has not been recognized before.

NORTHWEST AFRICA 1670: A NEW QUENCHED ANGRITE

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Northwest Africa 1670 (NWA 1670) is a new angrite recently discovered from occidental Sahara (total mass: 30.6 g). NWA 1670 shows a porphyritic texture composed of olivine megacrysts set in a very fine-grained lathy groundmass. The size of olivine megacrysts reaches 3 mm across. Euhedral (sometimes skeletal) olivines of smaller size (~1 mm) are also present and are often overgrown at the megacryst rims. The groundmass is composed of intergrown lath grains of anorthite, Al- and Ti-rich clinopyroxene (fassaite), and calcic olivine. Accessory minerals include hercynite spinel, chromite, and Fe sulfide. The lath grains in the groundmass are up to 1 mm long with the width of a few tens of μ m. Calcic olivine is present as patches in the fassaite laths. The modal abundances of minerals are 45% olivine, 24% fassaite, 23% anorthite, 7% calcic olivine, and 1% others. Unlike other angrites, NWA 1670 shows evidence for strong shock metamorphism. A minor impact melt vein is present, and olivine megacrysts display mosaicism or undulose extinction.

The olivine megacrysts have homogeneous cores except for the overgrown rims, although, some megacrysts are systematically zoned from core to rim. There is a variation in the core composition from one grain to another. The most magnesian olivine core is Fo₉₆. The olivine megacrysts contain 0.05–0.5 wt% Cr₂O₃ and 0.05–0.7 wt% CaO, respectively. Tiny spherules (~5 μ m) of Fe metal and sulfide are present in some olivine grains. Euhedral olivine grains are zoned (Fo_{85–65}) with ~1 wt% CaO at the rims. Plagioclase is essentially Na- and K-free and is nearly pure anorthite. FeO and MgO contents are 1~5 wt% and 0.1–2 wt%, respectively. Fassaite is also extensively zoned (fe#: 0.49–0.89). The Al₂O₃ content is generally 6–8 wt%, but some analyses reach ~16 wt%. The TiO₂ content is 1.5–3 wt%, and the Cr₂O₃ content is 0.5–0.0 wt%. The groundmass olivine is Fe- and Ca-rich (fe#: 0.58–0.87; CaO: 2–12 wt%).

Based on mineralogy and petrology, NWA 1670 is obviously a new angrite. The Fe/Mn ratio of olivine and pyroxene is in agreement with those of other angrites. The porphyritic texture of NWA 1670 is generally similar to "quenched" angrites with olivine xenocrysts (e.g., [1-3]). Fassaite and olivine compositions of the groundmass are close to those of Sahara 99555, which we believe to represent an angrite magma composition [4]. It is likely that NWA 1670 is comagmatic with other quenched angrites. Because of the extremely magnesian composition of the olivine megacrysts in contrast to the groundmass minerals, megacrysts in NWA 1670 are probably xenocrysts. The lath texture of the groundmass shows rapid cooling from the melt. The euhedral olivine and overgrown grains on the megacrysts are probably phenocrysts that crystallized from the same melt prior to the groundmass crystallization. The cooling rate of NWA 1670 would be comparable to, or faster than, that of other quenched angrites (LEW 87051, Asuka 881371, and D'Orbigny: ~10°C/hr [2]). The origins of the megacrysts are unclear. The Fo₉₆ olivine in NWA 1670 is the most magnesian olivine among all the known angrites. Since it is hard to produce such Mg-rich olivine by normal igneous differentiation processes, we need to consider a new story for the angrite petrogenesis.

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NOBLE GASES IN MASKELYNITE FROM THE MARTIAN METEORITE SHERGOTTY

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Introduction: The martian meteorite Shergotty is classified as basaltic shergottite [1], containing mostly pyroxene (pigeonite, augite) and maskelynite, further mesostasis, and opaques. [2]. The meteorite is not brecciated, but shows shock features. Shock pressures did not exceed 30 GPa [3].

Results: Maskelynite and pyroxene were separated by handpicking. Here, we present the data for the maskelynite, which was almost pure as confirmed by SEM investigations.

Amounts and isotopic compositions of light noble gases agree well with the data obtained by [4]. We found $88.7 \times 10^{-10} \text{ ccSTP/g of }^{22}\text{Ne}$, with a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 0.838 ± 0.008 and $^{21}\text{Ne}/^{22}\text{Ne}$ ratio of 0.750 ± 0.005 and $27 \times 10^{-10} \text{ ccSTP/g }^{36}\text{Ar}$, with a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 1145 ± 23 and a $^{38}\text{Ar}/^{36}\text{Ar}$ ratio of 0.956 ± 0.007 . The results for Kr and Xe are given in Table 1.

Table 1. Results for Kr and Xe. Amounts are in 10 ⁻¹² ccSTP/g.							
T-step	⁸⁴ Kr	¹³² Xe	⁸⁴ Kr/ ¹³² Xe	¹²⁹ Xe/ ¹³² Xe			
350°C	3.2 ± 0.3	0.8 ± 0.1	4.0	0.957 ± 0.074			
988°C	11.0 ± 0.9	1.7 ± 0.1	6.5	1.088 ± 0.050			
1535°C	24.8 ± 1.9	3.4 ± 0.3	7.3	1.363 ± 0.072			
1535°C	0.1 ± 0.2	0.7 ± 0.07	0.14	1.065 ± 0.177			
Sum	39.1 ± 2.1	6.6 ± 0.3	5.9	1.234 ± 0.033			

Fig. 1 shows the data obtained for the maskelynite together with bulk data from the literature [5, 6] for comparison. The $1535^{\circ}C$ step, in which >50% of the ^{132}Xe is released, shows a contribution of Martian atmosphere. The concentration of Martian atmospheric xenon is somewhat lower than that observed in bulk samples [5, 6], however.



Fig. 1. ¹²⁹Xe/¹³²Xe versus ⁸⁴Kr/¹³²Xe. Endmembers are taken from [6-8].

The data for the pyroxene will be presented at the conference.

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A DISSOLVED OLIVINE XENOCRYST COMPONENT IN THE ANGRITE MAGMA

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The angrites are a small group of achondrites characterized by unusual mineralogy and old ages (e.g., [1]). The recent discovery of additional angrite samples offers substantial information to understand this enigmatic achondrite group. These new angrites (Sahara 99555, D'Orbigny, and NWA 1670) show porphyritic to ophitic textures similar to LEW 87051 and Asuka 881371, which are suggestive of rapid cooling histories ("quenched" angrites) and are distinct from the other slowly cooled angrites (Angra dos Reis and LEW 86010) (e.g., [2-3]). The quenched angrites often contain large olivine grains out of Fe/Mg equilibrium with the groundmass melt. Our previous studies (e.g., [2]) pointed out that these olivine grains are essentially Cr-rich and Ca-poor and are possibly xenocrysts. The unique olivine composition in these samples also suggests that they share a common origin. Thus, the similar mineralogy of the groundmass minerals, as well as the presence of Cr-rich and Ca-poor olivine xenocrysts, indicates that these quenched angrites are closely related and they are comagmatic. We found strong correlations among major elements in these quenched angrites, further supporting this hypothesis. The range of bulk compositions is 9.2-12.5 wt% Al2O3, 10.8-15.1 wt% CaO, 6.5-19.4 wt% MgO, and 19-24.7 wt% FeO (e.g., [4]). These compositional variations are well understood by olivine control (Fig. 1). Because olivine xenocrysts are absent or very rare in Sahara 99555 and D'Orbigny, we suggest that their bulk compositions represent an angrite magma composition that is not contaminated by the xenocryst component. In contrast, LEW 87051 and Asuka 881371 contain ~10% olivine xenocrysts and appear to have bulk compositions that include large amounts of dissolved olivine xenocryst components. The newly recovered angrite NWA 1670 is also abundant in olivine xenocrysts [5]. Thus, we expect that its bulk composition would be similar to, or more mafic than, those of LEW 87051 and Asuka 881371.



Fig. 1. Variations of bulk compositions (Al, Ca, and Mg) among angrite meteorites. These figures show that olivine (Fo_{90}) addition is an important factor to control the bulk compositions of quenched angrites. Angra dos Reis (ADOR) and LEW 86010 seem to be unrelated to these trends.

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COMPARING EARLY SOLAR SYSTEM CHRONOMETERS

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Introduction: Short-lived radionuclides provide a tool for the precise determination of early solar system chronology but yield only relative ages. To compare different chronometers, and to obtain absolute ages, requires anchoring to a chronometer such as Pb-Pb in suitable solar system objects. Various solar system components have been proposed (summarized in [1]), but no scheme yet yields complete consistency. Here, we report results from I-Xe analyses of mineral separates of Indarch (EH4), Khairpur (EL6) and Asuka 881394 (cumulate eucrite) to further assess chronometer correlation schemes, particularly those proposed by [1]. These samples were selected because literature information from other chronometers was already available.

Experimental: Samples were crushed and hand-picked under clean conditions in Manchester and the NHM, London. These separates were then neutron irradiated along with chips of Shallowater (SW). Irradiated samples were analyzed for xenon isotopes using RELAX [2] in Manchester using a step-heating technique. Similar analysis of SW allows us to determine the ¹²⁸Xe/¹²⁷I conversion factor.

Results and Discussion: Step-heating of Indarch pyroxene (IndP), Khairpur silicate (KPB), and Khaipur magnetic (KPA) fractions produced excellent correlations, with identical results within error for KPA and KPB (Table 1). No ¹²⁹Xe*^{/127}I correlation was observed for either the eucrite feldspar (AsF) or pyroxene (AsP). Both the Al-Mg and Mn-Cr chronometers indicate an old age for A 881394 [3], suggesting that some late event (>60 Ma after SW) has completely reset the I-Xe system in this eucrite, hence, it is unsuitable for comparing chronometers.

Table 1. Analytical errors are 1σ . Negative relative ages indicate time after SW. Absolute ages obtained using the scheme provided by [1]. Mn-Cr ages calculated from [4] and [5].

Separate	IndP	KPA	KPB
100-1107-111-0			
$^{129}I/^{12}/I (\times 10^{-5})$	11.5 ± 0.39	9.25 ± 0.51	8.98 ± 0.31
[I] (ppb)	100	22	30
Age wrt. SW (Ma)	0.5	-4.4	-5.1
Abs I age (Ma)	4565.9 ± 1.2	4560.9 ± 1.3	4560.3 ± 1.2
Abs Mn age	4561.9 ± 0.6	4557.	7 ± 0.6

Comparing Chronometers: These I-Xe ages have been compared to the literature Mn-Cr ages for Ind [4] and KP [5] in the context of the calibration scheme proposed by [1]. The chronometers record similar age intervals between Ind and KP. However, there is a significant difference between the I and Mn absolute ages. Better agreement between I and Mn ages may be achieved for these samples by accounting for a possible solar system ⁵³Mn heterogeneity, proposed by [6].

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AN INVESTIGATION OF CARBON IN THE DAR AL GANI 319 POLYMICT UREILITE

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Introduction: The ureilite Dar al Gani 319 (DaG 319) is a polymict ureilite containing fragments and clasts of typical ureilite material, felsic lithic clasts, dark clasts containing phyllosilicates and sulphides, metal-rich clasts, chondrules, and chondritic clasts and isolated mineral grains [1]. The multi-stage history of the polymict ureilites offers insight into the origin and formation of the ureilite parent body and later processes, such as fragmentation, shock, and addition of "exotic" components. We have analyzed the abundance, isotopic composition, and form of carbon within "silicate" and "dark clast" sub-samples of DaG 319 (BM2002, M27) using a combination of high-resolution stepped combustion and mass spectrometry. Analysis of a sample by stepped combustion allows for the identification of different carbon phases, e.g., organic, graphitic, and diamond, as each phase has characteristic combustion behaviour (e.g. [2]). By understanding the nature of carbon within this complex sample, the role of carbon in ureilite petrogenesis may be better constrained.

Results and Discussion: *Silicate:* The total C yield is 2.2 wt% C, with a δ^{13} C of -4.0‰, similar to reported values for both polymict and monomict ureilites [2, 3]. The C release profile is bimodal, with peaks at 650° and 800°C. The maximum at 650°C has a δ^{13} C value of -2.6‰ and is probably from combustion of graphite. The peak at 800°C has a δ^{13} C value of -6.3‰, suggestive of diamond combustion or combustion of graphite with a higher crystallinity. Previous investigations indicate that ureilite diamond has an indistinguishable δ^{13} C composition from associated graphite [3]. The higher crystallinity graphite may be genetically related to the lower crystallinity phase, with the difference in δ^{13} C attributable to isotope fractionation between fluid/graphite during graphite formation. Alternatively, the different graphite components may be attributable to different phases (both ureilitic) within DaG 319. Taken individually, both components fall into the reported ranges of δ^{13} C for ureilite graphite [2, 3].

Dark Clast: The dark clast is petrographically similar to the dark clasts described previously [1]. The bulk C yield is 1.7 wt% with a δ^{13} C of -17.2‰. Unlike typical ureilite material, the major C release occurs below 500°C (1.1 wt%), with a δ^{13} C of -16.9‰, which is similar to carbonaceous chondrite (CC) macromolecular material (e.g., [4]). Between ~600 and 850°C, 0.3 wt% C is released with a δ^{13} C of -13.3‰, again similar to CC carbon [4, 5]. Above 1000°C, 0.3 wt% C is released with a higher δ^{13} C value of +19‰, attributable to contribution from minor amounts of isotopically heavy SiC [5].

These results indicate that DaG is diverse in its C complement suggesting multiple sources and/or different petrogenetic processes. The silicate fraction implies isotope fractionation processes, during graphite or, possibly, diamond petrogenesis. The dark clast is likely CC in origin, indicating interaction between ureilite body(ies) and CC bodies, perhaps during impact-induced fragmentation of the ureilite parent. Carbonate, a characteristic phase within some CCs, is absent, suggesting derivation from a carbonate-poor CC type, e.g., CV, CO, or CR.

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ELTANIN METEORITE AND IMPLICATIONS FOR THE MESOSIDERITE PARENT BODY

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Specimens of the Eltanin meteorite are sub-mm- to cm-sized fragments recovered from the coarse ejecta of a late Pliocene (~2.4 Ma) deep-ocean (5 km) asteroid impact into the Bellingshausen Sea. Ejecta has now been recovered from at least 24 deep-sea sediment cores, covering over 80,000 km² of ocean floor. Ejecta is almost entirely meteoritic in origin, being composed of ~10% meteorite fragments and ~90% impact melt rocks. The latter are composed of melted asteroid material mixed with ~3% salts (Na, Cl, and K) from a seawater target. The estimates of the mass of meteoritic material are ~2 × 10¹⁵ g. This is by far the largest known meteorite fall and is also the most meteorite-rich region known on Earth.

Eltanin was originally classified as an anomalous, low-metal mesosiderite. This classification is now confirmed. Meteorite fragments are mostly polymict breccias compositionally similar to mesosiderite silicates, with low molar Fe/Mn ratios in pyroxenes and at least one basaltic clast with a strong positive Eu anomaly (Eu/Sm $40 \times CI$). Thus, they are from a highly evolved asteroid, and experienced a significant redox event due to mixing of metal and silicates. Metal is rare, comprising only trace amounts of the ejecta, but common patches of Fe-oxides attached to ejecta particles indicate that at least small amounts were deposited by the impact.

The amount of metal in the precursor asteroid is estimated indirectly from siderophiles in the meteoritic melt rock. Fe/Si ratios of 0.76 in the melt rock are significantly higher than in mesosiderite silicates (<0.45) or howardites (0.6). This "excess" Fe (35 mg/g) and the average Ni (4.2 mg/g) and Ir (187 ng/g), are all consistent with a contribution from ~4% metal with a composition similar to that in mesosiderite metal nodules. It is highly implausible that the asteroid that produced the Eltanin meteorite had a significantly higher metal content than this, or anything approaching the 50% metal typical of other mesosiderites. Our current exploration of numerous sediment cores over a large area shows no significant variation in the siderophile content of the ejecta. There is no known mechanism to fractionate metal from the rest of the ejecta during the impact. Post-depositional removal by diagenetic alteration of large volumes of metal is ruled out, as this would be evident from redox reactions and large volumes of residual Fe-oxides at localities where the ejecta was buried almost immediately by tens of cm of disturbed sediments.

Most likely, the Eltanin asteroid was derived from the same object as other mesosiderites. Hack et al. (2003 LPSC) point out that it is difficult to justify the presence of two very large, differentiated objects as separate sources for the mesosiderites and the HED meteorites. A third such object is even more implausible. Our results indicate that large regions of the mesosiderite parent body, at least 1 km in size, had relatively low metal content. We also suggest that it is possible that meteorites with 50% metal may not be representative of the parent body surface. Although Eltanin is only a single meteorite, by mass it is many orders of magnitude more significant than the rest of the mesosiderites in captivity. Perhaps, the high metal content of most mesosiderites reflects the high survival rate of metalrich portions after disruption, subsequent impacts in space, and atmospheric breakup during fall. Models of mesosiderite formation should allow for the possibility that only a small fraction of the parent body surface is composed of metal. NITROGEN ISOTOPIC COMPOSITION OF PRESOLAR SILICON CARBIDE AS AN INDICATOR FOR SOLAR SYSTEM PROCESSES J. B. Smith and G. R. Huss. Department of Geological Sciences and Center for Meteorite Studies, Arizona State University, Tempe, Arizona 85287– 1404, USA. E-mail: juliesmith@asu.edu

Introduction: The isotopic compositions of presolar grains act as probes of galactic chemical evolution and stellar nucleosynthesis [1, 2], while abundances and characteristics of presolar grains record thermal processing in the solar system [3, 4]. We have found that N isotopic compositions of SiC grains from Colony (CO3.0) differ from those in other meteorites in ways that are not predicted by the compositions of other elements or the history of the host meteorite.

Background: The N ratios of SiC in a single meteorite vary with grain size (e.g., [1, 2]), so comparisons must be made using SiC of the same size. The isotopic compositions of Si, C, Ti, etc. indicate that all chondrites sampled the same mixture of presolar SiC grains [1, 2, 5]. The N ratios inherited from the stellar source are modified by spallation reactions, which lower the ¹⁴N/¹⁵N ratio. The N ratios are also subject to contamination by ¹⁵N-rich terrestrial N.

Discussion: Cosmic ray exposure in the host meteorite decreases ¹⁴N/ ¹⁵N. Cosmic ray interactions in surrounding materials increase the ²¹Ne/²²Ne of presolar diamonds with increasing cosmic ray exposure age. On a Ne 3isotope plot (Fig. 1a), diamonds from Orgueil, with a CR age of ~4.5 Ma, plot to the right of those for Murchison (CR age ~2 Ma). Colony diamonds plot in between, suggesting an intermediate exposure age. Murchison 3 µm KJG SiC is more ¹⁵N-rich than 2-4 µm Orgueil, and Colony 1 µm SiC is more ¹⁵N-rich than Murchison 1 µm KJE (Fig. 1b). Parent body cosmic ray exposure cannot explain these trends. We have also ruled out terrestrial contamination. Thus, differences in stellar sources, cosmic ray exposure history of the host meteorite, and terrestrial contamination did not produce the unusual N compositions of Colony SiC. This leaves differences in interstellar history (which would require packets of material to remain isolated both in interstellar space and in the solar system) and pre-accretionary history in the solar system. We suggest that the same nebular processing that produced the CO-chondrite bulk composition and abundance patterns of presolar grains [4] also produced excess cosmogenic 15N in SiC in the CO3 parent material prior to accretion of the host meteorite.



Fig. 1. Isotopic ratios for diamond separates (a), and SiC (b). Colony and KJE $<2 \mu m$; Orgueil and KJG 2–4 μm . Data: [1, 2, 4, 6, and 7].

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ISOTOPIC FRACTIONATION OF FISSION XENON FROM TEMPERATURE VARIATIONS: IMPLICATIONS FOR THE OPERATIONAL CONDITIONS OF THE OKLO REACTOR

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Introduction: Anomalous fission Xe, isotopically enriched in ¹³²Xe, ¹³¹Xe, and ¹²⁹Xe, was observed in Al-phosphate from Zone 13 of Oklo reactors [1]. However, these anomalies have never been addressed quantitatively. Here, we report new data and suggest a quantitative model for the observed isotopic effects (chemical fractionation). We use this model to estimate the operational conditions for this natural reactor.

Experimental: In addition to previously reported data [1, 2], we have analyzed a new polished section of material from Zone 13 with in situ laser extraction. The Xe concentrations in U-free Al-phosphate ($\sim 10^{-2}$ cm³ STP/g) were ~ 100 times higher than in U-oxides. Xe isotopic compositions in Al-phosphates were found to be extremely anomalous, while the Xe in U-oxides was relatively "normal" (mixtures of ²³⁵U, ²³⁹Pu, and ²³⁸U fission). To produce anomalies observed in Al-phosphates, Xe isotopes must have been generated in the following proportions: P₁₃₂/P₁₃₄ = 8.0, P₁₃₁/P₁₃₄ = 3.4, and P₁₂₉/P₁₃₄ = 1.05.

Model: The proposed model is based on three assumptions: 1) natural reactors operate in pulse modes. During a single pulse, the temperature increases until the moderating water vaporizes, terminating the chain reaction. Then, the temperature slowly decreases, water returns back to the active zone, and the chain reaction resumes. This negative feedback prevents runaway chain reactions after the natural reactor goes critical; 2) at elevated temperatures, Te and I (radioactive Xe precursors in fission chains) are less mobile than Xe. Experimentally determined Te, I, and Xe retention (e.g., [3]) supports this assumption; 3) during the reactor operation, fission Te and I migrate from U-oxide into Al-phosphate where they subsequently decay to Xe, which is only retained when the reactor cools down between pulses.

Operational Conditions: We have calculated the isotopic composition of Te as a function of two variables: the duration of a typical pulse of the reactor (d) and its inter-pulse cooling time (c) when Xe retention begins. We find a good (and only) match between the model and the three Xe ratios observed in the Al-phosphates with the parameters d = 30 min and $c = 2\frac{3}{4}$ hr, with c being a lower limit for the average time between the termination of a one pulse and the initiation of the next pulse. Interestingly, these parameters are quite typical for geysers (c = 5 to 50 minutes, d = 1/3 to 3 hours, [4]).

Implication: The proposed fractionation mechanism, and this model for Xe isotopic fractionation, may be useful not only in this study of natural reactors, but also in any process in which nuclear production involves intermediate products and takes place in an environment with varying temperature. As is this case, pseudo-components may be also generated by similar chemical migration.

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CHEMICAL FRACTIONATION AND ALTERATION TRENDS BETWEEN FIVE NAKHLITES

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Introduction: We combine new petrographic and geochemical (solution ICPMS) data on 5 nakhlites in order to show igneous fractionation and alteration trends between the samples.

Trace Elements: Nakhla (BM 1913, 26) and Y-00593 have nearly identical relative abundances of the REE, e.g., La/Lu = 3.5, 4.0, but Nakhla has $4.5 - 1.3 \times \text{CI}$ REE, with Y-00593 having higher abundances of $6.9 - 1.7 \times \text{CI}$. The abundances are consistent with Rayleigh fractionation of a LREE-enriched melt—composition from [1]—and crystallization of an ol-cpx adcumulate from it at F (fraction of melt remaining) = 0.6. The addition of \sim 5% trapped melt to this produces REE abundances similar to those of Y-00593. Nakhla has trapped slightly lower proportions of melt, or its melt experienced a lower degree of crystal fractionation.



Fig. 1. CI normalized trace elements in Y-00593—see also [2]—and Nakhla. These can be modelled as addition of trapped melt to an ol-cpx adcumulate derived from a LREE-enriched parental melt.

Siderite-Bearing Veins in NWA 998 and Y-00593: ASEM analyses of veins within the olivine of these 2 nakhlites show that they contain a mixture of Mn-bearing siderite and Fe-rich clay. The chemical and textural similarities between these veins and those of the other nakhlites suggest they have a related origin on Mars [3, 4]. The volume of these veins is smaller than those of the 3 other nakhlites we have studied [3]. Using the model of [3], the Fe-Mn dominated composition of the siderite/clay mixtures suggests that they formed at a similar, late stage of brine evaporation as the veins in Nakhla.

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KINETICS AND MECHANISM OF EXSOLUTION OF RU-FE IN THE SYSTEM FE-NI-RU: IMPLICATIONS FOR THE ORIGIN OF REFRACTORY METAL NUGGETS IN CAIS

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Introduction: Refractory metal nuggets (RMNs) in opaque assemblages composed mainly of NiFe metal, Fe-Ni sulfides, and magnetite occur in CAIs. Some investigators believed that they record nebular conditions prior to the formation of the CAIs, while others attributed their origin to exsolution, oxidation, and sulfidization of homogeneous alloys within the host CAIs during slow cooling (500°C) in the nebular or in a planetary environment. Regardless of their origin, their refractory sidrophile elements form solid solutions with Fe-Ni alloys during melting of the CAIs and then begin to exsolve during subsolidus cooling. Therefore, the study of the kinetics and mechanism of exsolution of refractory sidrophile elements from Fe-Ni alloys should provide clues on their cooling and equilibration history.

Experimental Techniques and Results: Homogeneous synthetic Fe-Ni-Ru alloys were prepared by melting puratronic-grade metals in alumina tubes at an oxygen fugacity two log units below the iron-wustite buffer. The homogeneity of the alloys were verified by the electron microprobe. The alloys were annealed isothermally under subsolidus conditions for 1 to 390 days. The progress of exsolution as a function of time was determined from electron microprobe X-ray maps. Three isothermal rate studies were performed at 800, 700, and 600°C. The experimental results show that the exsolution rate depends on temperature and supersaturation. The percent of supersaturation.

Discussion: Three mechanisms of exsolution are known. The continuous mechanism involves nucleation of the exsolved phase and its growth by volume diffusion. The discontinuous mechanism involves nucleation of duplex cells of two phases of approximately equilibrium compositions and growth by grain boundary diffusion along the incoherent boundary with the host. Spinodal decomposition, a process that may replace the nucleation event in the continuous mechanism, proceeds by growth of compositional perturbations small in degree but large in extent, and a new phase gradually emerges that is structurally coherent with its surrounding across a diffuse interface (Yund and McCallister 1970). For any given temperature, in our experiments, the exsolved phase has a fixed composition (within the analytical uncertainity) that precludes spinodal decomposition as the mechanism of exsolution. At 700 to 800°C, the formation of RuFe nuclei and their growth as a function of time are consistent with exsolution by the continuous mechanism. At 600°C, formation of duplex cells was observed consistent with exsolution by the discontinuous mechanism. In CAIs, RMNs occur as granule and rarely as sparse lamellae. These are mimicked by the textures in our experiments in which the mechanism of exsolution was the continuous mechanism. No evidence of cellular preciptation was observed in any natural RMN so far. Therefore, it is likely that exsolution ceased to occur at temperatures below 700°C. Exsolution of the RMNs may have occurred in the solar nebula. Oxidation and sulfidization of the Fe-Ni alloys may have proceeded at lower temperatures either in the nebula or in a planetary enviroment

DAG 983: A COMPLEX (POLYMICT, FELDSPAR CUMULATE, IMPACT MELT BRECCIA) EUCRITE FROM LIBYA

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Introduction: We have been conducting petrographic and chemical analyses of the mineral phases in the new eucrite Dar al Gani (DaG) 983. The 933 g meteorite was recovered in the Libyan desert last year. We will also present bulk noble gas and INAA data.

Petrographic Description: The in-hand specimen, DaG 983, shows a light gray, brecciated texture, several vesicle-bearing melt veins, and open cracks (Fig. 1). Occasionally, cracks and vesicles contain microcrystalline aggregates of terrestrial gypsum.



Fig. 1. DaG 983 (50 x 70 mm; Photo K.C. Lyncker).

Microscopically, three basic components can be distinguished: A considerable fraction of the meteorite is composed of pyroxene and feldspar megacrysts (up to 10 mm). They are embedded in a groundmass of variably coarse-grained pyroxene and plagioclase. The sample also shows recrystallized melt pockets and veins. The pockets locally display a spinifex-texture. In modal terms, DaG 983 contains about 47 vol% pyroxene, 34% plagioclase, 12% melt, 3.5% silica, 1.5% ilmenite, and 1.0% chromite, as well as accessory phosphates and troilite.

DaG 983 exhibits attributes of severe shock metamorphism including heavily fractionated mineral phases and strong mosaicism. Most of the plagioclase has been converted into maskelynite.

First Chemical Results: The megacrysts are made of pigeonite (Fs_{37.9}Wo_{4.4}) and plagioclase (An_{94.8}). The matrix of the rock comprises plagioclase (An_{93.6}) and relatively Fe-rich pigeonite (Fs_{54.6}Wo_{3.1}) with thin exsolution lamellae of augite (Fs_{25.0}Wo_{40.9}). Pigeonite of the spinifex-textured melt pockets is composed similarly to the pyroxene in the groundmass (Fs_{55.3}Wo_{2.1}), while the associated feldspar reveals a more sodic composition (An_{84.3}).

Preliminary Conclusions: The overall composition of DaG 983 is that of a eucrite. It further categorizes as an impact melt breccia containing pyroxene and feldspar megaclasts as well as melt veins and pockets. The recrystallized melt areas were most likely induced by a major impact event as the entire sample is strongly shocked (S5, [1]). The pyroxene megaclasts are relatively Mg-rich suggesting a cumulate origin (e.g., [2]). The pyroxenes of the highly brecciated basaltic host eucrite display a more ferroan composition.

MARTIAN BOLIDES AND EFFECTS ON CRATERING

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Introduction: We used models of atmospheric fragmentation of meteoroids to study meteoroid passage through present and past atmospheres of Mars. We calculated the sizes of the smallest objects to survive atmosphere passage, and hence, the sizes of the smallest expected craters. We have also analyzed the causes of "small clusters" (20 m scale pits scattered over few-hundred m areas) and also "large clusters" (500 m scale craters scattered over 5 km areas).

Fragmentation Effects: The smallest craters expected under current atmospheric conditions on Mars have diameters of the order of 0.3 m due to iron meteorites that survive atmospheric passage [1]. They might best be detected on Martian rocks, as discussed by [2]. The smallest Martian craters due to stony meteoroids range from 0.5 to 6 m in diameter, depending on the strength of the meteoroids, and the smallest craters due to hypothetical weak icy or icy/carbonaceous cometary meteoroids would be about 8 m across.

Fragmentation influences the crater formation process on Mars but primarily in hypothetical denser past atmospheres. In the present atmosphere, only the weakest bodies, with strength ~1 bar, would fragment. In dense atmospheres above 300 mbar, fragmentation processes should cause dramatically decreased crater numbers in diameter distribution below crater size of about 200–300 m, similar to the paucity of <300 m explosion craters on Earth. It may be hard to distinguish small crater clusters formed by our predicted breakup of ordinary stones and irons under 30–300 mbar atmosphere from the small clusters formed by weak stones in the present atmosphere. Craters much smaller than 0.3 m (such as "zap pits" in rocks) would be diagnostic of earlier periods with lower atmospheric pressure, perhaps caused by obliquity variations.

Martian Clusters: We have identified two types of crater clusters on Mars. Small clusters involve craters with diameter D up to a few tens of m spread over typically 100-300 m [3, 4], and large clusters involve craters with D ~100-900 m spread over 5 to 30 km [4–6].

Existing models and observations are consistent with weak meteoroids breaking up in the Martian atmosphere and causing the observed "small clusters."

The present fragmentation models fail to produce conditions that would explain our "large clusters" of 500 m craters spread over 5-30 km. Furthermore, we see no smooth continuum between the small and large clusters; they seem to represent two distinct phenomena.

We considered and rejected a number of possible explanations. The best explanation seems to be ejection of large, secondary fragmented blocks of material launched at sub-escape velocity out of impact craters. During their flight through the atmosphere, they could separate to the spacings required to create such large crater clusters after re-entry.

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ORGANIC MATTER ASSOCIATED WITH CARBONATES IN THE SNC METEORITE ALH 84001: A SIMS STUDY

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Carbon, oxygen, and nitrogen isotopic records of the different mineral phases of the meteorite ALH 84001 have been investigated by means of secondary ion mass spectroscopy (SIMS). Results of this study are in agreement with the findings of other workers as regards the zoning of oxygen and inorganic carbon isotopes in carbonate rosettes. In addition, the isotope records of the organic matter associated with the carbonates has been inferred from the composition of the emitted C₂ and CN secondary molecular ions and are found to be consistent with an endogenetic origin. The shift $\Delta^{13}C = \delta^{13}C_{org} - \delta^{13}C_{earb}$ is suggestive of biological fractionation.

Experimental: Analyses have been carried out with a Cameca ims-300 ion-analyzer using the intense negative secondary emission triggered by Cs⁺ ion bombardment. Electrostatic charge compensation was achieved by means of a coaxial electron gun and the sample equipotentiality monitored by means of an electrostatic mirror. Mass resolution power (M/ Δ M) was ~10⁴ and magnetic field (regulated by a NMR probe) stability was ~10⁻⁶ throughout this work. Spectral rays and energy bandwidth were selected with a resolution of 3 μ amu and 100 mV, respectively, by computerized adjustment of the voltage of the electrostatic peak-switching system and that of the electrostatic sector. To minimize terrestrial contamination, the (8 μ m diameter) analyzed areas in the carbonate were selected devoid of any detectable fissure by secondary ion imaging.

Results:

- 1. The oxygen isotope compositions measured in the carbonate are in agreement with those reported by [1] for the same chemical composition. The pyroxene $\delta^{18}O_{SMOW}$ is, within experimental uncertainties, identical to that obtained by gas phase mass spectrometry [2], and the maskelynite $\delta^{18}O_{SMOW}$ does not differ significantly from that measured by [3].
- 2. The carbon of the carbonate is isotopically heavy; it exhibits an unusually large range of isotopic compositions, $\delta^{13}C_{PDB}$ being comprised between +20 and +40‰, an observation in agreement with that made by other workers [4, 5];
- 3. As characterized by means of secondary molecular ions C₂ and CN, organics associated with the carbonate are also found to be enriched in ¹³C, but to a lesser degree; they also exhibit isotopic variability around a mean value $\delta^{13}C_{PDB}$ of +8‰. Also, the $\delta^{15}N$ of these organics is close to that measured by [6] and attributed by these authors to a trapped martian primitive atmosphere. Their atomic C/N ratio lies in the range of 3–11.

Implications: The high $\delta^{13}C_{PDB}$ value of the organic matter associated with carbonates in ALH 84001 seems to rule out the possibility that these organics are terrestrial contaminants of biogenic origin or, alternatively, kerogens brought on the surface of Mars by the infall of meteoritic or cometary matter, as proposed by [7, 8]. Rather, the high $\delta^{13}C_{PDB}$ value may be regarded as a signature of a martian origin. In addition, the low C/N value suggests that these organics are, at least in part, made up of aminoacids and nucleic acid bases.

References: [1] Leshin et al. 1996. [2] Clayton and Mayeda. 1996. [3] Romanek et al. 1996. [4] Valley et al. 1997. [5] Niles et al. 2002. [6] Murty and Mohapatra. 1997. [7] Bell. 1996. [8] Becker et al. 1999.

TRACE ELEMENT CONCENTRATIONS IN METALS OF CR CHONDRITES: INDICATORS FOR REDOX PROCESSES IN CHONDRULES?

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The formation of metal grains in metal-rich carbonaceous chondrites (CR, CH, CB) is not well-understood. Concentrations of Ni, Co, Cr, and Si in CB and CH metals suggest an origin by condensation in the solar nebula (e.g., [1, 2]). In CR chondrites, metal-silicate equilibration or other processes may have reprocessed metals during chondrule formation, erasing primary condensation signatures (e.g., [3, 4]). To better understand metal formation in CR chondrites, we have performed additional analyses of metal grains in chondrules, on chondrule rims and matrix of the CR chondrites Renazzo and Acfer 209 for Fe, Ni, Co, Cr, P, and Si. The Si contents of metals may, in particular, help to distinguish between these processes [5].



Fig. 1.

Results for Ni and Co in Acfer 209 are shown in the diagram (each symbol represents an individual chondrule). Metals from chondrules Δ and * show a positive correlation of Ni and Co, suggesting a condensation origin. In other chondrule metals (O, +, \Box , and \diamondsuit) Ni and Co are anticorrelated, probably due to redox processes. This was also suggested by [6].

The concentrations of Cr are compatible with condensation, while P contents are higher than expected. The Si concentrations are highly variable even within metals of individual chondrules. In one chondrule, Si contents in metals range from 70 ppm to 1200 ppm. Thus, Si contents in metals are neither compatible with an origin by condensation nor with metal-liquid silicate equilibrium.

Evidence exists for at least 3 processes that have contributed to the trace element patterns in CR metals: 1) condensation; 2) metal-silicate equilibrium; and 3) reduction of silicates. The large variations in Si are difficult to understand within this framework.

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SHORT COSMIC-RAY EXPOSURE AGES OF THE HORSE CREEK MESOSIDERITE AND PITTS IRON METEORITE

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Introduction: Most iron meteorites show cosmic-ray exposure (CRE) ages in the range of 10^8 – 10^9 yr [1], while mesosiderites show ages intermediate between those of stony and iron meteorites [2]. Here, we present evidence of two relatively small, metal-rich meteorites with unusually short exposure ages: Pitts, a ~4 kg IB-iron for which a complex exposure history was previously proposed [3] and Horse Creek, a 570 g, Si-bearing iron meteorite find that was classified as an anomalous mesosiderite. Horse Creek seems related to the aubrites, as the metal shows a high Si concentration (~2.5 wt%) and an unfractionated, chondritic trace element composition [4].

Analytical Methods and Results: We measured cosmogenic ¹⁰Be, ²⁶Al, ³⁶Cl, and ⁴¹Ca in small samples of Horse Creek and Pitts. The high ²⁶Al concentration in Horse Creek is mainly due to the production from Si. Model calculations using the LAHET Code System [5] show that, for iron meteorites containing 2.5 wt% Si and radii between 5–30 cm, the ²⁶Al production rate is 10–12 dpm/kg. The ²⁶Al concentration in Horse Creek, therefore, yields a CRE age of ~1.0 Myr, which is consistent with the low ¹⁰Be concentrations in Pitts correspond to a CRE age of ~0.9 Myr. The noble gas concentrations in Pitts (6.3×10^{-7} ⁴He, 1.48×10^{-9} ²¹Ne, and 8.1×10^{-9} ³⁸Ar cm³ STP/g) show that it had a complex exposure history, with a first stage of ~1.6 Gyr at very high shielding, followed by a second stage of ~0.7 Myr at low shielding. Noble gas measurements in Horse Creek are in progress.

Conclusions: Based on radionuclide concentrations, we found CRE ages of \sim 1.0 Myr for two metal-rich meteorites, Pitts and Horse Creek. Although one of these meteorites (Pitts) had a long first stage exposure at high shielding on its parent body, the short radionuclide exposure ages for both meteorites probably represent the transfer times from their parent body to Earth. Since the Yarkovsky effect is not very effective in moving iron meteorites across the asteroid belt [6], and these short transfer times are consistent with typical delivery times from the resonances to Earth [7], these two metal-rich meteorites must have been injected directly into one of the resonances.

Table 1. Cosmogenic radionuclide concentrations (dpm/kg metal) in Horse Creek and Pitts

Sample	¹⁰ Be	²⁶ Al	³⁶ Cl	⁴¹ Ca
Horse Creek Pitts	$\begin{array}{c} 1.73 \pm 0.04 \\ 1.61 \pm 0.04 \end{array}$	6.88 ± 0.14 1.90 ± 0.09	$\begin{array}{c} 18.6\pm0.4\\ 19.0\pm1.0 \end{array}$	21.4 ± 0.5 21.2 ± 1.3

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I-XE ANALYSES OF NANODIAMONDS FROM EFREMOVKA

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 129 Xe excesses in low temperature releases from nanodiamond separates are especially noticeable in meteorites such as CV3 chondrites that have been processed just sufficiently to lose the bulk of their Xe-P3 budget [1]. Here, we report xenon analyses of irradiated and unirradiated aliquots (~10 µg) of a coarse (>3.5 nm grain size) Effemovka nanodiamond separate (ED12) [2] that has a particularly striking low temperature release of 129 Xe.

In Fig. 1, irradiated and unirradiated aliquots have high ¹²⁹Xe^{/132}Xe in low temperature releases, but the irradiated sample also has excesses of ¹²⁸Xe produced from ¹²⁷I. In releases 5–15, a good correlation exists between ¹²⁹Xe and ¹²⁸Xe, verifying that ¹²⁹Xe was produced from ¹²⁹I decay. The dashed line represents a ¹²⁹I/¹²⁷I ratio on closure to a xenon loss of ~4.4 × 10⁻⁵, which we believe corresponds to loss of the P3 component [3]. If the nanodiamonds incorporated iodine from a solar system reservoir, this corresponds to closure 20 Ma after the closure of the Shallowater standard. High T releases from the irradiated sample (inset) suggest addition of iodogenic ¹²⁸Xe* to Xe-P6 unirradiated data are consistent with P6. This would require a P6 I/Xe ratio higher than solar, consistent with the observed depletion of the lighter noble gases relative to Xe [3].



Fig. 1. See text. Typical error bars shown on point 4. Low temperature releases are numbered in sequence.

References: [1] Verchovsky et al. 1999. Abstract #1746. 30th Lunar and Planetary Science Conference. [2] Gilmour et al. 2002. *Meteoritics & Planetary Science* 37:A52. [3] Huss and Lewis. *Meteoritics* 29:791–810.

THE ISOTOPIC NATURE OF GEMS IN INTERPLANETARY DUST PARTICLES

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Introduction: An abundant component of anhydrous interplanetary dust particles (IDPs) are sub-micrometer glassy objects with embedded metal and sulfide grains (GEMS). These objects are interesting because they may be the irradiated remnants of cosmically abundant interstellar silicate grains [1] with which they share many infrared spectral properties [2]. A positive proof that GEMS are interstellar in origin and not a product of the early solar system would be the observation of clearly nonsolar isotopic abundances, although, the absence of such anomalies would not disprove a presolar origin. The first analytical tool for isotopic measurements of individual GEMS, the NanoSIMS, has only recently become available [3] and, indeed, a study of O isotopic compositions in IDPs has found isotopic anomalies in a small portion (2 out of 42) of GEMS [4]. The majority of GEMS, however, appear normal with respect to their O isotopic composition, possibly due to exchange with isotopically normal material. To better understand the isotopic nature of GEMS, we have studied a large number of GEMS-rich TEM sections of IDPs with the NanoSIMS. The results of imaging measurements of the C, N, O, Si, and S isotopic compositions in these particles and aspects of the sample mounting routines will be discussed.

Analytical Methods: The detailed mineralogical compositions of 16 slices from 3 chondritic, anhydrous IDPs were determined with the transmission electron microscope (TEM). These samples were selected for their high concentration of GEMS, and each TEM section contained many individually identified GEMS. After the mineralogical studies, the entire TEM grids were mounted for NanoSIMS measurements. Isotopic measurements were made in multicollection imaging mode where up to 5 secondary ion species plus secondary electrons were analyzed simultaneously. Most sample sections were destroyed during the measurements, which typically take several hours. Whenever useable samples remained after the first measurement, the same sections were used for additional measurements of other isotopic systems. Results were then converted into isotope ratio images to allow a direct subgrain by subgrain comparison with the corresponding TEM images.

Results: No large isotopic anomalies—as seen in other IDP studies [4, 5]—were observed in any of the C, N, O, Si, and S isotopic measurements of the GEMS. Several sections do show isotopic variations that are marginally statistically significant. Detailed data processing will be required to isolate such grains from the surrounding areas of the sample with solar isotopic compositions. If, indeed, GEMS are of presolar origin but contain mostly isotopically normal material, a better understanding of grain processing and isotopic exchange in the interstellar medium and solar nebula is required.

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EVIDENCE FOR CA-LOSS FROM MESOSTASIS GLASS OF AN ALKALI-RICH CHONDRULE FROM UOC DAR AL GANI 369 A. Pack and H. Palme. Institut für Mineralogie und Geochemie, Zülpicher

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Introduction: Chondrule mesostasis glass is usually enriched in elements that are incompatible with respect to the major chondrule silicates (ol, px) [1, 2, 3]. Using EPMA and LA-ICPMS (RSES, ANU Canberra), we have analyzed major, minor, and trace element contents of mesostasis glass and forsteritic olivine from a chondrule from UOC Dar al Gani 369 (L/H3).

Results: Chondrule RF02 from DaG 369 is a ~700 μ m large FeO-poor type-I POC with Ca-poor and Na- and K-rich mesostasis. The brownish mesostasis glass appears vitreous in crossed polarized light. Most refractory lithophile elements are enriched in the mesostasis glass by a factor of ~10–15 × C1. A notable exception is Ca, which is extremly low in the mesostasis glass (~0.1 wt%), while luminescent forsteritic olivine phenocrysts in chondrule RF02 have CaO contents in the range of 0.4–0.5 wt%.

The REEs in the mesostasis are uniformly enriched by $\sim 10 \times C1$, but show negative anomalies in Eu, Yb, and notably also in Sm.

Discussion: Using Ca-partitioning data by [4], forsteritic olivine with 0.4–0.5 wt% CaO is in equilibrium with a silicate melt with \sim 13 × C1 CaO. The CaO in the olivine is clear evidence for the presence of CaO in the melt at the time of crystallization of the forsterite. Hence, the chondrule must have lost almost its entire CaO after crystallization of the olivine. The unaltered nature of the glassy mesostasis, however, is indicative for only very limited hydrous alteration of the parent body. We, therefore, suggest that preaccretionary alkali-Ca metasomatism [5] may have been responsible for the Ca-loss and the high alkalies in chondrule RF02.

The negative anomalies in Eu and Yb can be explained in terms of incorporation of refractory material (CAI with group-III REE pattern) into the precursor material of chondrule RF02. Ash et al. [6] report chondrule mesostasis glass with a well developed, complementary group-II CAI REE pattern.

The depletion in Sm, however, seems to be unique, and we have no explanation at present for the anomalous behavior of this element. At the same day, BCR-2G glass, as well as other meteortical components including two cryptocrystalline chondrules, were analyzed. In these measurements, no anomalous behavior of Sm was observed. Additional measurements will be performed to verify the anomalous behavior of Sm.

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COPPER ISOTOPE SYSTEMATICS IN CR, CH-LIKE, AND CB METORITES: A PRELIMINARY STUDY

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Introduction: Copper isotopes have recently been measured in a series of meteorite groups, and systematic differences in composition have been recorded [1]. These differences may be due to mixing of different copper sources in the early history of the solar system, or the isotopic composition may have been affected by exchange during hydrothermal alteration [1].

Samples: We analyzed bulk samples and separates from meteorites of the CR meteorite clan: Renazzo (CR), NWA 801 (CR), Hammadah al Hamra 237 (HaH 237) (CH-like), and Bencubbin (CB). This chondrite clan was selected because its members experienced very little nebular alteration and recycling [2, 3] and variable but low amounts of parent body processing [2].

Techniques: Ion exchange separation was performed at the University of Oxford using techniques described elsewhere [4]. Samples were measured at the University of Oxford (Nu MC-ICP-MS) using the sample-standard bracketing method [4]. The same samples were measured on the NHM-IC (London) Isoprobe MC-ICP-MS using sample standard bracketing plus a Zn dopant as a qualitative indicator for mass bias shifts [5].

Results: All of the meteorites are lighter in Cu isotope composition than terrestrial mantle. The total range of Cu-isotope composition is just over 1 per mil. Bencubbin displays the heaviest bulk Cu-isotope composition $(\delta^{65}Cu = -0.82 \text{ per mil})$ and HaH 237 the lightest $(\delta^{65}Cu = -2.04 \text{ per mil})$.

Effects of Desert Weathering: Two fragments of NWA 801 were analyzed in addition to a bulk sample and are distinct in isotopic composition. Sample #1 was a pristine sample, and its isotopic composition was similar to the bulk value (δ^{65} Cu = -2.0 per mil). Sample #2 was extremely heavily oxidized and had a Cu-isotope value different from the bulk. Thus, the isotope composition of Cu may be affected by weathering processes, especially for heavily oxidized fractions. The other meteorites studied here were falls or fresh finds.

Implications: Overall, there is no clear correlation between oxygen isotope composition ($\delta^{17}O$) and Cu-isotopic composition, as was previously observed for CI-CM-CO-CV meteorites [1]. Thus, the Cu isotope data of carbonaceous chondrites cannot be explained by simple mixing of a 63 Cu-, 16 O-rich oxygen component into the carbonaceous chondrite source regions. Instead, the copper isotope composition of carbonaceous chondrites was most likely defined by a complex mix of sources and fractionation processes. The sample with the lightest measured Cu isotope composition, HaH 237, also has an extreme elemental fractionation favoring refractory elements over volatile elements. The reason for the depletion of volatile elements in CH-like meteorites is unlikely to be due to evaporation into a gas of nebular pressure, as this would be expected to leave a residue that is isotopically heavy with respect to Cu.

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GAMMA-RAY FLUXES FROM THICK TARGET IRRADIATIONS: EXPERIMENTS AND MONTE CARLO SIMULATIONS

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Introduction: The surfaces of planetary bodies are bombarded by cosmic rays. The resulting interactions of the particles are the main sources of gamma rays. These γ rays, which carry information about the nucleus that emitted them, are diagnostic for the composition of the surface material and can be used as an analytical tool [1]. To evaluate the method of planetary gamma-ray spectroscopy, accelerator experiments were carried out.

Thick Target: All four thick targets consisted of three parts: a surface target for the gamma-ray emission, an inner core to stop the primary proton beam, and an iron sleeve to confine secondary particles. The total size was $1.8 \times 1.6 \times 1.5$ m³. The measured gamma rays originate mainly from near the surface, and, therefore, the thickness of the surface target was selected to be 40 cm in all four experiments. Target 1 contained basalt blocks; target 2 was made of pure iron; targets 3 and 4 consisted of similar basalt blocks as target 1 plus thin PVC inserts (chlorine, hydrogen, and carbon) and sulfur sheets. Target 3 contained additional sheets of polyethylene plastic, simulating higher water content. For all basalt targets, an inner core of pure basalt, and for the iron target, an inner core of iron was used.

Simulation Method: Our numerical simulations are based on the Los Alamos LAHET Code System (LCS) [2, 3], which is a system of generalpurpose, continuous-energy, generalized-geometry, time-dependent, off-linecoupled Monte Carlo computer codes that treat the relevant physical processes of particle production and transport. This code system and its application to planetary problems are discussed in more detail in [4, 5]. We are not concerned with scattered gamma rays, which contribute to the continuum, but only with those gamma rays that undergo no interactions before they escape from the surface. Therefore, having calculated the production of a particular gamma ray at each distance from the front surface of the thick target, we calculated the flux of gamma rays at a detector located in the front of the thick target, accounting for the attenuation of gamma ray between the location of their creation and detector position.

Conclusions: Comparison of measured and simulated intensities of gamma rays produced by the accelerator beam inside the thick targets prove that gamma-ray spectroscopy can provide accurate information on concentrations of all major and some minor rock forming elements contained in the target composition and can be applied to the study of planetary surfaces.

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WAS THE DIVERSITY OF CHONDRULE COMPOSITIONS ACHIEVED BY EVAPORATION AND CONDENSATION PROCESSES?

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Introduction: Despite numerous trials to explain the origin of the diversity of chondrule compositions, a model that satisfactorily reproduces the whole range of diversity does not exist. The diversity has been attributed to variation of the precursor materials but is inconsistent with recent finding of evidence for evaporation and/or condensation of various elements. Alkalies and Fe vaporize and condense at low temperatures, and their behavior differs from other major elements such as Mg, Si, Ca, and Al. Mg/ Si fractionation plays a key role for common ferromagnesian chondrules and (Mg + Si)/(Ca + Al) fractionation for Ca-Al-rich chondrules. Thus, it is important to specify process(es) responsible for such fractionation.

Experiments: Evaporation experiments in the system CaO(C)-MgO(M)-Al₂O₃(A)-SiO₂(S) were carried out to determine the evaporation rate of the each component. The composition of the starting material (57 wt% SiO₂, 9 Al₂O₃, 27 MgO, and 7 CaO) is richer in the Ca, Al-components than the CI composition but poorer than the staring material used by [1], who aim to model the variation of CAI compositions. The starting materials were isothermally heated at 1600°C to 1300°C for 1 to 144 hr. Fragments of the glass synthesized from oxide mixtures at 1 atm and 1600°C were kept in a vacuum or in graphite capsules. The change of weight and composition were measured and compared with the thermodynamic calculation to determine evaporation coefficients.

Results: The starting material remains to be totally molten at 1500 and 1600°C within a plausible degree of evaporation, which differs from previous evaporation experiments using compositions close to CI. The evaporation degree reaches to ~50% in 144 hr at 1500°C and in 30 hr at 1600°C in a vacuum and larger when the samples were kept in graphite capsules due to enhancement of evaporation in more reducing conditions. The residue composition changed almost linearly with the progress of evaporation, where CA/CMAS (initially 0.15) becomes ~0.3 and S/MS (0.58) becomes ~0.46 at ~50% evaporation. The evaporation coefficients, which are the ratios of the actual evaporation rate against the theoretical maximum rate, are ~0.05 at 1600°C and ~0.1 at 1500°C for Mg and ~0.07 at 1600°C and 0.09 at 1500°C for Si.

Discussion: The results are applied to estimate the change in composition of a silicate dust with the CI composition, which is instantaneously heated and subsequently cooled to cause recondensation of once vaporized gas. The silicate dust (silicate melt) behaves as an open system, while the dusts and surrounding gas act, on the whole, as a closed system. The quantitative model is based on [2], which assumes constant and the same evaporation and condensation coefficients for all elements. The calculation results show that the variation of type IA chondrules are reproduced by evaporation of CI precursor materials, but the diversity of type II chondrules requires isolation of partially evaporated Si-rich gas to recondense separated from Mg-rich residue. Back reaction is important for Mg/Si fractionation because Si is more volatile than Mg and the earlier vaporized gas is more enriched in Si. Ca-Al-rich chondrule compositions are unable to be reproduced by this process. They need precursors that are fractionated in the forsterite component from the CI composition.

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CHARACTERISTICS OF THE MULTI-RING IMPACT BASIN OF CHICXULUB, MEXICO, AS DERIVED FROM DRILL CORE DATA AND NUMERICAL MODELING

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Introduction: The ~200 km Chicxulub multi-ring impact basin has been drilled commercially (PEMEX drillings C1, S1, Y1, Y2, Y4, Y5A, Y6, T1) and scientifically (UNAM 1–7 and recently ICDP drilling Yaxcopoil-1). The drill cores, in part incompletely preserved, cover a radial range of 23 to 205 km from the center of impact (Table 1) and are structurally located in the central basin, in the annular trough, at the final crater rim, and in the ejecta blanket.

Table 1. Drill core data at the Chicxulub impact basin [1].

	Radial	Total	Main lithologies from top to bottom;
Nr	dist. (km)	depth (m)	figures (approx.) are in m ^a
C1	23	1581	1075 Pc, 175 suev, 330 melt r
S1	29	1530	1060 Pc, 360 suev, 110 melt r
Y6	47	1631	1100 Pc, 130 suev, 360 melt r, 40 dbr
Yax-1	60	1510	795 Pc, 100 suev, 615 Cc
T1	95	3575	545 Pc, 930 Cdabr, 2100 Cda
U5	110	503	173 Pc, 30 melt r, 300 suev
U7	125	700	250 Pc, 150 suev, 300 Ccabr
Y2	135	3474	260 Pc, 660 Cdabr, 2555 Cdla
Y5A	140	3003	450 Pc, 490 Cdabr, 2065 Cdla
U6	150	702	260 Pc, 25 gypsum br, 417 Ccabr
Y1	156	3221	335 Pc, 610 Cdabr, 2275 Cdla
Y4	205	2398	380 Pc, 310 Cdabr, 1710 Cdla

^aPc = post-impact carbonates; suev = suevite; melt r = melt rock; C = cretaceous; d = dolomite; l = limestone; a = anhydrite; br = breccia.

Type, Stratigraphy, and Geologic Setting of Impact Formations: From the data, a consistent pattern emerges as a function of depth and radial distance from the impact center: coherent impact melt of unknown thickness (C1, S1) topped with suevite inside the peak ring located at ~40 km from the center; moderately thick impact melt overlain by suevite outside the peak ring (Y6), thin suevite layer with very minor layered impact melt on top of megabreccia in the outer zone of the annular trough (Yax-1); suevite plus minor impact melt of variable thickness (0–330 m) on top of polymict breccia in the continuous ejecta blanket (1–2 crater radii: T1, U5, 7, 6), which ranges in thickness from ~900 to 300 m at 1–2 crater radii.

Origin and Mode of Emplacement of the Impact Formations: Numerical modeling suggests that after 100–130 sec, the falling ejecta curtain passes through the position of the Yax-1 drilling. Simultaneously, i. e., some 70–100 sec after the central uplift started to form, the target surface beyond the central region subsides as part of a growing circular depression. All ground surged material (suevite, coherent melt, megablocks, etc.) was emplaced during this time, and the deposition of the main mass of ballistic ejecta (polymict dolomite-limestone-anhydrite (mega)breccias) took place on a slowly subsiding surface. Some 6 min after impact, the 20 km-high central uplift collapses, probably causing high-speed mass transport radially outward shortly before the peak ring forms. The collapse of the ejecta plume and the deposition of the suevite layers inside and outside the final crater is a later process which may continue for hours. The petrographic, geologic, and geophysical data are compatible with this model.

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RADIATION PRESSURE, LONG-TERM STABILITY, AND GROWTH OF LARGE SILICON CARBIDE CRYSTALS

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Introduction: Presolar silicon carbide grains more than 10 microns in diameter have been extracted from meteorites [1], yet, it has been shown [2] that such crystals require on the order of 100,000 years under near equilibrium conditions to grow that large. Equilibrium growth [3, 4] occurs at total pressures on the order of 100 dyns/cm² in a hydrogen atmosphere at temperatures on the order of 1750 K in the outer reaches of the shells of Asymptotic Giant Branch Stars (AGB). Even at the reduced surface gravity expected under such conditions (~2 to 4 m/s²), grains 1 to 2 microns in diameter will quickly reach terminal velocities on the order of 15 m/s and fall into the much hotter interior of the star well before they could grow much larger. Here, we outline a mechanism that could serve to stabilize growing silicon carbide crystals and might even offer a natural explanation for their size distribution.

Model Considerations: We will demonstrate that the long-term stability of growing silicon carbide grains in the atmospheres of AGB stars is the result of a balance between two forces: the inward pull of gravity and the outward push of stellar radiation pressure. The residence time of grains formed in any given zone of an AGB star will depend on the width of the zone, the net acceleration on the grain due to radiative and gravitational forces, and the overall viscosity of the surrounding gas.

For very small grains (r <0.1 microns), the radiative pressure scales as r^6T^8 (Rayleigh Scattering), while for larger particles (r >1.0 microns), the force scales as r^2T^4 , where T is the effective temperature of the stellar photosphere rather than the temperature at the point of grain growth. The gravitational acceleration simply scales as r^3 . The effective temperatures of the photospheres of AGB stars of initial mass 1, 3, 5, and 7 solar masses are on the order of 4000 K, 5500 K, 8000 K and 11000 K, respectively [5]. Taken together, we will show that for low mass AGB stars (1 to 3 solar masses), grains less than ~0.1 micron and greater than a few tens of microns in diameter will experience a net inward pull due to stellar gravity, while grains between ~0.1 and ~50 microns will experience a net outward push due to radiation pressure. A wider distribution of grains is potentially expelled at much higher net accelerations from higher mass AGB stars (provided that grains ever formed there), ranging from both much smaller to much larger grain sizes.

At the low densities where crystalline silicon carbide grows in equilibrium, the molecular mean free path (\sim 1 cm) is much greater than the dimensions of the grains, thus, invalidating the use of Stokes Law to calculate atmospheric drag. Using a molecular-kinetic description for drag, very small grains are subject to both low net acceleration as well as relatively high drag forces. Condensation nuclei can, therefore, grow larger. Large particles are subject to high levels of radiative acceleration and decreasing drag as they ascend. This might set a practical upper limit to the sizes of SiC crystals produced in AGB atmospheres.

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INVESTIGATION OF A BROWN WEATHERING PRODUCT FOUND IN NAKHLA MELT INCLUSIONS

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Introduction: In the course of a comprehensive study on melt inclusions in olivine of Martian meteorites, a brown microcrystalline phase was discovered in two vitrophyric Nakhla inclusions from different thin sections [1, 2]. Its optical properties resemble those of the typical weathering product ("iddingsite") primarily found in olivine cracks of Nakhla and Lafayette [3–5]. This material (WPO hereafter) is supposed to be a result of hydrothermal alteration processes that took place on Mars: invading saline fluids dissolved the precursor material (olivine, Si-rich mesostasis glass) and substituted it by the WPO—retaining some chemical signature of the precursor material, e.g., in the Al, Si, Fe, and Mn compositions [5, 6].

The brown phase in Nakhla inclusions (BPI hereafter) cannot be related to an olivine precursor because olivine was never found within typical vitrophyric melt inclusions [7]. Therefore, to get new insights into the involved alteration processes, we investigated the relation of the BPI to the WPO and another similar phase found adjacent to pyroxene grains.

Experimental: The major element composition was analyzed with an electron microprobe. High resolution (\sim 0.3 µm) TOF-SIMS [8] was used to obtain the concentration and lateral distribution of major, minor, and trace elements.

Results and Discussion: The BPI in the two inclusions show remarkably similar element compositions. This indicates an identical precursor material and little variation in the composition of the intruding fluid.

Contents of 46.3 wt% SiO₂, 29.5 wt% FeO, 10.1 wt% MgO, and 9.6 wt% Al₂O₃ (normalized to 100 wt%) are unlike usual WPO compositions [4] but resemble those of the also analyzed alteration product adjacent to pyroxene. However, absolute and especially relative abundances of a set of minor and trace elements, Li, K, Rb, Sr, Cs, and Ba, show a signature different from Lafayette "iddingsite" [6], as well as from all other analyzed phases, including the alteration phases adjacent to olivine and pyroxene.

It does not seem plausible that the composition of the fluid is responsible for this particular signature. It is more likely that the signature results from the precursor material. Concerning the textural position of the BPI, pyroxene seems implausible, because the BPI occurs as intersertal phase inside the well-preserved pyroxene framework. Another proposed precursor would be siliceous glass [5]. However, none of the analyzed glasses within Nakhla inclusions matches the trace element signature. It seems more plausible that the precursor material of the weathering product in Nakhla olivine inclusions was an amphibole. Amphiboles were found in melt inclusions before [9]. Typical partition coefficients are consistent with the concentrations of the trace elements in this phase and the neighboring glass.

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SIMULATION OF COSMOGENIC RADIONUCLIDES RETENTION DURING ATMOSPHERIC ENTRY OF MICROMETEORITES

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Introduction: Cosmogenic nuclide concentrations in micrometeorites (MM) provide the exposure ages and sizes of these objects in interplanetary space. Recent simulation experiments indicate that MMs might have undergone significant textural, mineralogical, and chemical modification during their deceleration in the Earth's atmosphere [1]. Light noble gases, especially He, were shown to be drastically degassed during even a short period of heating [2]. In this work, we examined the behaviors of the cosmogenic radionuclides ¹⁰Be, ²⁶Al, and ³⁶Cl during pulse-heating experiments carried out as an analogue to atmospheric entry of micrometeorites.

Analysis: Fragments of Orgueil matrix were heated in a furnace at $1200-1425^{\circ}$ C for different run times from 2 to 120 s with different oxygen fugacity [2]. Be, Al, and Cl were chemically separated from individual heated Orgueil grains (50–470 µg) and ¹⁰Be in each grain was measured by AMS at LLNL.

Results: ¹⁰Be concentrations in individual Orgueil grains are shown in Table 1 along with heating conditions. The ¹⁰Be concentrations in heated samples were 30–60% higher than that of unheated Orgueil meteorite. The major target elements for the production of ¹⁰Be are C and O. Orgueil contains 2% of H and 3.2% of C [3] and at least 17% of O, present as hydrates, water, or carbonates. After only 2 s of heating, ¹⁰Be became enriched by more than 30% due to the evaporation of H₂O and CO₂, even though the texture didn't change very much [1]. Further enrichment of ¹⁰Be at longer heating indicates up to 33% of mass loss. However, such ¹⁰Be enrichment has never been observed in the fusion crust of meteorites. If the origins of MMs are CI- or CM-like objects, the enrichment of ¹⁰Be concentration during atmospheric entry will lead to an overestimate of the ¹⁰Be exposure ages of MMs [4]. The measurements of ²⁶Al and ³⁶Cl in same Orgueil materials are in progress.

	Fable 1	. Concentra	ations of	¹⁰ Be in	heated	Orgueil
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Temperature	Duration	Oxygen	Mass	¹⁰ Be
(°C)	(sec)	$Log(fO_2)$	(µg)	(dpm/kg)
1200	10	-6	87.4	28.2 ± 0.7
1200	20	-6	49.4	31.7 ± 1.2
1200	40	-6	90.0	32.7 ± 0.8
1350	2	Air	301.0	27.5 ± 0.6
1350	2	-0.68	34.8	26.5 ± 0.9
1350	2	-3.6	127.0	27.3 ± 0.7
1350	5	Air	467.4	30.9 ± 0.7
1350	10	Air	204.5	28.5 ± 0.7
1350	20	-3.6	56.4	29.4 ± 1.0
1350	120	Air	196.7	28.0 ± 0.9
1425	20	-6	76.2	28.8 ± 1.0
Untreated				20.5 ± 0.9

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THE HYDROGEN ISOTOPIC COMPOSITION OF FOSSIL MICROMETEORITES: IMPLICATIONS FOR THE ORIGIN OF WATER ON EARTH

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Introduction: Although still debated, the origin of water on Earth is usually ascribed to a late veneer of hydrous primitive bodies [1]. The isotopic composition of water hydrogen (D/H ratio) in a diversity of primitive extraterrestrial materials can help to assess the nature of the late veneer agent. Here, we present measurements of D/H ratios of hydrated silicates in carbonaceous chondritic microclasts (CCMs) recently identified within the achondrite howardites [2]. These CCMs have been interpreted to be fossil micrometeorites trapped in the howardite parent-body in early solar system history [2].

Results: Measurements of D/H ratios of silicate water in the matrix of 6 CM2-like and 6 CR2-like CCMs were performed by Secondary Ion Mass Spectrometry following the procedure described in [3]. D/H ratios from CM2-like carbonaceous chondritic microclasts' matrix range from 117.6 × 10^{-6} to 171.0×10^{-6} , with an average value of 132.7×10^{-6} . D/H ratios from CR2-like carbonaceous chondritic microclasts' matrix range from 112.8 × 10^{-6} to 203.8×10^{-6} , with an average value of 169.4×10^{-6} . D/H ratios in CM2-like microclasts compare well to bulk CM2 carbonaceous chondrites [4]. D/H ratios in CR2-like microclasts are significantly lower than D/H measured in bulk CR2 chondrites [4]. This discrepancy probably arises from the fact that bulk measurement techniques on meteorites take into account D-enriched organics in addition to water. The average value of all the microclasts' population is D/H = $152.0 \pm 4.8 \times 10^{-6}$.

Discussion: The CCMs D/H average value compares favorably to the terrestrial value ($149 \pm 3 \times 10^{-6}$). This match suggests that fossil micrometeorites could be a candidate for the late veneer agent that has endowed Earth with water. The calculated micrometeorite flux in the early solar system is adequate to account for the entire reservoir of terrestrial water. We will discuss the other constraints on the late veneer agent such as the Platinum Group Element content and the Osmium isotopic composition [5].

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FORMING WELL-COMPACTED METEORITES BY SHOCK EVENTS IN THE SOLAR NEBULA

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Introduction: Chondrites are well-compacted stones with porosities generally less than 10% [1], and that porosity occurs mostly as post-lithification cracks [2]. Pressure, temperature, and water are the agents that lithify terrestrial rocks. By contrast, though all meteorites have experienced some metamorphism, most have not seen sufficient pressure, temperature, or aqueous alteration to account for their lithification. Even meteorites of low shock state [3] are well-lithified, and thus, their original accretion into meteorite parent bodies had to have been at impact velocities much lower than those that would be required for shock melting and lithification. Static pressures of 1–10 GPa are needed to compress terrestrial sandstones, But, 1 GPa static pressures are reached only at the center of a Ceres-sized body [4]. How did collections of nebular dust and chondrules become well-lithified meteorites?

Shock Lithification: During early accretion in the solar nebula, relative particle velocities are controlled and limited by nebular gas drag. The maximum possible impact velocity equals the deviation of the gas from Keplerian rotation. Millimeter-sized particles coupled to the gas impact on meter-sized or larger bodies at roughly 50 m/s, compressing under dense "fairy castle" structures, though hardly lithifying them. Such bodies would be coherent enough to participate in further accretion but would have very high porosity.

The Effect of Jupiter: The gravitational influence of Jupiter forming in the solar nebula (perhaps also while inducing shocks to form chondrules) will perturb all nebular material and planetesimals within several AU. The larger the planetesimal, the smaller the damping due to nebula drag, so the effect of Jupiter becomes more important as Jupiter accretes. In our models, Jupiter can perturb a 100 km diameter planetesimal, even those not near a major resonance, to eccentricities fluctuating from 0 to 0.1. 10 km bodies should attain eccentricities of 0.05, while smaller ones would continue to be damped to low eccentricity by gas drag until the gas has dissipated. At deviations in eccentricities of 1 km/s, producing an energy density equivalent to a GPa. Furthermore, the decompression following the passage of a lithifying shock could produce the microcracks responsible for the ubiquitous 5-10% porosity [5].

While Jupiter has "pumped up" the eccentricity of the larger planetesimals, the solar nebula is still in place and largely unaffected by Jovian perturbations. Essentially, larger planetesimals would be sweeping through the nebula at high relative velocity, collecting vast numbers of smaller bodies in relatively high-energy impacts. These impacts would be far too small to disrupt a large parent body (this would require similar-sized bodies) but would deposit a huge amount of impact energy isotropically across the surface. This process would produce lithified layers in a more porous unconsolidated matrix (similar to that seen in impact experiments with porous targets [6]). Subsequent collisional disruptions caused by impacts of similarly sized planetesimals would dissipate any surviving lowdensity matrix but allow the lithified regions to survive to the present.

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EVIDENCE FOR SILICATE LIQUID IMMISCIBILITY WITHIN SILICATE INCLUSIONS DURING RAPID COOLING OF THE SOMBRERETE (UNGROUPED) IRON METEORITE

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Introduction: Fifteen silicate inclusions in the Sombrerete iron meteorite were studied using SEM and EMP methods to better characterize this poorly-studied but interesting meteorite. Sombrerete silicate inclusions have highly fractionated compositions reminiscent of those in some IIE iron meteorites, but they contain more phosphate than in any other known meteorite [1, 2]. Oxygen-isotopic compositions [3] appear to preclude Sombrerete form being a IIE iron. Prinz et al. [2] suggested that silicates in Sombrerete formed by impact-mixing of fractionated silicate with metal, although the processes leading to the formation of such fractionated compositions were unclear. We analyzed 10 inclusions in a thin-section (AMNH 4493–2) previously studied by Prinz and coworkers, as well as 5 additional inclusions prepared in new polished mounts.

Textures, Mineralogy, and Rapid Cooling: Inclusions in Sombrerete are dominated by sodic glass, microphenocrysts, and crystallites, which include orthopyroxene (Opx, Wo₁₋₃En₆₂₋₇₂), plagioclase (Plag, $Ab_{10-54}An_{89-46}$), Cl-apatite (Apat), and ilmenite. Mineral assemblages and textures vary from one inclusion to another. One type of inclusion contains euhedral Apat microphenocrysts set in a glassy groundmass. A more common type contains euhedral Opx and subhedral Plag set in glass with numerous smaller Apat crystallites. One of the larger inclusions contains strongly zoned chromite set in glass. Features consistent with rapid cooling in the inclusions include abundant glass, crystallites aligned in patterns suggestive of quenching, and skeletal crystals.

Immiscible Liquids: Many inclusions show evidence for the separation of immiscible liquids on about a few hundred micron scale, manifested most obviously by the presence of fine-grained, P-Cl-rich segregations, but also by regions of differing mesostasis compositions and textures. Three basic types of segregations have been identified: 1) P-Cl-rich segregations have sharp boundaries that appear to be menisci, along which nucleation and sometimes diffusional exchange occurred. These segregations vary in composition but appear to contain an intimate mixture of phosphate, orthopyroxene, and feldspathic glass, as well as elevated proportions of ilmenite. The segregations occur only in inclusions of the most common type, which lack Apat microphenocrysts; 2) inclusions also show evidence for separation of Na from K in melts that solidified to produce sharply-defined pods of compositionally distinct glass or compositionally and texturally distinct mesostases. In some inclusions, Mg in melt moved together with K to form K-Mg-rich mesostasis, which produced few Plag and Opx crystallites. K-Na separation occurred in all types of inclusions, after the crystallization of Apat, Opx, and Plag microphenocrysts; 3) another type of segregation, found in one inclusion as an "orb" and as regions along the margins of other inclusions, crystallized Plag and Si-polymorph intergrowths ("spongy feldspar").

Conclusions: We found evidence for the separation of various immiscible liquids within individual Sombrerete inclusions during rapid cooling. Our results suggest that immiscibility could be important for helping to establish the highly fractionated compositions of silicate inclusions in Sombrerete and other iron meteorites.

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CHROMIUM-BEARING PRESOLAR OXIDE GRAINS IN A $^{54}\mathrm{CR}\text{-}$ RICH ORGUEIL RESIDUE

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Introduction: Chromium-54 is enriched in certain leach fractions of several chondrites, most likely indicating the presence of one or more as-yet-unidentified presolar phases, soluble in the usual treatments used to isolate presolar grains [1–3]. Here, we report the discovery of two Cr-rich presolar oxide grains in the Orgueil (CI1) meteorite. The grains were identified in a ⁵⁴Cr-enriched residue and are, hence, strong candidates for being among the anomalous ⁵⁴Cr carrier(s).

Experimental: An organic-rich residue was prepared by treating an Orgueil sample with a CsF-HF solution; previous measurements showed that Cr leached from this residue with hot HCl has δ^{54} Cr/⁵²Cr ~20‰ [3]. An aliquot of the residue was ashed in an O plasma to destroy the organics, and a ~1–5 µm size separate of the remaining material was deposited on a gold foil for ion probe analysis. SEM-EDS indicates that the residue consists of ~33% MgAl₂O₄, ~15% TiO₂, ~14% Cr₂O₃, ~13% MgCr₂O₄, and ~12% other Cr-rich oxides with varying amounts of Fe, Mg, Al, and/or Mn. Minor amounts of Al₂O₃, hibonite, and contamination phases make up the remainder. Individual O-rich grains were automatically analyzed for ¹⁷O/¹⁶O, ¹⁸O/¹⁶O, and AlO⁻/O⁻ ratios with the Carnegie ims-6f ion probe [4].

Results and Discussion: Of ~260 analyzed grains with reasonable errors, 3 had O-isotopic compositions indicative of a presolar origin. Subsequent SEM analysis showed that 2 of these are a new presolar mineral phase rich in Mg, Al, and Cr. EDS analysis suggests that both grains are ~50: 50 solid solutions of spinel (MgAl₂O₄) and magnesiochromite (MgCr₂O₄). Although both pure spinel and pure MgCr₂O₄ are common in our Orgueil residue, the mixed phase is very rare (<2%) and is apparently dominated by presolar grains. The third presolar grain was completely consumed during the O measurement, so its mineralogy cannot be determined.

Grain ORCR1 is a group 2 grain [5] with $\delta^{17}O = +2130\%$, $\delta^{18}O = -900\%$; ORCR2 is a group 1 grain with $\delta^{17}O = +1840\%$, $\delta^{18}O = -200\%$. Both grains were ~1 µm prior to the O measurement, and sufficient material remains for NanoSIMS measurements of Cr and Mg isotopes. It is unlikely that significant nucleosynthetic effects in Cr would be found in the low-mass O-rich stellar parents of group 1 oxide grains like ORCR2. However, the highly ¹⁸O-poor composition of ORCR1 is consistent with hot-bottom burning in an intermediate mass AGB star. Neutron-capture reactions in such stars are predicted to result in enhanced surface ⁵⁴Cr/⁵²Cr ratios, but about normal ⁵⁰Cr/ ⁵²Cr and ⁵³Cr/⁵²Cr ratios [6]. Thus, it is plausible to expect that at least grain ORCR1 could be ⁵⁴Cr-rich, though this obviously needs experimental verification.

It is unlikely that spinel-magnesiochromite is sufficiently soluble in HCl to be the major ⁵⁴Cr-rich carrier in Orgueil, though we cannot rule out that very small grains could dissolve. However, stepped leaching indicates that there could be more resistant ⁵⁴Cr phases as well [2], and our grains are obvious candidates. That C-rich AGB stars are expected to have about monoisotopic ⁵⁴Cr excesses indicates that the dominant anomalous phase could in fact be soluble Cr-rich sub-grains of presolar SiC and/or graphite.

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SOURCES OF SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM

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Many short-lived radionuclides were present in the early solar system (e.g., ¹⁰Be, ²⁶Al, ⁴¹Ca, ⁵³Mn, ⁶⁰Fe). Short-lived radionuclides are produced in several ways including by nucleosynthesis in stellar interiors [1], by explosive nucleosynthesis during nova or supernova explosions [2], by cosmic-ray interactions [3], and by interactions between high-speed stellar ejecta and ambient interstellar dust [4]. A major challenge facing cosmochemists is to determine which of these sources contributed significantly to the solar system inventory of short-lived radionuclides. Keys to resolving this issue are to identify radionuclides that are produced by only one process and to study coproduction of different nuclides by a single mechanism.

¹⁰Be is produced efficiently only by spallation, either by cosmic rays or through high-speed collisions between parcels of gas and dust. The discovery [5] that ¹⁰Be was abundant in CAIs ([¹⁰Be/⁹Be]₀ \sim 1 × 10⁻³) [5–7] raises the possibility that spallation could have produced most of the short-lived radionuclides. One calculation seems to indicate that ¹⁰Be, ²⁶Al, ⁴¹Ca, and ⁵³Mn could have been produced in the observed abundances by irradiation of core-mantle protoCAIs with low-energy ³He-rich solar cosmic rays in the reconnection ring near the protosun [3]. However, the conditions necessary for this to work, especially for ²⁶Al, are very specific and quite extreme [6]. Also, ¹⁰Be and ²⁶Al are decoupled in some CAIs [6, 7], making an irradiation source for both unlikely. ¹⁰Be (and ⁴¹Ca) can be produced efficiently by typical early solar system proton fluxes.

In contrast, 60Fe is not produced at all efficiently by spallation, so an inferred solar-system abundance greater than the steady-state abundance in the galaxy would require a stellar input. Earlier this year, our group [8, 9] and the Mainz group [10] reported clear evidence of ⁶⁰Fe in primitive ordinary chondrites at abundances that require a stellar source. The type of stellar source can perhaps be determined from the solar system initial ⁶⁰Fe/⁵⁶Fe, estimated to have been between $\sim 3 \times 10^{-7}$ and $\sim 1 \times 10^{-6}$ ([8–10], also see [11]), and from the relative abundances of various radionuclides. An AGB source can only produce the inferred 60Fe/56Fe ratios under extremely neutron-rich conditions occurring in higher-mass stars [1]. However, AGB stars of >~3 solar masses have internal structures that inhibit the cool bottom processing necessary for high abundances of ²⁶Al [12]. A supernova efficiently produces ²⁶Al and ⁶⁰Fe and could generate their observed abundances. Both ²⁶Al and ⁶⁰Fe are produced primarily in the O/Ne zone of the pre-SN star, so they should remain correlated in SN ejecta, regardless of the details of mixing or shredding or the nature of injection into the solar nebula [2].

Although the nature of the stellar source is still uncertain, it is now clear that both spallation and stellar nucleosynthesis contributed short-lived radionuclides to the early solar system.

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THE METEORITE FALL AT L'AIGLE ON APRIL 26, 1803 AND THE BIOT REPORT

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"Il est tombé des pierres aux environs de l'Aigle le 6 Floréal an 11." Stones fell around l'Aigle on July 26, 1803. Thus ends the results section of the Biot report [1] read in front of the Institut de France, the 29 messidor an 11 (July 17, 1803). In a France that still used the revolutionary calendar, Jean-Baptiste Biot, a young scientist aged 29, was sent by the Home Office Secretary Chaptal to report on the spectacular fall of stones at l'Aigle, 140 km northwest of Paris.

At the time of the l'Aigle fall, the mere existence of meteorites was harshly debated [2, 3]. Chladni's book on iron masses [4] had been published in 1794, but his ideas had not yet convinced the savants of the time. Biot himself defended the theory of a lunar volcanic origin for meteorites [5, 6]. This might be the reason why Chaptal, a scientist himself, sent Biot to l'Aigle when rumors started to fill Paris with stupor and astonishment [7].

Despite, or because of, his interest in the matter, Biot claimed himself as "a witness foreign to any system" [1] when he departed from Paris to l'Aigle with a compass, a 1/86400th map of the area, and a sample of the Barbotan meteorite (fall, 1790). He did not start his enquiry at l'Aigle but in the nearby town of Alençon to check on the local mineralogy and human artefacts. Traveling between Alençon and l'Aigle, he questioned travellers and coachmen about the meteor seen the same day the stones fell. Once in l'Aigle, he questioned clergymen as well as laymen on the apparition of stones and on the meteor.

Summarizing his observations, Biot distinguished 2 kinds of evidence of an extraterrestrial origin of the stones. Physical evidence included the absence of any stone or human artifact in the area similar to the fallen stones and the sudden appearance of a large number of identical stones similar to previous meteorites such as Barbotan. Moral evidence included the number of witnesses who saw "a rain of stones thrown by the meteor" as well as their diversity in terms of profession, interests, and social status. Together, these lines of evidence pointed toward the fact that extraterrestrial stones fell around l'Aigle on July 26, 1803 [1].

With the Biot report, the existence of meteorites was recognized. In addition to a celebration of the bicentenary of the l'Aigle fall and the Biot report, our paper will aim at retracing the social context that lead a scientist, for the first time, to a thorough enquiry of stones fallen from the sky.

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EFFECTS OF PYROXENE COMPOSITION ON THE EUROPIUM OXYBAROMETER: IMPLICATIONS FOR THE OXYGEN FUGACITY OF THE MARTIAN MANTLE

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Introduction: This study is part of an ongoing effort [1, 2] to calibrate the pyroxene/melt REE oxybarometer for conditions relevant to the martian meteorites. Redox variations have been reported among the shergottites [3, 4] based on Eu/Gd partitioning and FeTi-oxide equilibrium. The Eu anomaly technique and the Fe-Ti oxide technique essentially show the same trend, with Shergotty and Zagami being the most oxidized and QUE 94201 and DaG 476 being the most reduced. Thus, the variation in fo₂ appears to be both real and substantive. However, although the redox trends indicated by the two techniques are similar, there is as much as a 2 log unit offset between the results of [3] and [4]. One explanation for this offset is that the Eu calibration used for the shergottites was actually designed for the LEW 86010 angrite, a silica-undersaturated basalt whose pyroxene (diopside) compositions are rather extreme. To correct this, Musselwhite and Wadhwa [1] and McCanta and Rutherford [2] have conducted experiments on the redox relationship of Eu partitioning relative to Sm and Gd for pyroxene/melt compositions more relevant to Martian meteorites. Here, we report preliminary results for experiments on pigeonite/melt partitioning as a function of fO₂.

Experimental: Pigeonite/melt partitioning experiments were run in a gas-mixing DelTec furnace at fO_2 ranging from IW – 2 to IW + 4. The starting composition was designed to produce martian composition pigeonite on the liquidus. This composition was doped with 1% each of Sm, Eu, and Gd. Samples were suspended from a Re wire loop in the furnace. The samples were first raised to super liquidus temperature (1300°C), held for 30 min, ramped down at 1° per min to run temperature (1240°C), then quenched after 24 hr. Run products were analyzed for all elements with the SX100 EMP at NASA/JSC and for REE with SIMS at UNM.

Results: Fig. 1 shows experimentally determined $D_{Eu}/D_{Sm, Gd}$ with fO_2 for this study. Also plotted are pigeonite/melt data from [2] (M'02 in Fig. 1). The pigeonites in both studies have similar Ca contents (Wo₅). The pigeonites in this study have higher Mg/Fe (En₇₅ cf. En₆₀) than [2]. We are currently investigating REE pig/melt versus fO₂ for higher Ca pigeonites. Stay tuned to this space.



Fig. 1.

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EXPERIMENTAL DETERMINATION OF ACTIVITY COEFFICIENTS OF SILICON IN METAL AND THEIR RELEVANCE FOR SILICATE-METAL EQUILIBRIA IN PLANETESIMALS

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Introduction: The equilibration of silicate melts with iron-nickel metal is a fundamental process in planetary differentiation (e.g., core formation). A sensitive indicator for the conditions of metal separation is the amount of Si in metal. In calculating Si partitioning between metal and silicate, the knowledge of the activity coefficients of silicon in iron-nickel alloys is essential. For pure iron, some experimental data are available in the literature [1, 2, 3]. However, little is known for FeNi-alloys. We, therefore, performed experiments to determine the activity coefficients at different temperatures in alloys with different iron-nickel ratios.

Experimental Techniques: Loops of FeNi-alloys were equilibrated with silicates of an anorthite-diopside-quartz mixture, saturated in quartz, at temperatures from 1300 to 1400°C in highly reducing CO/CO₂ gas mixtures. All experiments were carried out at 1 bar total pressure. After having reached equilibrium, the silicate melt was quenched to glass and the silicon content of the metal phase was determined by EMPA. Because of the low silicon content, a probe current of approximately 2 μ A, a voltage of 10 kV, and a beam diameter of 20 μ m were used.

Results: Preliminary results indicate that, at a given temperature, the activity coefficient of silicon in the metal phase shows a strong dependence on the nickel content. For 1400°C, the activity coefficient decreased with increasing nickel content from 8.1×10^{-4} (pure iron) to 4.6×10^{-5} (pure nickel). At a temperature of 1350°C, the activity coefficient had a value of 1.2×10^{-4} for pure iron and a value of 2.2×10^{-5} for pure nickel. In addition, the activity coefficient is strongly temperature dependent. Relevant measurements are in progress.

Implications: Using these data, model calculations were performed for a silicate melt of eucritic composition in equilibrium with an iron-nickel alloy $Fe_{90}Ni_{10}$. Two scenarios were considered: equilibration of metal and silicate by 1) partial melting at 1200°C; and 2) by fractional crystallization at 1600°C. Metal in equilibrium with a melt at 1200°C would have 0.26 ppm Si, while at 1600°C, we calculate a factor of 25 higher Si content of 6.9 ppm.

Silicon concentrations in iron meteorites are below 30 ppm (e.g., [4]). More precise data are presently not known. It is, however, within the capability of modern micro-chemical instruments to determine Si in metal at the ppm level. Such data would be important for better understanding the formation of iron meteorites.

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DISSOLVED CARBON MONOXIDE IN HYDROTHERMAL FLUIDS ON SOLAR SYSTEM BODIES: EXPERIMENTAL STUDY OF REACTIVITY AND ORGANIC SYNTHESIS

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Introduction: Carbon monoxide was the major carbon gas in the solar nebula and was involved in the formation of comets and some bodies in the outer solar system (e.g., Triton, Pluto). Heating of bodies containing CO and H₂O ices should have led to interaction of CO with liquid water. At low temperatures, this interaction results in formation of formic acid, but at higher temperatures, CO_2 and H₂ form via the water-gas shift reaction: $CO + H_2O \rightarrow HCOOH$ (formic acid) $\rightarrow CO_2 + H_2$ (1). We conducted experiments to investigate the rate of reaction (1) in liquid water and observe formation of organic byproducts of the CO-H₂O interaction.

Hydrothermal Experiment: A 1200 hr experiment was conducted in a flexible gold-titanium cell apparatus at 350 bar and 150°C, 200°C, and 300°C without a mineral phase. The apparatus [1] allows sampling and injection of fluid during runs. A 150 mmolar solution of isotopically enriched (99% ¹³C) formic acid in deionized water was initially heated at 300°C. During the experiment, changing temperature, injections of deionized water, and injection of CO gas perturbed the C-O-H system. Following formic acid decomposition, the concentration and isotopic composition of CO₂(aq), H₂(aq), aqueous hydrocarbons, carboxylic acids, and alcohols were monitored with GC, GC-MS, and IC.

Results: At 300°C, comparison of measured CO, CO₂, and H₂ concentrations with values predicted at thermodynamic equilibrium for reaction (1) in liquid water indicate equilibration on time scales of hours. Perturbation of the system by decreasing the temperature from 300°C to 200°C resulted in fast (<24 hr) re-equilibration among aqueous CO, CO₂, and H₂. After a temperature decrease from 200°C to 150°C, the concentration of CO decreased slightly toward an equilibrium value but had not attained equilibrium after 63 hr. Following injection of CO and deionized water at 150°C, we observed a decrease in CO concentration and an increase in CO₂ and H_2 concentrations according to reaction (1). Although reaction (1) is relatively sluggish at 150°C, the half-life $(t_{1/2})$ for conversion of CO to CO₂ and H₂ is estimated at about 550 hr, which is very rapid on a geologic time scale. The rate of reaction (1) increased after the temperature was elevated from 150°C to 200°C. At 200°C, $t_{\!\prime_{\!2}}$ is ~25 hr. Aqueous CO, CO_2, and H_2 reached equilibrium concentrations in ~300 hr after the last temperature increase. At 300°C and 200°C, measured concentrations of formic acid corresponded to calculated equilibrium amounts. At 150°C, the equilibration of formic acid was not attained during the time of the experiment. Although ¹³C-labeled CH₄ and methanol were detected, measured concentrations are much lower than at chemical equilibrium. Production of C2+ organic compounds was not observed.

Discussion: Heating of H_2O - and CO-bearing solar system bodies would have rapidly converted CO-rich solutions to H_2 - and CO₂-rich solutions. If H_2 escapes owing to low solubility, the remaining aqueous solution becomes more oxidizing and CO₂-rich. Reaction (1) could have contributed to oxidation of bodies in the other solar system and, to a lesser extent, parent bodies of chondrites.

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MARTIAN COMPLEX IMPACT CRATERS: A SIZE AND MORPHOLOGY PROGRESSION, AND A NEWLY RECOGNIZED STRUCTURAL ELEMENT, THE PERIPHERAL PEAK RING

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Using Viking and MOC images, 680 Martian impact craters were classified into the following categories: Central Pit, Central Peak, Collapsed Central Peak, Peak Ring, Degraded, and the newly defined Peripheral Peak Ring. Although the transition between Central Peak and Collapsed Central Peak morphology is gradational, a distinction is made based on the presence of single versus multiple summits and the height to diameter ratio. Classification of Peak Ring and Collapse Ring craters is unambiguous.

A general size and morphology progression is observed from Central Peak to Collapsed Central Peak to Peak Ring morphologies. This morphologic progression is similar to that obtained by [1] for Venusian complex craters, But on Mars, transition diameters are more variable. The ratio of final crater diameter to peak ring diameter decreases as the crater diameter increases from ~7 to ~2, reaching an apparent limit at the latter value. This indicates peak ring formation geometry is dependent on the input energy to the modification phase and supports the concept that peak ring craters are formed via stability overshoot of the central uplift [1], with the Collapsed Central Peak being a transitional form.

In a fraction of Martian complex craters between 10–70 km diameter, a new morphological element is observed; a topographically symmetric ring with morphologies generally similar to those of peak rings, but occurring proportionately farther out near craters' rims. These rings always occur at a strikingly constant rim to ring ratio of ~1.3 (Fig. 1). Examples of this additional ring sometimes occur in craters with conventional peak rings, resulting in craters with two concentric peak rings. We propose the term Peripheral Peak Ring for these features to denote their proximity to the crater rim and symmetric shape. The constant rim/ring ratio is thought to reflect the near constant, but linearly varying, complex crater depths during their formation.



Fig. 1.

The restricted geographic distribution of Peak Ring craters (primarily to the southern cratered highlands) and complex craters containing peripheral peak rings (midlatitudes within 40° of the equator) further suggests that local crustal strength (or other crustal property, such as water content) varies across the Martian surface and influences final crater morphology.

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TUNGSTEN ISOTOPES AND THE TIME-SCALES OF PLANETARY ACCRETION

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Hafnium-tungsten chronometry is critically dependent on knowledge of the initial W isotopic composition of the bulk solar system (or $\varepsilon^{182}W_{BSSI}$). The difference between this and the present day W isotopic composition precisely redefined with new data [1] for carbonaceous chondrites at $\varepsilon^{182}W =$ -1.9 ± 0.1 relative to the silicate Earth, provides the most reliable current constraints on the initial Hf isotopic composition of the solar system or (182Hf/180Hf)_{BSSI}. The least radiogenic W isotopic compositions have been found in iron meteorites [2, 3] and provide evidence that the $(^{182}Hf/^{180}Hf)_{BSSI}$ is $\geq (2.1 \pm 0.7) \times 10^{-4}$. Recently, these data have been called into question [4] in support of the proposition that the $(^{182}Hf/^{180}Hf)_{BSSI}$ is closer to 1.0×10^{-4} [1, 5]. We have redetermined the W isotopic compositions of several iron meteorites using N-TIMS and MC-ICPMS and find a spread in values consistent with parent body accretion over millions of years and extending to $\epsilon^{182}W \sim 4.0$ for Tlacotopec and Arispe. No resolvable nucleosynthetic or cosmogenic effects exist; the results hold independent of the normalization scheme deployed. The implied $({}^{182}\text{Hf}/{}^{180}\text{Hf})_{BSSI}$ is $\geq (1.4 \pm 0.2) \times 10^{-4}$. This estimate is easier to reconcile with W isotope data for the Earth [1, 5, 6], Moon [7], Mars [8], and Vesta [9].

A common misconception exists that the W isotope composition of the silicate Earth defines an age of terrestrial core formation. This is only likely to be true for rapidly formed objects, and even then, the duration is unconstrained. In objects like Earth, the protracted time-scales of accretion limit W isotopic effects [10, 11]. The same holds true for U-Pb [10]. With $\epsilon^{182}W_{BSSI} = -4.0$, the mean life of accretion, assuming exponentially decreasing rates, is 13 Myr. The W isotopic data for the Earth and Moon are consistent with an age for the Giant Impact of ~40 to 45 Myr. Though longer than recently proposed [1, 5], these time-scales are shorter than those obtained from Pb isotope modeling. The values obtained from most recent estimates of the Pb isotopic composition of the silicate Earth are >15 Myr for the mean life and >45 Myr for the Giant Impact. This apparent discrepancy might reflect the relative rates of refractory W versus volatile Pb isotopic equilibration during accretion. The spread in published W isotope data for martian meteorites also is more readily explained if the (182Hf/180Hf)_{BSSI} is \geq (1.4 ± 0.2) × 10⁻⁴ given the low Hf/W of the martian mantle. The timescales for accretion and differentiation still have to be rapid (<107 yr). The W isotope data for eucrites indicate that the time-scales for the accretion and differentiation of Vesta are $\sim 10^7$ yr, consistent with other isotopic data.

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A COSMIC-RAY ORIGIN FOR CAI BERYLLIUM 10

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Synopsis: We attribute the short-lived (mean life 2.18 Myr) radionuclide ¹⁰Be incorporated live into CAIs at the birth of the solar system, at levels of ${}^{10}\text{Be}/{}^9\text{Be} \sim 10^{-3}$ [1–5], to galactic cosmic rays (GCRs). Spallation reactions involving GCR protons and He nuclei account for 20% of the ¹⁰Be, while ¹⁰Be GCRs slowed and trapped in the Sun's molecular cloud core account for the other 80% [6].

Calculation: We have used the calculations of [7] to model the time evolution of the magnetic field strength and column density of gas in a collapsing molecular cloud core. With the magnetic field strength, we account for magnetic focusing and mirroring and pitch-angle redistribution. With the column density, we calculate the loss of kinetic energy of GCRs as they ionize gas molecules. GCR protons and He nuclei easily enter the cloud core and induce spallation reactions, making ¹⁰Be. GCR ¹⁰Be nuclei with energies <10 MeV/n are slowed and trapped in the cloud core, increasing ¹⁰Be directly. We use the GCR spectrum of [8] but multiply the flux by a factor = 2, based on multiple lines of evidence that GCR fluxes were 2 times greater 4.5 Gyr ago [6]. Accounting for trapping, production by spallation, and decay, we calculate the time evolution of the ¹⁰Be/9Be ratio in a collapsing molecular cloud core. By the time the protoSun formed, we predict ${}^{10}\text{Be}/{}^{9}\text{Be} = 1 \times 10^{-3}$, with 50% uncertainty. Preliminary calculations also indicate that this ratio is spatially homogeneous within the cloud core to <<10%

Discussion: We dispute the conclusion that the presence of ¹⁰Be implies irradiation of solar nebula material by energetic particles from the early Sun [9]. At least half of the ¹⁰Be, and probably all of it, is attributable to GCRs. Production of ²⁶Al, etc., by in situ irradiation [9, 10] would necessarily overproduce ¹⁰Be [6]. The new evidence for live ⁶⁰Fe in the solar nebula [11, 12] suggests a supernova origin for all the radionuclides, except ¹⁰Be, which we attribute to GCRs.

The spatial homogeneity of ¹⁰Be, and its origin before the formation of the first solar system solids, renders it an excellent chronometer of early solar system events. The spread in ¹⁰Be/⁹Be ratios in CAIs suggests melting spanned 2 Myr, consistent with the spread in ages from Fe-Ni [11], U-Pb [13], and Al-Mg [2] systematics.

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ARE THE METEORITES CATHODE-ANODE SYSTEMS PLACED IN THE SOLAR WIND? IONIC CAVITIES BY EGD EFFECT ON THE SURFACE OF THE METEORITES

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Abstract: Electrostatic and electrogasdynamic (EGD) transport effects triggered by the solar wind's corpuscular, gamma-ray, X-ray, and UV radiations may partially explain the bowl shaped cavitated surface of some meteorites.

Introduction: Orbiting surfaces are affected by the radiations and the solar wind from the Sun. Such effects were also studied on the Surveyor missions to the Moon. [1]. We used these effects in making an experimental lunar quasiatmosphere [2–7]. In this study, we extended the possibility of the anode-cathode transport effects to the irradiated meteorite surfaces.

How the Meteoritic Surface Can Work as an Onode-Cathode System: The surfaces of the orbiting meteorites are always bombarded by the solar gamma, X-ray, and UV radiation of the Sun and other corpuscular particles of the solar wind. These sources deliver enough energy for the outer surface of the meteorite that some electrons escape. Escaping electrons leave an extra positive charge on the surface of the meteorite. Because of this, the charge gradually grows very high, from 100 V up to 100 kV electrostatic potential, depending on the generating radiation. The charged meteorite surface acts as a cathode-anode system [2–3].

Cathode/Anode Effects—Ion Transport on the Surface: Suppose that the charged meteorite meets with a rare ionized gas cloud (in the vicinity of the sun or in the ionosphere of Earth). The meteorite pushes positive ions but attracts the large negative ions. Impacts of the large negative ions may cause the ioncavity effect.

In this scenario, the surface is randonly bombarded. However, if the flux of the impacting ions is large enough, then the self magnetic force field of this stream contains the ion-stream and causes expressed cavities on the surface. The local surfaces are hyperboloides (these are the bowl shaped cavities). The overall shape and the local relief of the meteorite are boundary conditions of the final cavity places and formation [8]. This effect causes local mass loss on all moving objects (meteorites and spacecrafts). In our experimental chamber, we continue the studies of meteoritic ion-cavity formation. There, we use oxide cathodes and water vapor for the gas of large negative ions.

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REINVESTIGATION OF THE NI AND CO METAL-SILICATE PARTITION BEHAVIOR AND IMPLICATIONS FOR PLANETARY DIFFERENTIATION PROCESSES

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In the past years, several experimental studies have focused on the determination of the metal/silicate partition coefficients (D_{met/sil}) of Ni and Co (summarized in [1]). Application of these low pressure, low temperature (1300-1600°C) partition data at P-T-fO2-conditions appropriate to core formation, assuming core-mantle equilibrium and a chondritic Ni/Co ratio for the bulk Earth, yields calculated Ni- and Co-contents and a Ni/Co ratio of the mantle that are significantly lower than those observed in today's upper mantle rocks. Li and Agee [2] have shown that Ni becomes more lithophile with increasing pressure. Co shows a similar but less pronounced effect. Increasing temperature has exactly the same effect, strongly decreasing Ni D_{met/sil} and moderately decreasing the corresponding Co partition coefficient, while Fe is essentially independent of temperature along the Fe-FeO equilibrium. The purpose of the present study is to better define the temperature dependence of the D_{met/sil} for Ni, Co, and Fe, which will allow us to disentangle the effects of temperature and pressure. In addition, the new data will allow us to better understand core formation in small planetesimals.

Metal loops were equilibrated with silicate melts of anorthite-diopside eutectic composition in vertical gas mixing furnaces at the Universität zu Köln at temperatures of 1300 to 1600°C. Charges were analyzed with a JEOL JXA 8900RL electron microprobe at 15 kV, 400 nA, and a defocused beam (raster size $20 \mu m$).

The first results confirm earlier data by [3] but are more precise because of improved analytical procedures. The Ni $D_{met/sil}$ decreases by a factor of 2.5 from 1300 to 1600°C along the Fe-FeO equilibrium. The strong temperature dependence of Ni $D_{met/sil}$ may be applied to the formation of meteoritic basalts and allows us to distinguish between silicates formed by partial melting at about 1200°C and fractional crystallization at about 1600°C [4].

Further experiments with the piston cylinder apparatus at the Universität Münster were performed to study the temperature dependence at higher pressures. In these experiments, $Fe_{54}Ni_{29}Co_{17}$ alloys were equilibrated with liquid basaltic silicates. The results of these runs are currently analyzed for Ni, Co, and Fe. The new data will allow us to distinguish between the effects of temperature and pressure on the partition behavior of Ni and Co between coexisting silicate and metal phases.

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A SEARCH FOR NUCLEOSYNTHETIC TELLURIUM ISOTOPE ANOMALIES IN CARBONACEOUS CHONDRITES

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Tellurium has eight stable nuclides that are a mixture of p-process, sprocess and r-process components. As such, Te is well suited for the study of nucleosynthetic processes. Here, we report Te isotopic compositions of leachates of the carbonaceous chondrites Orgueil (CI), Murchison (CM), and Allende (CV). Nucleosynthetic anomalies in leachates of carbonaceous chondrites were found for ⁵⁴Cr, ⁴⁰K, Mo isotopes, and ⁹⁶Zr [6–10]. In contrast, Fe and Se isotopes show no anomalies for similar leachates [11, 12]. Bulk chondrites, iron meteorites, and leachates of Allende measured by TIMS and MC-ICPMS display isotopic homogeneity in Te [1–5]. In this study, the samples were sequentially leached with reagents of increasing strength [5–11], namely: 2.5% acetic acid, 50% acetic acid, 4 M HNO₃, 6 M HCl, 3 M HCl-13.5 M HF, and concentrated HF-HNO₃ in a bomb (Table 1). All measurements were performed by MC-ICPMS.

Table 1. Relative Te contents of carbonaceous chondrite leachates.

Leachate	Orgueil	Murchison	Allende	Allende [5]
2.5% HAc	0%	0%	_	_
50% HAc	7%	1%	0%	0%
4 M HNO ₃	19%	16%	24%	4%
6 M HCl	65%	73 %	65%	68%
HCl-HF	8%	8%	11%	28%
HF-HNO ₃	1%	2%	0%	0%

For all three samples, the majority of the Te (>85%) was found in the 6 M HCl and the 4 HNO₃ leachates (Table 1).

The isotopic composition of Te was determined for the HNO₃, HCl, and HCl-HF leachates of all 3 meteorites and for the 50% acetic acid leachate of Orgueil. The Te isotope data obtained for the HNO₃ leachates of Murchison and Orgueil show small positive deviations in the abundances of the isotopes ¹²⁸Te and ¹³⁰Te. However, these positive deviations are barely resolvable given the analytical uncertainties and, thus, require confirmation with additional analyses. Because both ¹²⁸Te and ¹³⁰Te are r-process only isotopes, the positive anomalies are in accord with previously identified r-process signatures of Mo and Zr in leachates of carbonaceous chondrites [9, 10].

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MARTIAN MULTI-ELEMENTAL MAPS FROM THE MARS ODYSSEY GAMMA-RAY SPECTROMETER

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Introduction: The Mars Odyssey spacecraft has been in its 400 kmhigh polar mapping orbit around Mars since the beginning of 2002. The Mars Odyssey gamma-ray spectrometer (GRS) collected gamma-ray spectra in cruise and in early mapping until it was deployed on a 6 m boom in June 2002. Since then, it has been collecting its prime martian spectra. Gamma-ray spectra in early 2002 helped to quantify the distribution of hydrogen, believed mainly to be in the chemical form of water, in the top meter of Mars near the martian poles [1]. Initial gamma-ray results for K, Th, Si, and Fe were presented at the 34th Lunar and Planetary Science Conference [2–5]. Additional results for these five elements are reported here.

Data Reduction: Spectra are accumulated every 19.75 seconds, corrected to a common gain, and added together to get adequate counting statistics. Depending on the signal strength, spectra are summed for different size bins (5°, 10°, or 15°), and the areas under the gamma-ray peaks are determined. Spectra collected during and just after solar particle events or when there is a CO_2 layer on the surface were not used. These peak areas were then compared to expected counts based on calculations to get concentrations [2].

Results: The hydrogen content is, in water, equivalent by weight and is normalized to 94% water near the north pole. H concentrations assume that the H is uniformly distributed with depth to several meters and that the composition of the soil with respect to major neutron absorbing elements is the same as that of Mars Pathfinder soil [6]. In the regions never covered by CO_2 , between 45 degrees north and south, H varies between 1% and 7%. The H content increases polewards of 45° and reaches ~43% near the south pole.

Results for K, Th, Si, and Fe are currently limited to regions recently free of surface CO₂ that have many spectra, between 65°N and 45°S. For large regions (many degrees square), the concentration of K varies from about 0.2 to 0.5% and of Th between 0.7 and 1.6 ppm, higher than in most Shergottites [4]. The K/Th ratio varies between about 1800 and 4000, which could reflect both primary production and secondary alteration processes [4]. Preliminary results for Si and Fe were normalized to their concentrations at the Mars Pathfinder landing site [6]. Iron varies between ~11–17% Fe by weight, and Si varies between ~19–23% Si by weight.

Our preliminary concentrations do not show any strong correlations with other remote-sensing results for Mars, such as thermal inertia, albedo, and rock abundances [5]. The region between 40° and 60° N that was identified as "type 2" in TES spectra [7] (either andesitic [7] or weathered basalt [8]) is enriched in K and Th.

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UBIQUITOUS NANOPHASE FE, NI CARBIDES IN MURCHISON FINE-GRAINED RIMS: POSSIBLE RELICTS OF NEBULAR FISCHER-TROPSCH REACTIONS

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Introduction: An understanding of the distribution and mineralogical associations of solid organic material in carbonaceous chondrites can provide important clues as to the possible origins of this material. We have been studying the Murchison CM2 chondrite to determine exactly where organic material is located in situ using EFTEM techniques. We [1] reported the presence of putative Fe, Ni metal grains in fine-grained rims in Murchison that are associated with carbonaceous material. Further, TEM studies show that the identification of these phases as Fe, Ni metal is incorrect and that they are, in fact, Fe, Ni carbides. Here, we report the detailed occurrence and possible implications of these Fe, Ni carbides.

Results: Fe, Ni carbide grains have been found in three different finegrained rims. Although their abundance is not high, they are encountered frequently in ion-milled samples. The carbides occur as isolated grains, but clusters of several grains are most common. The grain size of the carbides varies from 10 to 38 nm and they typically have a rounded morphology, although elongate grains are sometimes found. All the carbide grains are surrounded by continuous rims of nanocrystalline magnetite (6-7 nm in thickness) that are separated from the carbide core by a very thin layer of low-Z material. EFTEM imaging shows that this layer is carbon-rich and appears to be amorphous based on HRTEM imaging. EDS analysis indicates that two different carbide phases are present: one with Ni contents of 1-2 wt%, and the second with higher Ni contents, close to 8 wt%. We have not yet been able to definitively identify the carbide phases based on the available electron diffraction data. However, our preliminary data are most consistent with cohenite and, possibly, haxonite. EFTEM imaging shows that the carbide grains are commonly associated with regions of carbonaceous material that show enrichments in nitrogen immediately adjacent to the carbide grains.

Discussion: Fe carbides, such as haxonite and cohenite, can form as a result of carburization of Fe, Ni metal within an asteroidal environment during mild thermal metamorphism [2, 3]. Temperatures in excess of ~400°C are required to stabilize cohenite [4], values that are clearly unreasonable for the CM chondrites, which have estimated alteration conditions <50°C [5]. At these conditions, Fe-carbide phases that are stable at low temperatures, such as ϵ -carbide and Hägg carbide should form, not cohenite. Neither of these phases appear to be present in Murchison indicating that an asteroidal origin is unlikely. The fact is well-known that cohenite can form during Fischer-Tropsch catalysis reactions as a result of progressive carburization of Fe metal [4] and can be associated with amorphous carbon. The clear association of carbon-rich material with the carbides in Murchison appears to be consistent with the formation of the carbides during nebular Fischer-Tropsch reactions. This is generally consistent with the presence of nitrogen-rich carbonaceous material, which is probably organic in character, rimming the carbide grains. The rims of magnetite indicate that Fe carbides underwent oxidation after their formation, probably in the CM parent body. This is consistent with the observations made by [3] for carbides in Semarkona. Alteration of the carbides probably did not go to completion because of the build up of an impermeable layer of amorphous carbon released during the oxidation of the carbide.

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THE ¹⁷⁶LU DECAY CONSTANT DISCREPANCY: TERRESTRIAL SAMPLES VERSUS METEORITES

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Introduction: The use of initial Hf compositions of rocks and zircons for constraining early Earth's crust-mantle differentiation history requires: 1) a well-constrained Hf isotopic evolution curve for the bulk silicate Earth; and 2) an accurate ¹⁷⁶Lu decay constant (λ^{176} Lu). λ^{176} Lu remains controversial; recent estimates range from 1.70 to 1.98×10^{-11} yr⁻¹ [1–3]. Two approaches have been used to measure the beta decay of ¹⁷⁶Lu to ¹⁷⁶Hf. The first comprises physical counting experiments in which decay events in a Lu sample are counted as characteristic particle or radiation emissions. The second type, "age comparison," involves measuring the amounts of ¹⁷⁶Lu and radiogenic ¹⁷⁶Hf (= ¹⁷⁶Hf*) in geologic or meteoritic samples of known age (t), and using the relationship: λ^{176} Lu = ln(¹⁷⁶Hf*/¹⁷⁶Lu + 1)/t.

Discussion: Fig. 1 shows recent λ^{176} Lu determinations from counting experiments, terrestrial age comparisons, and meteorite age comparisons. Counting data from different laboratories scatter beyond reported errors, suggesting the presence of additional systematic errors in some of those experiments. Age comparison data produce more consistent results, but there is still a ~5% difference between the mean terrestrial and meteorite λ^{176} Lu values. Existing Hf data for pre-3.5 Ga zircons and rocks viewed in light of the higher λ^{176} Lu suggest that substantial mantle depletion occurred in the Hadean without much evidence for a complimentary enriched reservoir. The same data reinterpreted with the lower decay constant suggests that a small volume of ≥4.3 Ga crust was produced, but without large-scale mantle depletion at that time. The λ^{176} Lu discrepancy must be settled before Hf data can be used to choose between such vastly different scenarios for the early crust-mantle differentiation of the Earth, the Moon, or Mars.



Fig. 1. λ^{176} Lu determinations since 1980. The vertical shaded bars indicate 2 s.d. limits from mean values (vertical lines).

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INSIGHTS INTO FE-NI METAL SURVIVAL IN THE HYDRATED FINE-GRAINED RIMS IN THE Y-791198 CM2 CARBONACEOUS CHONDRITE

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Introduction: Fe-Ni metal grains occur juxtaposed against hydrous secondary minerals in fine-grained rims around chondrules, etc. in the weakly altered CM chondrite, Yamato-791198 (Y-791198). These metal grains have been cited as conclusive evidence for pre-accretionary alteration [1, 2]. In contrast, a number of lines of evidence have been reported that cannot be adequately explained by nebular or pre-accretionary alteration (e.g., [3–5]). In an effort to resolve this controversy, we have undertaken a SEM and TEM study of the Fe-Ni metal grains in the fine-grained rims of Y-791198.

Results: Fe-Ni metal grains in Y-791198 fine-grained rims are both rare (1–2 grains per rim) and very small (<10 μ m). We are applying focused ion beam (FIB) techniques to prepare site-specific TEM sections of Fe-Ni metal grains. So far, we have studied one FIB-prepared metal grain (~4 μ m) using a variety of TEM techniques. These studies demonstrate conclusively that the metal grain shows clear evidence of alteration at the sub- μ m level. Z-contrast STEM imaging shows that, locally, the grain has developed re-entrant features, a few 10s of nm in depth, similar to Fe metal that has experienced pitting corrosion [8–11]. These re-entrant features have a lower Z than the rest of the metal grain and show an O-enrichment in EFTEM maps that is consistent with local oxidation of the Fe.

Discussion: These observations are evidence that metal grains in Y-791198 have undergone aqueous alteration, although the extent of alteration is extremely limited. We propose that the limited extent of reaction can be explained by considering the geochemical behavior of altering fluids. Computer modeling of aqueous alteration in CM chondrites [6] suggests that immediately after fluid-rock contact, the pH of the fluid soared from 7-9 and the continued to rise to 12. This effect can be attributed to the rapid consumption of H+ ions required for hydrolysis of the precursor anhydrous materials, which may have been amorphous [7]. Studies of the corrosion behavior of Fe metal in alkaline solutions [8-11] show that increases in pH (>10) result in a significant increase in corrosion resistance. Also, the corrosion susceptibility is inversely proportional to Ni-content and as little as 2 wt% Ni is needed to inhibit corrosion [8]. Corrosion resistance is a result of formation of a protective film [8], and the presence of organics, HCO3⁻, and dissolved silica act to inhibit corrosion [9-11]. The corrosive effects of dissolved sulphide and Cl- are neutralized in alkaline solutions [9]. These observations show that the presence of Fe-Ni metal grains is not definitive evidence for pre-accretionary alteration. Instead, the resistance of metal grains during the early stages of alteration is consistent with the predicted increase in alkalinity of the early fluid. This is also congruent with the observation that the FIB-prepared metal grain is not pristine, but shows evidence of incipient alteration. These results are entirely consistent with an early, alkaline stage of parent body alteration, as modeled by [6].

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RIDGECREST—NEW CLASSIFICATION, RECOVERY INFORMATION

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Introduction: This paper reports on a recent characterization of the Ridgecrest meteorite by researchers at UCLA. This stone is now reclassified as an ordinary chondrite (H5). This paper proposes that the following revisions to the Catalogue of Meteorites should be posted in the Meteoritical Bulletin:

Ridgecrest, new classification	35°35′N, 117°34′W
San Bernardino County, California, USA	
Found: 1958 May 24	
Ordinary chondrite (H5)	
(1 stone, 9.7 grams)	

Dr. Ed Krupp graciously supplied the stone from the Griffith Observatory Collection, and the author (Verish) cut a 0.3 g sample for analysis. Alan Rubin (UCLA) conducted the characterization of this stone. The following are his results:

Ridgecrest: class, H5; shock stage, S2; weathering grade, W2; olivine, Fa18.6 \pm 0.2%.

Recovery Information: Note that the Cuddeback Dry Lake 005 (H5, S2, W4, Fa18.7 \pm 0.6%) and CuDL 009 (H5, S2, W5, Fa18.6 \pm 0.2%), both characterized by A. Rubin (UCLA), have find localities that are within 20 miles of the Ridgecrest (H5) find location.

Neither meteorite has been paired with certainty to any other find from this region. Clearly, the reference to F. C. Leonard's paper in Meteoritics 1963 (pairing Ridgecrest to the Muroc and Muroc Dry Lake L chondrites) should be deleted from the Catalogue of Meteorites [1]. Also, the documented find location has been confirmed through conversations with the finder (L. E. Humistonn 2002, personal communication). The finder recovered this meteorite while hiking in open desert on the northwest sloping pediment of the Spangler Hills. The find, a small, black, teardrop-shaped stone, was easily spotted because it contrasted against the lighter-colored surface of decomposed granodiorite. This location is just east of the county line in San Bernardino County. The finder still has in his possession the original correspondence (1958) in which F. C. Leonard conjectured that the find location might be, instead, "Kern County." This assumption became the documented find location in [2]. For the next 22 years, the literature would erroneously refer to the Ridgecrest find location as "Kern County." The actual find location coordinates were properly recorded in 1980 by J. T. Wasson. The coordinates in the Catalogue of Meteorites are correct, per the referenced document, "J. T. Wasson, letter of 15 April, 1980, in Min. Dept., NHM. London."

Conclusion: The new characterization of the Ridgecrest meteorite by Alan Rubin (UCLA) should be incorporated in the Catalogue of Meteorites, and these proposed revisions should be posted in the Meteoritical Bulletin as "Ridgecrest, new classification."

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OXYGEN-ISOTOPE COMPOSITION OF RELICT GRAINS IN CARBONACEOUS-CHONDRITE CHONDRULES

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Introduction: Type-II porphyritic chondrules in CO3.0 chondrites contain low-FeO relict grains [1]; the overgrowth thicknesses are thin, \sim 5 µm. Similarly, thin overgrowths occur on coarse high-FeO olivine phenocrysts, suggesting that these are also relict grains. Recycled chondrule materials, thus, constitute the dominant component of type-II chondrules, suggesting that these chondrules formed relatively late during the chondrule-forming period. Flash evaporation and recondensation causes the composition of the solid precursors to move towards the composition of the gas. Microscale in situ analyses of O-isotope compositions can help assess the degree of heterogeneity among chondrule precursors, as preserved as relict grains, and help us understand the nebular processes that caused these isotopic differences.

Experimental: The CO3.0 Yamato-81020 (Y-81020) chondrite [2] is well suited for this study because it experienced minimal aqueous/thermal alteration. Relict and host olivine grains in six type-II chondrules from Y-81020 were analyzed for their O-isotopic compositions. The microanalyses were performed by secondary-ion-mass spectrometry with the Cameca IMS-1270 instrument at UCLA in a peak-jumping mode.

Results: Five of the chondrules contain low-FeO relict grains with Fa <10 and host phenocrysts with Fa₁₅₋₃₅; one chondrule has a Fa₂₅ relict and Fa₆₀ phenocrysts. The results of the O-isotope analyses are summarized in Fig. 1.



Fig. 1: O-isotope distribution of relict grains and host phenocrysts from Y-81020 type-II porphyritic chondrules.

Discussions: Because Fe is reduced at high and oxidized at low nebular temperatures in a solar gas, one might expect relict-grain-bearing chondrules to record changes in the Δ^{17} O of the nebular gas. Five low-FeO relict grains have low Δ^{17} O (δ^{17} O – 0.52 × δ^{18} O) composition relative to the host phenocrysts. The difference between relict grains and phenocrysts varies from 0 to 3‰ in Δ^{17} O. The results are similar to those of [3] and the unpublished study of [4]. Because relicts predate host phenocrysts, the observed heterogeneity is consistent with the picture that there was an upward drift in Δ^{17} O with time in the CO-chondrule forming region. However, one high-FeO (Fa₂₀₋₃₀) relict grain has a higher Δ^{17} O value compared to the host phenocrysts. This either implies that the drift in Δ^{17} O was not monotonic or, more likely, that sampling heterogeneities were present on the scale of chondrule precursors.

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NI ISOTOPE ANORMALIES AND ⁶⁰FE IN SULFIDES FROM UNEQUILIBRATED ENSTATITE CHONDRITES

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Recent studies have demonstrated the existence of short-lived ⁶⁰Fe in unequilibrated ordinary chondrites [1–3]. In this report, we investigate both the ⁶⁰Fe-⁶⁰Ni and the ⁵³Mn-⁵³Cr isotopic systematics in sulfides of enstatite chondrites. We identified 37 sulfide grains or assemblages with apparent low Ni and Cr contents from 4 unequilibrated enstatite chondrites (UECs): Qingzhen (EH3), Sahara 97072 (EH3), EET 87746 (EH3), and MAC 88136 (EL3). Isotopic analyses were carried out using the Cameca ims-6f at Arizona State University. The minerals analyzed include alabandite, daubréelite, kamacite, niningerite, sphalerite, and troilite.

Most sulfides in the 4 UECs have Fe/Ni ratios too low to permit detection of the expected small anomalies in ⁶⁰Ni. However, a few sulfide grains do show resolved 60Ni excesses. A troilite-kamacite-niningerite assemblage (QZ3-S4) in Qingzhen has Fe/Ni ratios up to 130,000 and gives an apparent isochron with an initial ${}^{60}\text{Fe}/{}^{56}\text{Fe}$ ratio ([${}^{60}\text{Fe}/{}^{56}\text{Fe}$]_o) of (3.4 ± 2.1) \times 10⁻⁷ (2 σ error). The three troilite grains with the highest Fe/Ni ratios in MAC 88136 (M3641-T1, M3641-T11, and M3641-T14) also contain ⁶⁰Ni excesses, and the inferred (60 Fe/ 56 Fe)_o values are (~2.0 ± 1.0) × 10⁻⁷. In general, the (60Fe/56Fe)_o ratios in these two UECs are consistent with those observed in troilites from Krymka [1, 2] but lower than that from Semarkona [3]. One object shows a very different result. Sphalerite in a sphaleritealabandite-troilite assemblage (M3645-S5) from MAC 88136 gives large excesses at ^{60}Ni and ^{62}Ni ($\delta^{60}Ni$ = 129 \pm 128‰; $\delta^{62}Ni$ = 238 \pm 147‰; Fe/Ni = \sim 350,000) with ⁶¹Ni as the reference isotope. If we correct for mass fractionation using ${}^{62}\text{Ni}/{}^{61}\text{Ni}$, the resulting ${}^{60}\text{Ni}$ excess yields $({}^{60}\text{Fe}/{}^{56}\text{Fe})_0 =$ $(8.2 \pm 4.1) \times 10^{-7}$, similar to that inferred for Semarkona troilite [3]. If, instead, we use an external fractionation correction, the inferred (⁶⁰Fe/⁵⁶Fe)₀ ratio is $(2.8 \pm 2.7) \times 10^{-7}$, close to that inferred for Krymka troilite [1, 2]. However, the Ni isotope anomalies may not be due to live ⁶⁰Fe, but may instead be of nucleosynthetic origin, inherited from a presolar precursor. The isotope pattern for 60Ni, 61Ni, and 62Ni is very similar to the pattern observed in several Allende inclusions by [4], although the magnitude of the M3645-S5 anomalies is much larger.

Using several short-lived radionuclides together to explore the evolution of the early solar system would be ideal. Therefore, we also examined Mn-Cr isotopic systematics in some of the sulfides. Excesses of ⁵³Cr were detected in two sulfide assemblages from MAC 88136. The sulfide assemblage with large Ni isotope anomalies, M3645-S5, has ⁵³Cr excesses corresponding to an inferred initial (53 Mn/ 55 Mn)_o ratio of (1.7 ± 0.5) × 10⁻⁷. A second troilite-sphalerite assemblage (M3645-S1) gives an isochron with (53 Mn/ 55 Mn)_o = (5.7 ± 0.8) × 10⁻⁷. The inferred (53 Mn/ 55 Mn)_o values and their variability agree with previous data from MAC 88136 [5]. The spread in (53 Mn/ 55 Mn)_o ratios probably reflects diffusional redistribution of Mn and Cr after the decay of 53 Mn. Therefore, chronological interpretations of these 53 Mn- 53 Cr data are not warranted. Further work is clearly required before a comprehensive chronology based on multiple short-lived radionuclides can be developed.

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OXYGEN ISOTOPIC COMPOSITIONS OF UNIQUE CARBONATES IN MARTIAN METEORITE ALLAN HILLS 84001

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Introduction: Numerous isotopic studies of ALH 84001 have been conducted in attempts to determine and understand the environmental conditions [1–4]. In this study, we report new oxygen isotopic compositions of unique carbonate occurrences [5–7] in ALH 84001.

Results: Measurements were obtained from two separate thin sections of ALH 84001 (302 and 303) using two different ion microprobes (the CAMECA ims 6f at Arizona State University and the CAMECA ims 1270 at the University of California at Los Angeles). Major element compositions of the carbonates analyzed in this study were well-characterized prior to isotopic analysis using ~900 electron microprobe analyses obtained at the University of Chicago [5-7]. These new isotopic analyses extend the range of high-Ca carbonates in ALH 84001 that have been analyzed by ~10 mol%. The δ^{18} O of the carbonates ranged from 4.2-34.7‰ relative to SMOW, extending the range of previous oxygen isotope values (0.3 to 26.9% relative to SMOW [1-4]) by ~8‰. Besides having heavier isotopic values, the slab carbonates have similar $\delta^{18}O$ values to the previously studied rosettes, but they are significantly more Ca-rich. Textural and chemical features of slab carbonates indicate that they formed under similar conditions to rosettes, if not in the same event [6]. New isotopic compositions suggest that the mechanism causing differences in the chemical compositions between these types of carbonate is not directly linked to the mechanism causing the isotopic variations. These data, then, are not consistent with a simple fluid-mixing model. However, these data do suggest that the fluid from which the ALH 84001 carbonates precipitated was not homogenous throughout the meteorite and was probably not present in large volumes. Carbonates likely formed in isolated pockets (each possibly acting as separate, closed systems) containing limited amounts of a fluid whose composition was actively evolving as carbonate precipitation progressed. This is in contrast to an open system model [2] where carbonates would have formed from a large volume of fluid of constant composition under continuously changing environmental conditions.

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THE FALL, RECOVERY, AND CLASSIFICATION OF THE PARK FOREST METEORITE

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Introduction: On March 26, 2003, at ~23:50 CST, a fireball lit up the sky, accompanied by detonations loud enough to waken sleepers. Meteorites shattered windows and pierced roofs in and around Park Forest, ~40 km south of Chicago. Park Forest police brought specimens to their station and asked residents to do the same. Specimens were brought in for several days. So far, >40 find sites, mostly in Park Forest, have been identified. The strewnfield extends from Crete, Illinois in the south to Olympia Fields, Illinois in the north, a distance of ~8 km. Fragments range from pebble-sized to 2.7 kg. The total mass of these individuals is ~18 kg. Additional specimens probably fell in a heavily-wooded forest preserve; others were sold before their weights and locations could be recorded.

Sample Description: Individuals range from completely fusion crustcovered to nearly fusion crust-free. The rock is a breccia, consisting of angular, light-grey clasts enclosed in a dark matrix. Most specimens are dominated by the former or contain both lithologies; a few are dominated by the dark lithology. Anhedral grains of metal and sulfide visible to the naked eye are present in both lithologies.

Analysis: A 232 g specimen was coincidence-counted for cosmogenic radionuclides on a high-efficiency NaI(Tl) γ -spectrometer for 7727 min beginning at 17:19 CST on March 29th. Absorption corrections were made against mockup meteorites. Activities were very low for ⁵⁶Co (~0.1 dpm kg⁻¹), indicating an interior specimen, high for ²⁶Al (69 ± 4) and ⁶⁰Co (66 ± 3) and normal for ²²Na (95 ± 5).

Polished thin sections of both lithologies were studied optically and with the SEM and analyzed by electron probe. The two lithologies have the same mineralogy and different textures. Both are dominated by anhedral olivine (ol), low-Ca pyroxene (pyx), troilite, and Fe-Ni metal. High-Ca pyroxene and sodic plagioclase (now maskelynite) are sparse and typically 40-50 µm. Accessory phases are chromite and Ca-phosphate. Barred and porphyritic ol chondrules, 600 µm to 1800 µm across, are present in both lithologies and range from distinct to barely visible. The light lithology is coarser-grained, with ol and pyx grains mostly >200 µm across. Some clasts contain dark melt veins. The dark lithology has ol and pyx mostly <150 µm across and a fine network of sulfide-rich veinlets like those in some black chondrites. Within error, the two lithologies have identical mineral and oxygen isotope compositions. The average fayalite content in olivine (286 analyses) is 24.7 mol% ($1\sigma = 1.1$); the average ferrosilite content in pyroxene (211 analyses) is 20.7 mol% (1 σ = 0.6). Bulk δ^{18} O = +4.69‰ and δ^{17} O = +3.44‰ (L chondrite fall average: $\delta^{18}O = +4.70\%$, $\delta^{17}O = +3.52\%$ [1]).

Discussion: The average olivine, low-Ca pyroxene and O-isotope analyses show that Park Forest is an L chondrite, and that its light and dark lithologies are related. The latter is likely a sulfide-dominated partial impact melt of the former. From the homogeneity of the phases, the degree of preservation of chondrules, and the grain sizes of diopside and maskelynite, we classify it as a type 5. The presence of maskelynite, along with planar deformation features and opaque shock veins, indicates the shock stage is S5 [2]. The ⁶⁰Co and ²⁶Al data indicate a preatmospheric mass of 500–1000 kg.

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I-XE AGES OF THE DARK INCLUSIONS FROM THE REDUCED CV3 CHONDRITES LEOVILLE, EFREMOVKA, AND VIGARANO

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Dark inclusions (DIs) are lithic clasts commonly observed in the oxidized (CV_{ox}) and reduced (CV_{red}) subgroups of the CV chondrites [1]. The mineralogy and petrology of the CV DIs indicate that they experienced different types (Fe-alkali metasomatic, aqueous) and degrees of alteration in an asteroidal setting before subsequent excavation and incorporation into their host meteorites [2–4].

To estimate the duration of this alteration, we studied I-Xe systems of DIs from the CV_{red} and CV_{ox} . I-Xe ages of the 17 Allende (CV_{ox}) DIs have been reported previously [5, 6]. These DIs yielded well-defined isochrons with ages ranging from 2.77 to 0.46 Ma older than the Shallowater standard (4566 \pm 0.2 Ma). Here, we present new I-Xe data for DIs from the CV_{red} Vigarano (2226), Efremovka (E80), and Leoville (LV, LV2), whose mineralogy and petrology have been described previously [1, 7–10].

Previously reported I-Xe ages of Efremovka DIs E53 and E39 ([9], Table 1) correlate with their degree of alteration and O-isotopic compositions, with the least altered E53 being the oldest. DI E80 studied in this work shows the highest degree of replacement of primary minerals by secondary fayalitic olivine, andradite, and phyllosilicates among Efremovka DIs. The I-Xe age of E80 is concordant with the age of E39 [9] and indicates that this sample was altered either later than, or underwent longer alteration than, E53. DIs LV1 and E80 are mineralogicaly similar [8, 9]. LV-1 yields a well-defined isochron with a single release peak. In contrast with other CV3 DIs, LV2 shows little evidence of aqueous alteration. Although its I-Xe system is somewhat disturbed, it has an apparent isochron age younger than LV1 [Table 1] and abundant trapped Xe. DI 2226 is composed of high- and low-Ca pyroxene and olivine fragments set in a fine-grained matrix with bands of densely packed, fine-grained matrix-like material, interpreted to be products of sedimentary processes [10]. The I-Xe age of DI 2226 is 8.8 ± 0.6 Ma younger than Shallowater.

The I-Xe ages of 23 DIs from the CV_{ox} and CV_{red} span ~14 Ma, suggesting a long period of low temperature alteration.

Table 1. The I-Xe ages of DIs from CV3 meteorites relative to the age of Shallowater, 4566 ± 0.2 Ma (negative means older).

		(
Chondrite	Sample	I-Xe age (Ma)	References
Allende	17 DIs	from -2.77 to -0.46	[5, 6]
Efremovka	E53	-4.9 ± 1.8	[9]
	E39	0.8 ± 2.0	[9]
	E80	-1.0 ± 0.5	Present work
Leoville	LV1	3.0 ± 0.1	Present work
	LV2	9.5 ± 2.3	Present work
Vigarano	2226	8.8 ± 0.6	Present work

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ABUNDANCES AND CONDENSATION TEMPERATURES OF THE ELEMENTS

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In the past years, many new determinations of elemental abundances in the solar photosphere and CI carbonaceous chondrites have become available. I used these results to assemble new abundance tables of the elements for the photosphere and the solar system. I computed self-consistent condensation temperatures for all elements using the new abundances [1].

Recent results from standard solar models and helioseismology show that helium and heavy elements settled from the photosphere, which means that current photospheric abundances are not equal to solar system abundances (i.e., proto-solar at 4.55 Ga ago). Therefore, we have to consider two elemental abundance sets (photospheric and proto-solar). However, when elemental abundances are normalized to the cosmochemical scale of Si = 1e6 atoms, only the H and He abundances differ in both abundance sets.

The major changes in photospheric abundances for C, N, O, and noble gases (summarized in [1]) decrease the mass fractions of heavy elements (Z) also altering the hydrogen (X) and helium (Y) mass fractions. The photosphere has X = 0.7491, Y = 0.2377, and Z = 0.0133, and the proto-solar mass fractions are $X_o = 0.7110$, $Y_o = 0.2741$, and $Z_o = 0.0149$. The decrease in C, N, and O abundances leads to a photospheric Z/X = 0.0127, significantly lower than previous values ranging from 0.0270 to 0.0208, which have steadily revised downward since 1984. In contrast, the protosolar Z_o/X_o is 0.0210, which shows that only about 84% of the heavy elements now remain in the photosphere.

The difference in heavy element content increases the condensation temperatures by about 10 K for a solar-system composition gas by comparison to the photospheric composition. The changes in C, N, and O abundances introduce significant changes in the C/O ratio, the amount of oxygen removed by rocky condensates, and in the mass distribution of rocky and icy condensates. The C/O ratio for the new abundances is 0.50 and about 23% of the total oxygen condenses into rock, which increases the C/O ratio to 0.65. For comparison, the composition in [2] gives C/O = 0.42, and only about 15% of the total O condenses, causing a modest increase in C/O to 0.50. The new abundances result in water ice/rock ratios of 1.17, just half of the water ice/rock = 2.09 from [2]. This reduction in the ice/rock ratio should have important consequences for aqueous alteration processes on meteorite parent bodies and for the chemistry of the outer solar nebula and comets.

A summary of the recommended solar system abundances and condensation temperatures will be given at the meeting and on our web page at http://solarsystem.wustl.edu.

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METHANOL STICKING AND THE ACCRETION OF CENTIMETER-SIZED PARTICLES IN THE SOLAR NEBULA

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Summary: We report sticking and energy loss in collisions of an ice ball incident on a water ice surface, both coated with pure methanol frost. Significant energy loss is also seen with frosts of pure water and 5% aqueous methanol.

Introduction: In the last decade or so, cosmochemists have proposed mechanisms for formation of organics everywhere in the young solar system [1, 2]. Methanol is among these organics and has been observed in some comets [3]. Small particle accretion models are supported by the observation of dust particles sticking in experimental simulations at low velocities [4]. Surface hydrocarbon frosts enhance this kind of sticking in protoplanetary disks. Our experiments suggest this is true at least for the limiting case of pure methanol [5, 6].

Experiment: Collisions occurred between 5–50 cm/s and 120 to 180 K. A simple pendulum in a freezer box was used to measure kinetic energy loss (coefficient of restitution $\varepsilon \equiv v_{after}/v_{before}$) in collisions of an ice ball (diameter 2.5 cm) with a flat ice surface. The data presented below agree with lower velocity data obtained by [5] using a compound pendulum, as illustrated in the figure pertaining to the pure water frost case. Complete sticking ($\varepsilon = 0$) occurs for water frosts near zero velocity. We have observed sticking at 10 cm/s for methanol frosts, though this limit was imposed more by the timeline of the experiment than by the properties of the frost. Sticking may have occurred at higher velocities in recent experiments, but this result is still subject to verification.



Fig. 1.

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CHEMICAL IMAGING OF CARBONATES IN MARTIAN METEORITE ALH 84001 USING TIME OF FLIGHT SECONDARY ION MASS SPECTROMETRY

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Introduction: Carbonates in ALH 84001 offer our best clues to ancient fluid-rich environments on Mars, particularly due to the scarcity of hydrous silicates. Trace element analyses of these carbonates have typically been collected using magnetic sector ion microprobes [1–3], which is often hindered by the lack of applicable standards. Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) analyses, as performed by [4], provide complementary information as to the spatial distribution of trace elements, including organics [4], that may aid in the better understanding of formation mechanisms for the carbonate minerals.

Methods: Ion images were collected from unique carbonate occurrences in ALH 84001 [5, 6] using ToF-SIMS at the Smithsonian Institution. Images were collected using a sub-micron Ga primary beam in an ion optical mode that is an optimal combination of spatial and mass resolution.

Results: Major element images (Ca, Mg, Mn, and Fe) are consistent with previous analyses using the electron microprobe [5, 6]. Si is concentrated in silica glass located between Ca-rich carbonate and magnesite. As expected, Sr follows Ca within the carbonate. We also find Ti, Cr, and Al within the carbonate, with Cr concentrated in the early-formed, Ca-rich carbonate and Ti found only in the magnesitic carbonate inferred by [6] to be a later generation. Although the incorporation and partitioning of these elements in carbonates is poorly understood, Ti and Cr are not particularly mobile elements and the occurrence of Al and Ti preferentially in the magnesitic carbonates supports a second-generation origin.

Of particular note are Na, Li, H, and OH secondary ion distributions, all of which represent volatile elements and can be detected within carbonate slabs. The H and OH images support previous suggestions for the incorporation of martian hydrogen [7, 8], probably from a water-rich fluid. More extensive ToF-SIMS imaging should help elucidate the siting of H as well as variations in concentration between different generations of carbonate. This will significantly increase our understanding of the relationships between the carbonate generations and the interpretation of H isotopic data obtained from these minerals. Equally important, the association of Li and Na may provide important constraints on the nature of the fluid, as we would expect evaporative brines to be enriched in these elements, while we have no a priori expectation for hydrothermal fluids to contain these elements. We suggest that our data support the evaporative brine model previously postulated for ALH 84001 [8–10] and the nakhlites [11, 12].

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PETROPHYSICAL CHARACTERIZATION OF METEORITES IN THE NATIONAL METEORITE COLLECTION OF CANADA: INITIAL RESULTS

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Introduction: Various petrological, mineralogical, and magnetic techniques have been used for the classification of meteorites (e.g. [1–4]). Because of the high rate of discovery of new meteorites, there is a particular need for fast, easy, and non-destructive methods for classification. Appropriate petrophysical techniques include low field magnetic susceptibility, intensity of natural remanent magnetization (NRM), and bulk density [1–4].

The National Meteorite Collection of Canada contains 2700 meteorite specimens belonging to 1100 different meteorites. Among these are 730 different stony meteorites. The Canadian collection has not previously been systematically assessed for petrophysical properties, and thus, represents an opportunity to expand the global database [1–4]. Recently, there has been a concerted effort to obtain magnetic susceptibility data from collections around the world [3, 4], and herein, we report initial magnetic susceptibility results from the Canadian collection. Future work on the Canadian collection will report on NRM intensity and bulk density.

Magnetic susceptibility represents a fast, non-destructive, and systematic method for classifying meteorites essentially based on Fe-Ni content [1–4]; Fe-Ni is the most magnetic material and, thus, carries the bulk of the magnetic signal. Since current petrological/mineralogical classification is also primarily based on Fe-Ni content, magnetic susceptibility classification should correlate with accepted classifications. The magnetic susceptibility technique may also help in identifying misclassified meteorites and help with the interpretation of magnetic fields around asteroids [3, 4].

Results: A database of magnetic susceptibility measurements on 203 stony meteorites and one stony-iron meteorite is presented. Meteorite classes show distinct susceptibility ranges following trends governed by metal content. Susceptibility values increase from carbonaceous chondrites through LL, L, and H to enstatite chondrites. As expected, based on its higher metal content, the lone stony iron (mesosiderite) measured yielded the highest susceptibility.

A frequency dependence is observed within each class when using frequencies of 825 Hz and 19000 Hz [5, 6]. Initial results suggest that the H and carbonaceous chondrites, along with the SNCs, have the greatest frequency dependence, while the aubrites and lone howardite sample have the lowest.

A proxy method was used for an estimation of anisotropy of magnetic susceptibility [5, 6]. The aubrites, enstatite chondrites, and SNCs have the largest inferred anisotropies, while the LL chondrites, carbonaceous chondrites, and the howardite have the lowest.

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SUPRACENTER: LOCATING FIREBALL FRAGMENTATIONS USING DIRECT ACOUSTIC WAVE ARRIVALS RECORDED BY SEISMOMETERS

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Introduction: As large meteors penetrate deeper into the Earth's atmosphere, stresses and pressures increase, often causing the bolide to explosively fragment. This fragmentation may occur as a single large event (terminal burst) or as a cascading series of smaller explosions. Acoustic waves produced by these explosions can and have been recorded by nearby seismometers [1, 2]. Using acoustic wave arrival times and ray tracing, the position of these explosions, or supracenters can be found in four dimensions (3 spatial + 1 temporal). The process is analogous to earthquake location, but is complicated by atmospheric winds that can reach significant fractions ($\leq 20\%$) of local sound velocities in the upper atmosphere. SUPRACENTER, a new computer program, has been designed specifically to locate these explosive events in a moving and stratified atmosphere.

The SUPRACENTER Program: Designed as a series of command functions for Matlab, SUPRACENTER includes several types of fitting, weighting, and residual options. ASCII text files are used for input of seismic station coordinates, arrival times, and custom model atmospheres. In the absence of a custom atmosphere, the 1978 U.S. Standard Atmosphere is used.

Morávka Meteorite Fireball: Although SUPRACENTER has demonstrated its ability to locate individual terminal bursts [3], it is also capable of determining a fireball's trajectory and velocity. The recent fall of the Morávka meteorite [4] and the seismic detection of several of its fragmentations [5] have provided the opportunity to test this ability. Using 1) the model atmosphere of [6] for the Morávka region; 2) the arrival times as identified by [5]; and 3) the satellite observed time of 11:51:52.5 UT, SUPRACENTER located the positions of 6 fragmentations along the fireball's trajectory.

Overall positions were in good agreement with those of [5], yet lay consistently south of their solutions, most notably, event K, which was repositioned ~1.5 km to the southwest. These differences are due to the simpler, but less accurate, isotropic atmosphere and wind adjustments used by [5]. All fragmentation solutions exhibited very low travel time residuals, with mean absolute values ranging between 0.17 and 0.43 sec. A comparison of SUPRACENTER's solutions from the perspective of the Kunovice video shows improved alignment with the recorded fireball fragment trajectories. Fitting a trajectory to the repositioned fragmentations gives an azimuth of 171.8°, elevation angle of 18.9°, and a fireball velocity of 22.1 km/s. These values are similar (within 2–4 degrees and 0.5 km/s) to those derived for the fireball through video analysis [4].

Conclusions: When the acoustic arrivals of several explosive fragmentations from a fireball are recorded by seismometers, both the trajectory and velocity of the fireball can be accurately determined by locating the supracenters of individual fragmentations.

Acknowledgments: Special thanks to Peter Brown for providing both the model atmosphere of the Morávka region and findings of the Morávka meteorite fall investigation.

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LONGITUDINAL VARIATIONS OF IMPACT CRATER DENSITY ON VENUS

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Introduction: There are about 1000 impact craters on the planet Venus, which has a surface area of 460×10^6 km². A difference in impact crater density is considered a criterion for the estimation of the relative geologic age of the surface regions on planets. At first, the craters on Venus look to be situated over the surface randomly. The density of the craters is about 2×10^6 km⁻², which is low in comparison with the other planetary bodies such as Moon, Mars, Mercury, and many of the satellites of the giant planets. To discover any possible regularity within such low crater density, it is necessary to analyze the crater distribution over the sufficiently large areas of Venus.

Approach: Analysis of the crater distribution by the planetographic longitudes has been used in this work to derive an estimation of differences in crater density. 967 craters have been counted within 36 sectors. Each sector is located from the North Pole to the South Pole and is bounded by two meridians which are 10° of longitude apart. Each sector contains 27 ± 11 craters. The values have been smoothed with three different running windows: 30, 90, and 180 degrees of longitude. The step of moving in all three cases was 10 degrees of longitude, i.e., one sector (of the 36 original sectors).

Results: It has been found with a 180° running window that there is a meaningful difference in crater density between the two longitudinal hemispheres of the planet bounded with $100/280^{\circ}$ E meridian. The hemisphere $100-190-280^{\circ}$ E contains 463 craters, and the supplemental hemisphere $280-10-100^{\circ}$ E contains 504 craters. The smoothing with 30 and 90° running windows revealed very sharp boundary in crater density along 270° E meridian.

Interpretation: It could be concluded that there are considerable differences in crater density between the regions of Venus and that 270–280°E is a boundary zone of the sharp difference. This boundary could be important with respect to geological structure and/or evolution. The differences in crater density are more clearly within the Northern hemisphere of Venus and they are traced in the Southern hemisphere in a subdued, but still readable, expression. This observation could point to the process of crater elimination being more intensive (it could have been active for a longer period) in the Northern hemisphere, where it took place within certain regions, resulting in the present differences in crater density. In the Southern hemisphere, the eliminating process was less intensive (its duration was shorter), but it took place within the same longitudinal regions, as in the Northern hemisphere.

IN SITU STUDY OF THE SULPHUR ISOTOPIC COMPOSITIONS OF FE-NI SULPHIDES IN CI1, CM1, AND TAGISH LAKE CARBONACEOUS CHONDRITES: PRELIMINARY RESULTS

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Introduction: C11, CM1, and the anomalous C2 [1] Tagish Lake chondrites have endured variable degrees of aqueous alteration. The sulphides present in carbonaceous chondrites may form in both nebula and parent body environments. Sulphur isotope distributions between the sulphides and other S-bearing phases may reflect the degree of aqueous alteration and/or their primitive nebula composition. A detailed study of the petrology and mineralogy of the sulphides, combined with sulphur isotope data measured in situ, can provide clues as to whether differences within and between each group are due to the different degrees of aqueous alteration or whether they are the result of nebula heterogeneity.

Previous Studies: Carbonaceous chondrites exhibit ~7‰ variation in $\delta^{34}S$, and previous $\delta^{34}S$ values for Orgueil sulphides have been inconsistent. Gao and Thiemans [2] reported values for $\delta^{34}S$ of +6.5‰ in the sulphides, while Monster et al. [3] reported lower values of around +2.6‰. Sulphur isotopes have been studied in only one CM1 sample: the CM1 lithology sulphides in the brecciated meteorite Kaidun [4, 5]. The data obtained by [5] shows a range of $\delta^{34}S$ values from -5.7‰ to +1.1‰

Method: Two thin sections of Alais and one of Orgueil were taken to represent the range of C11s. One section of the CM1 chondrite ALH 88045 and two sections of Tagish Lake were also studied. The isotopes ³²S, ³³S, and ³⁴S were measured with the UCLA Cameca IMS 1270 in multicollector mode following the method outlined in [6].

Observations and Discussion: The majority of the sulphides in the C11 chondrites are pyrrhotite [7], although ~10 μ m grains of pentlandite are found in Alais. By contrast, Tagish Lake and ALH 88045 contain a variety of Fe-Ni sulphide compositions, from pyrrhotite, through intermediate sulphides, to pentlandite. In the C11 and Tagish Lake samples, the sulphides are surrounded by matrix phyllosilicates, while in CM1 ALH 88045, the sulphides occur as rims around remnant chondrules and as discreet grains in the matrix. The sulphide grains in the CM1 chondrite are significantly larger than those in either of the C11s or Tagish Lake. Data obtained thus far for δ^{34} S fall within previously observed ranges, and δ^{33} S values are consistent with the modern terrestrial mass-dependent fractionation line.

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MODEL OF ELEMENT AND ISOTOPE COMPOSITION OF PRESOLAR GRAINS

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The element and isotope compositions of meteorites are analyzed. The collation is made of the results and nuclear reaction modeling. The conclusion is drawn that some fragments of meteorites may be considered the results of nuclear fusion reactions—directly beyond s- and p- processes. This deduction is illustrated by reaction trees. They have been developed by a computer program for modeling nuclear reactions. The program evaluates 3669×3669 pairs of isotope interactions—all-by-all—and derives the reaction tree. The graph theory method is used to build the reaction tree. The criteria is $m_{result} < m_1 + m_2$, according to Einstein's formula mc². Each isotope in the model may be distinguished from 1H. This approach illustrates an explanation of the isotopic composition of presolar grains from the Murchison meteorite.

MULTI-TECHNIQUE ANALYSIS OF MICROMETEOROIDS CAPTURED IN LOW EARTH ORBIT

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Introduction: The use of low-density silica aerogel as the primary capture cell technology for the NASA Discovery mission Stardust to Comet Wild-2 [1] should be a strong motivation for researchers within the Meteoritics community to develop techniques to handle this material. The unique properties of silica aerogel mean that dust particles can be captured at hypervelocity speeds and remain relatively intact, although the same unique properties present difficulties in the preparation of the particles for analysis. Notwithstanding these problems, our previous work [2-3] has shown that particles can be routinely extracted from aerogel. It is now important not only to further refine these extraction techniques but also to develop protocols for analyzing the captured particles. However, as Stardust does not return material to Earth until 2006, researchers must either analyze particles that are impacted in the laboratory using light-gas-gun facilities (e.g. [4]) or examine aerogel collectors that have been exposed in low-Earth orbit (LEO) [5]. While there are certainly benefits in laboratory shots, i.e., accelerating known compositions of projectiles into aerogel, the LEO capture particles offer the opportunity to investigate real particles captured under real conditions.

Experimental: The aerogel collectors used in this research are from the NASA Orbital Debris Collection Experiment that was exposed on the MIR Space Station for 18 months [5]. Preserved impact features have been located using optical microscopy and then subsequentially extracted using the methods described in [2–3]. The extracted aerogel wedges containing both the impact tracks and the captured particles have been characterized using the synchrotron total external reflection X-ray fluorescence (TXRF) microprobe at SSRL, the Nuclear Microprobe at LLNL and the synchrotron infrared microscopy at the ALS facility at LBL.

Discussion: The techniques that have been applied on the extracted wedges are essentially non-destructive or have limited detrimental effects on the particles. While it is important to assess the suitability of the various analytical techniques, the particles captured in LEO offer an opportunity to examine material that has not been subjected to selection and modification processes that occur during atmospheric transit by the particles terrestrial repositories of cosmic dust. Of course, the captured particle may have undergone alteration during hypervelocity capture. From the X-ray maps acquired using proton induced X-ray emission, it is clearly possible to identify fine Fe-rich particulate material on the sub-micrometer scale that have fragments down the length of the impact track. However, the identification of light elements from the data acquired from proton elastic scattering analysis and proton backscattering analysis would suggest that while the particles may fragment during hypervelocity capture, the volatile elemental chemistries are not lost. This is clearly important when it comes to the analysis of any organic material.

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MORE TEXTURAL AND MINERALOGICAL STUDIES OF PRIMITIVE ORDINARY CHONDRITES

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Introduction: Our research on two primitive ordinary chondrites, Saratov (L4) and an unnamed Antarctic find (L/LL3), was undertaken to compare their mineralogy and textures because they were close in petrologic grade. So far, our studies have confirmed that Saratov is at a slightly higher grade, probably L4, while the L/LL3 is probably of grade 3.5 to 3.6 [1]. An unexpected result is the discovery of texturally and mineralogically similar or identical chondrules, and other common features, in the two meteorites. A simple descriptive classification scheme can be derived for chondrules in these meteorites that exhibit similar petrologic grade. Our conclusions may have implications for other ordinary chondrites. Systematic and consistent descriptions, e.g., of the textures and mineralogy of chondrules selected for isotopic analyses, is lacking within the literature.

Methodology and Observations: Polished thin sections of the meteorites were documented with digital color photomicrographs and back-scattered electron (BSE) photos and photomosaics from a scanning electron microscope (SEM). The photomosaics allow maps of whole thin sections to be examined. Images of individual chondrules and results from energy-dispersive spectrometry (EDS) spot analyses allow comparison of textures and identification of phases. Chondrules with similar textures and similar contained phases can be grouped.

Results, Photomosaics: There are a few distinct textural components to these meteorites: intact chondrules consistent with their petrologic grade; intact chondrules inconsistent with their petrologic grade; primitive matrix; chondrule fragments resulting from crushing during lithification; secondary matrix resulting from recrystallization of fragments and primitive matrix; late veins or melt zones.

Results, Chondrules: The intact chondrules and the chondrule fragments comprise textural/mineralogical groups of different porphyritic olivine (PO), porphyritic olivine-pyroxene (POP), radiating olivine (RO), and radiating pyroxene types (RP). We have identified at least 6 groups of chondrules that occur in each meteorite and a category of chondrules whose recrystallization has occurred at a higher grade but which are embedded in the lower grade meteorites.

Implications and Summary: In a recent bulk trace element study of nonporphyritic micro-objects in primitive ordinary chondrites [2], the classification scheme used was chondrules (C), chondrule fragments (CF), irregular fragments (IF) and unidentified particles (U). Some were also categorized as barred olivine chondrules (BOC) or barred olivine fragments (BOF). Given the ability to image these objects in detail and to determine their mineral components, it is important to describe chondrules and chondrule fragments more completely, possibly as part of a general and consistent scheme, before trace element or isotopic analyses. Comparable mineralogy and textures may indicate that they are samples from the same chondrule reservoir; this can be tested by subsequent analyses on selected similar objects from different meteorites, as we are trying to identify.

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THE DISPOSITION OF HYDROGEN IN MARTIAN METEORITE ALTERATION

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Introduction: Understanding the volatile budget of the Martian hydrosphere requires knowledge of the behavior of the most volatile element: hydrogen. In the absence of sending well-equipped probes to the surface of Mars capable of drilling some 10s of meters in fortuitously suitable locations, we are left with examining secondary minerals in the meteorite collection to gain an understanding of fluid/Martian rock interaction. Because the preterrestrial nature of alteration in the nakhlites has been well established [1, 2], this study focuses on determining the precise siting of hydrogen within secondary mineral assemblages in the Nakhla and Lafayette SNC meteorites.

Analytical Method: The time of flight-secondary ion mass spectrometer (ToF-SIMS) was used to collect high spatial resolution-mass resolved images of alteration veinlets. A pulsed Ga⁺ primary ion beam (~0.25–0.27 μ m spot size) was used principally at low mass resolution to obtain greater sensitivity for mass one ions. The instrument was operated in dual beam mode, where samples were subjected to cycles of Cs⁺ sputtering (to remove surface contaminants) followed by a pulse of Ga ions and negative secondary ion collection.

Results and Discussion: Ion images collected to date suggest that hydrogen and hydroxyl are not restricted to clay minerals alone. These species are, instead, distributed among all alteration phases to varying degrees, including: carbonate, clay, and Si-rich and Fe-rich amorphous silicates. The latter three phases comprise what is commonly termed "iddingsite." Because ion yields differ as a function of matrix composition, it is not possible at this time to determine the relative concentrations of H in each of the secondary minerals. Once suitable standard materials are obtained, spectra can then be used to construct a detailed mass balance for water in low temperature phases in SNC meteorites, an exercise that has not yet been conducted.

The nature of the distribution of hydrogen in multiple phases will impact the way in which high precision-bulk extraction isotopic data are interpreted [3, 4] and highlight the need for additional magnetic sector D/H measurements on H-bearing silicate phases to compliment those already performed on carbonate [5].

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ORIGINS OF AMORPHOUS AND CRYSTALLINE MICROGRAINS IN CHONDRITE MATRICES

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Introduction: Matrix rims and interchondrule matrix in the primitive C chondrites Acfer 094 and ALHA 77307 consist mostly of μ m- and nm-sized particles of amorphous Fe-Mg silicate material, forsterite, and enstatite [1, 2], with minor carbonaceous, refractory, and presolar materials. These matrices probably represent the precursors for all C chondrite matrices. Abundant fayalitic olivines and phyllosilicates in altered chondrite matrices appear to have formed (as in ALHA 77307 [1]) by hydrothermal alteration of amorphous material. Evidence for crystalline, nebular, FeO-rich micrograins is lacking. Unaltered O and E chondrite matrices are poorly characterized. Matrix in Kakangari (and possibly E chondrites) may have formed from briefly heated amorphous material [3], which resembled the local chondrule precursor material.

Enstatite and Forsterite: Ubiquitous Fe-poor silicates (Fa_{<5}, Fs_{<5}) 10–300 nm in size occur in all unaltered chondrite matrices; some are Mnrich as in IDPs [4]. Matrix enstatites commonly show ortho-clino intergrowths indicating quenching at ~ 10^{3-4} °C/hr from the protoenstatite stability field >1000°C [1, 2]. Solar-like O isotopic compositions indicate a local origin [5] by nebular condensation or annealing of amorphous material. Condensation appears more plausible as annealing above 1000°C may form Fe-rich silicates, which are absent in Acfer 094 [2, 6]. Forsterite and enstatite micrograins, which are ubiquitous in comets and around young and evolved stars (e.g., 7, 8]), are rare in the interstellar medium (<5%). Fe-poor silicate micrograins in matrices and most of those in IDPs probably formed close to the protosun prior to transport to cooler regions by bipolar outflows or turbulence [9, 10], or in shocks in cooler regions [11].

Amorphous Phase: Amorphous matrix grains in unaltered C chondrites [1, 2] resemble amorphous phases in IDPs [12], are $1-5 \mu m$ in size, are non-igneous, and are heterogeneous with Al/Ca, Ni/Si, and P/Si ratios above CI values. Metallic Fe, Ni and pyrrhotite occur locally, as in GEMS [13], but are $10 \times$ larger. Most GEMS and virtually all matrix grains have solar-like oxygen isotopes [5, 14]. Since GEMS may have been isotopically homogenized in the interstellar medium [13], the O isotopic data do not preclude presolar origins. Amorphous dust occurs around young and evolved stars [7, 15] and may form by rapid condensation or amorphization by radiation. Since Fe-poor silicates in C and K chondrite matrices were clearly quenched from >1000°C like chondrules, some amorphous material and nearly all the crystalline matrix silicates may have formed in brief, high temperature nebular events under conditions when melts were unstable.

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COMPARATIVE STUDY OF METEORITES BILIBINO AND SIKHOTE-ALIN BY MÖSSBAUER SPECTROSCOPY

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Introduction: The Sikhote-Alin and Bilibino iron meteorites were classified as coarsest octahedrite IIB with an average Ni concentration of about 5.8–6%. However, the Bilibino meteorite has an age of about 200,000 yr in terrestrial conditions, while Sikhote-Alin has an age of about 60 yr. Earlier microscopic study of Bilibino showed that about 80% of the section area displayed recrystallized regions [1]. TEM showed incoherent and semicoherent precipitates in new kamacite grains that were observed in this meteorite [1]. The Ni gradient between parent and new kamacite grains was also observed [1]. In this work, we compare the Sikhote-Alin and Bilibino meteorites by Mössbauer spectroscopy.

Experimental: Mössbauer spectra were measured at room temperature using the constant acceleration precision high stable spectrometer SM–2201. Meteorite samples were prepared as powder.

Results and Discussion: Mössbauer spectra of Sikhote-Alin and Bilibino are shown in Fig. 1 (a and b, respectively). The spectrum of the Sikhote-Alin sample consists of the main component 1 (magnetic sextet with $H_{eff} = 331$ kOe) and minor component 2 related to the high spin ferric compound (~2%). The spectrum of the Bilibino sample consists of three magnetic sextets: 1) $H_{eff} = 328 \text{ kOe} (\sim 72\%)$; 2) $H_{eff} = 335 \text{ kOe} (\sim 18\%)$; and 3) H_{eff} =342 kOe (~9%); and minor component 4 related to the high spin ferric compound (~1%). Differences between these meteorite samples may be related to the presence of several regions in Bilibino in contrast to Sikhote-Alin. These various regions in Bilibino may be considered as three types of kamacite with different Ni concentrations in comparison to the initial concentration: 1) low Ni concentration; 2) initial Ni concentration; and 3) high Ni concentration. These data are in agreement with previous results [1]. Thus, we could conclude that nucleation of new kamacite grains may be caused by diffusion induced grain boundary migration under the weathering conditions



Fig. 1.

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MEASUREMENT OF A METEORITE VOLUME USING A NON-CONTACT 3D LASER SCANNER

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Introduction: The ability to accurately measure the volume of a meteorite using a non-contact method is highly desirable. Standard methods of volume measurement employ immersion techniques that may physically and chemically contaminant samples, significantly affecting results of later research. We describe a process of acquiring 3D surface data of a meteorite sample and building a 3D model from a finite set of scans. The various sources of error in the data acquisition and model generation are considered. The quality of the volume measurement is investigated with various spatial sampling settings to determine an optimum accuracy to speed ratio. Suggestions to provide automation of the process are included.

3D Scanning Technology: An auto-synchronous 3D laser scanner has been developed by Neptec Design Group. The scanner is space flight qualified (on NASA shuttle mission STS-105) [1]. The scanner has a spatial accuracy of 200 μ m at a standoff distance of 1.2 m with a wide field of view (30 × 30 degrees). This technology has been selected as a tool to assist rock classification at terrestrial and extraterrestrial sites, and in other terrestrial applications [2]. Previous work with the scanner has produced some high quality 3D models of meteorites [2]. The models are used to capture the high spatial detail of the surface of the meteorite as shown in Fig. 1.



Fig. 1. St. Robert, Forcier 1. Sample: 2290 gm, .695 L.

Summary: The ability to build closed 3D volumetric models means that densities of fragile or reactive materials, like meteorites, can be calculated by weighing them and imaging them. Closed 3D volumetric models can be used to reproduce casts of original objects. Laser camera images and models of valuable objects can be stored and shared amongst investigators without compromising the real objects' security and integrity. There are clearly potential uses of this technique in many disciplines.

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THE DECAY CONSTANT OF ¹⁷⁶LU DETERMINED FROM LU-HF AND U-PB ISOTOPE SYSTEMATICS OF TERRESTRIAL PRECAMBRIAN HIGH-TEMPERATURE MAFIC INTRUSIONS

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After 20 years of Hf isotopic work on both terrestrial and extraterrestrial samples, it has recently become clear that the decay constant of 176 Lu is not defined to better than 5% [1]. At present, isochrons based on meteorites [2] appear to suggest higher values for the λ^{176} Lu than those based on terrestrial igneous intrusions dated by other methods [3].

Cross-calibration of U-Pb and Lu-Hf isotopic systems on mineral fractions from the Sorkka and Karlshamn dolerites in Finland and Sweden was performed to determine the decay constant of 176Lu. These dykes were selected on basis of: 1) fresh, magmatic mineralogy including olivine; 2) petrological characteristics that indicate rapid crystallization from a homogeneous, high-temperature magma; and 3) their abundance of baddeleyite that can be dated precisely with U-Pb geochronology. The samples were collected from fresh exposures in quarries, laying at least 15 m below ground surface. The Lu and Hf isotopic compositions of plagioclase, olivine, pyroxene, apatite, ilmenite, and baddeleyite were determined by MC-ICPMS at the University of Arizona. Calibrating the Lu-Hf results against baddeleyite U-Pb dates of 1256 ± 2 and 954 ± 2 Ma for the two dolerites yield a mean λ^{176} Lu of 1.866 ± 0.009 × 10⁻¹¹ yr⁻¹. This value is significantly lower than the decay constant used during the last 23 years $(1.93-1.94 \times 10^{-11} \text{ yr}^{-1})$, but is identical to the value presented by [3]. The robustness of our determined decay constant lies in the linear distribution of mineral fractions as illustrated in the 176Lu/177Hf versus 176Hf/177Hf plots with MSWD values of 0.64 and 0.72. Typically, this feature demonstrates constant Hf isotope composition during crystal growth and no post-intrusive isotopic disturbance. The high 176Lu/177Hf ratio recorded for apatite in the dolerites (2.66 and 4.77) indicates that the Lu-Hf method is capable for dating the crystallization of mafic intrusions with an error of a few Myr or better

The close agreement between our result for λ^{176} Lu and that of [3], coupled with the fact that our dolerite intrusions cooled rapidly from high-temperature homogenous magmas, argues strongly that the true value of λ^{176} Lu is between 1.86 and 1.87×10^{-11} yr⁻¹. The meteoritic and terrestrial data sets that bear on this problem may need to be evaluated for internal, as well as external, consistency.

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INITIAL ANALYSIS PROGRAM FOR THE COMETARY SAMPLES RETURNED BY THE STARDUST SPACECRAFT MISSION

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The NASA Stardust comet sample return mission is functioning very well and it is nearing its comet sample collection phase which will occur during a 6.1 km/s close flyby of comet Wild 2 on Jan 2, 2004. Over 1000 comet particles >15 μ m are expected to be collected by impact into low density silica aerogel. The samples will return to Earth on Jan 15, 2006 via parachute recovery near Salt Lake City and they will be processed at the NASA Johnson Space Center curatorial facility. Following a ~6 month period of examination by a Preliminary Analysis Team (PAT), the samples will be made generally available to researchers by an allocation system modeled after NASA lunar sample and cosmic dust programs. The goal of the preliminary examination will be to: 1) provide information needed for optimum requests and utilization of the samples; and 2) provide an initial scientific assessment of the samples.

Given the exceptional value of these returned samples, and obvious desire for release of exciting results to the planetary science community and general public at large, we are considering running the preliminary examination in an accelerated, and hopefully exciting manner. The analysis plan has not been finalized, but we are considering the following general scheme. We are proposing that a broad cross-section of the extraterrestrial sample community be invited to participate in the preliminary analysis phase. We would like to have several PAT sub-teams, each focused on different analytical techniques, including isotopes, min-pet, noble gases, organics, bulk composition, etc. Sub-teams would receive a limited number of samples, generally prepared to be ready for business-as-usual analysis by existing state-of-the art techniques. Investigators would normally receive microtome slices or the equivalents of "potted butts" and they would not have to deal with aerogel extraction processes. The PAT sub-teams would focus on a few basic problems such as comparison of the comet samples with known extraterrestrial material types and estimation of the ratio of presolar to nebular solids in Wild 2. The PAT sub-teams would work quickly and be required to publish the preliminary investigations with all group members as coauthors. We anticipate that some PAT members would apply for funding from the NASA Participating Scientist Program and that such participants would participate in project responsibility for organization and coordination of sub-group activities. We encourage interested and qualified scientists to consider the PAT effort, how they might participate, and how the overall analysis program should be implimented. After the preliminary examination period, samples will be open to general allocation to interested researchers, including PAT members.

INTERPLANETARY DUST AND PARTICLES CAPTURED IN AEROGEL: FAR-INFRARED SPECTROSCOPY

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Introduction: Far-infrared (IR) (~15–100 μ m) spectroscopy provides a means of rapid, non-destructive mineralogical analysis. In this wavelength (λ) range, the position of characteristic bands for specific minerals also provides compositional information (e.g., Mg/Fe in olivines and pyroxenes). We have previously shown that far-IR measurements are possible on anhydrous interplanetary dust particles (IDPs) [1]. Here, we report the first in situ far-IR measurements of an extraterrestrial particle captured in aerogel. The aerogel measurements are important because samples of comet dust collected in aerogel will be returned to Earth for analysis by the STARDUST mission in January of 2006.

Methods: We used a modified Spectra-Tech Irµs IR microscope installed on Beamline U4IR of the National Synchrotron Light Source (Brookhaven National Laboratory), which allows access to the full far-IR region (600–10 cm⁻¹). IDPs are analyzed on thin Formvar substrates, while the aerogel samples were self-supporting. FTIR spectra were collected in transmission mode over the λ range from 15 to 200 µm (660–50 cm⁻¹) with 4 cm⁻¹ resolution and converted to absorbance for comparison purposes.

Results and Discussion: Particle "2DO3 No. 1" was extracted from aerogel flown on the ODCE collector on Mir [2]. The extraction procedure is described in [3]. The sample consists of a thin wedge "keystone" of aerogel that contains the entire particle track plus the particle (~8.5 μ m in diameter) [3]. The IR measurements are compromised somewhat by saturation of the strong Si-O bending vibration from the thick aerogel substrate, but there are "windows of opportunity" both above and below the aerogel feature where crystalline silicates have diagnostic bands. After subtraction of the aerogel background, the far-IR spectra of particle 2DO3 No. 1 shows three strong absorptions at 16.6, 19.6, and 24.6 μ m consistent in position and intensity to an olivine (Fo₇₅) standard (Fig. 1). These results are consistent with synchrotron X-ray fluorescence and microdiffraction data on the same particle that show a chondritic composition and X-ray diffraction lines of fayalitic olivine [4].



Fig. 1. Far-IR spectra of an extraterrestrial particle captured in aerogel, Fo_{75} olivine standard, and aerogel substrate.

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SULFUR ISOTOPIC COMPOSITIONS OF INTER-PLANETARY DUST PARTICLES

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Introduction: Interplanetary Dust Particles (IDPs) are among the most primitive material available for laboratory studies of astrophysical processes. The high abundance of presolar silicates, including S-rich GEMS grains, in IDPs [1] suggests that presolar S-isotope anomalies could be present in IDPs. We previously reported the first S measurements of five large (>~10 μ m) sulfide-rich IDPs [2]. Here, we report additional isotope data for ~130 S-rich grains of 0.1–15 μ m from nine IDPs. We have found no evidence for large S isotopic anomalies, though we identified an ¹⁷O rich presolar grain, similar to those reported by [1].

Experimental: Seven 10–15 µm sulfide grains were measured with the Carnegie ims-6f ion probe for ³³, ³⁴S/³²S ratios. Two of these were pressed into Au foils and 5 were polished thick sections embedded in epoxy. Measurements of standards indicate a reproducibility of 5–10‰ (1 σ). Five ultramicrotomed sections of two IDPs were analyzed by multi-collection scanning ion imaging (~100 nm resolution) with the Washington University NanoSIMS. All 5 were analyzed for ¹⁷O/¹⁶O and ³⁴S/³²S, 2 of the five were also analyzed for ¹⁸O/¹⁶O, and ³³S/³²S was determined for the other 3. Isotopic ratios were determined for 125 individual S-rich subgrains defined in the images. We corrected for instrumental fractionation by normalizing isotopic ratios to the average of all subgrains within a given image.

Results and Discussion: Repeat analysis did not confirm a previouslyreported [2] marginal anomaly in one IDP. In fact, there is no hint of δ^{33} S or δ^{34} S values outside of ±50‰ for the ~130 grains we have measured. One Srich grain (probably GEMS) was found to have a large ¹⁷O excess (δ^{17} O ~500‰) indicating a presolar origin. Both the ¹⁸O/¹⁶O and ³⁴S/³²S ratios were within error of normal in this grain.

The lack of large S isotopic anomalies in IDPs is perhaps not surprising given the high degree of homogeneity of this element in bulk meteorites [3] and CAIs [4]. Unlike the presolar GEMS reported by [1], the grain reported here is rich in ¹⁷O. ¹⁷O-rich compositions of refractory oxides are taken to indicate condensation in a red giant star's atmosphere. However, it is not clear that grains with the physical and chemical properties of GEMS would condense in circumstellar outflows. Perhaps the ¹⁷O is a vestige of a larger initial anomaly, which has been diluted, but not erased, by processing in the interstellar medium. In such a case, any original S-isotopic anomaly might have been completely erased. Alternatively, S isotopes might be very uniform in different stellar sources so that circumstellar grains would not exhibit anomalous S. Nucleosynthetic considerations suggest that the largest anomalies in Galactic S would be expected in ³⁶S [5], but the low abundance of this isotope has thus far precluded its measurement in IDPs.

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TRAPPED XE IN DARK INCLUSIONS II: NEW DATA FROM REDUCED CV3 METEORITES

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I-Xe isochrons are mixing lines between trapped and iodine-derived components. Because the I/Xe ratio in the solar nebular was ~ unity, and ¹²⁹I/¹²⁷I about 10⁻⁴, the ¹²⁹Xe/¹³²Xe ratio in trapped Xe did not appreciably evolve. While in a closed systems with elevated I/Xe it is possible that a trapped components has ¹²⁹Xe/¹³²Xe ratios higher than normal trapped OC-or Q-Xe [1], "sub-planetary" trapped Xe compositions with *lower* ¹²⁹Xe/¹³²Xe ratios, or *higher* ¹²⁸Xe/¹³²Xe ratios, are implausible. We have previously reported evidence for "sub-planetary" trapped Xe in 17 dark inclusions from Allende [2]. In this work we present new data for sub-planetary trapped Xe in four dark inclusions from three reduced CV3 meteorites (Elfremovka, Leoville and Vigarano) and explore some of the implications.

Although these 23 DIs show various degrees of alteration which correlate with their I-Xe ages (spanning at least 12 Ma) [3], and all require "sub-planetary" trapped Xe, there is no correlation between trapped composition and I-Xe age. The figure below shows the I-Xe isochron for Allende DI 4314-2, which clearly requires "sub-planetary" trapped Xe. One DI, E80 from Efremovka, has two different I-host phases, distinguished in the release profile. These phases have isochrons of identical slope (same I-Xe age), but different trapped components: the higher temperature isochron requires OC-Xe; the lower temperature isochron requires "sub-planetary" trapped Xe. If 127I were mixed and indistinguishably emplaced with xenon, a pseudo trapped component with enhanced ¹²⁸Xe would be produced after neutron irradiation [2]. Why do these DIs show this effect and what do they have in common? Elfremovka DIs show evidence of mild shock reflected in their elongated shape [4], as do Allende DIs. If the shock occurred long after precipitation of iodine host, while Xe and some I were still in solution, perhaps iodine could, in fact, be emplaced in a way indistinguishable from Xe.



Fig. 1.

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OVERGROWTHS, OSCILLATORY ZONING, AND FIRST-GENERATION PHENOCRYSTS IN SEMARKONA CHONDRULES: MULTIPLE MELTING EVENTS, HIGH COOLING RATES

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Wasson and Rubin [1] investigated high-FeO chondrules in CO3.0 Yamato-81020 and found that low-FeO relicts were ubiquitous and that thicknesses of olivine overgrowths and the radii of "new" olivine crystallites were about 5 μ m following the last melting event. They concluded that the large, >50 μ m phenocrysts in these type-II chondrules are relicts produced in multiple melting events in the present chondrule or in earlier generations of chondrules. Wasson and Rubin [2] studied high-FeO chondrules in LL3.0 Semarkona and LL3.1 Krymka and made similar observations; low-FeO relicts and shards retaining their fragmental shapes were common, and 5- μ m overgrowths were observed to be the norm following the last melting events.

We have extended this study to include 15 additional chondrules in Semarkona section USNM 1805–3. In high-FeO porphyritic pyroxene chondrule L4 we find compositional evidence of multiple overgrowth layers, and in others, evidence of two overgrowth layers. Compositional and petrographic evidence show that rhythmic zoning in banded pyroxene in some high-FeO chondrules results from continued growth on structures that were initially skeletal; bands of mesostasis exsolved more evolved pyroxene (i.e., with higher CaO and/or FeO) to produce continuous pyroxene bands.

If, as we infer, most melting events produced only about 5 μ m of new olivine or pyroxene, it is important to find chondrules containing first-generation phenocrysts without overgrowths. In Fig. 1, we show one candidate, chondrule G7; it consists mainly of glassy mesostasis with thin (10–30 μ m) skeletal bars of Fa_{0.1} olivine and scattered sparks of Ca pyroxene. Mesostasis occupies regions within the olivine bars. After allowing for oblique sectioning, the thickness of olivine slabs appears to be 5 μ m or less. We suggest that additional melting events would have been necessary to make continuous, thicker olivine bars.



Fig. 1. First-generation skeletal olivine bars in chondrule G7.

Because overgrowth thicknesses are $>10\times$ smaller than phenocryst radii used in past studies to estimate cooling rates, it follows that these earlier rates are too low by factors >100.

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THREE DIMENSIONAL GRAVITY FIELD MODELLING OF THE CHICXULUB IMPACT CRATER

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Synopsis: Three dimensional gravity field modeling of the Chicxulub crater's gravity field has refined our working structural model (e.g. [1, 2]) and differs somewhat from the results of [3]. The 3D gravity modeling method employed is that of [4]. Regional anomalies must be separated to allow 3D modeling. The 3D gravity model indicates that the central uplift rises to within ~2 km depth and is, therefore, within reach of scientific drilling.

Model Results-Central Uplift: The model results reveal details of the crater's central structures. The central uplift is a twin peaked structural high with vergence toward the southwest, as previously indicated by 2D models [1] and consistent with seismic refraction results [5]. An arm extends toward the northeast, in contrast to the steep gradients that bound the central uplift to the southwest. The width of the uplift at 4 km depth is ~45 km broadening to ~65 km at 5 km depth, basically consistent with 2D modeling, but slightly broader due to the geometric effect of 3D versus 2D model bodies. The central uplift rises into the melt sheet to ~2 km depth in contrast to the results of [3] where a top of ~4 km was obtained. However, as refraction results [5] independently constrain the central uplift width and the central uplift density contrast is limited (here, +0.11 gcm⁻³), this is probably a realistic result. The shape of the modeled central uplift is radically different from that advocated by [6] who, based on seismic refraction results, proposed a cup-shaped central uplift (concave top) with a top at ~3 km depth, but of similar width. This interpretation requires substantial departure from density-velocity proportionality.

Model Results—Melt Sheet: The filling of the collapsed disruption cavity, which we interpret as melt, is revealed as a body slightly elongated NE-SW with a diameter slightly smaller than previous 2D model results. With the density contrast measured from the top of the melt sheet, its base lies near ~4 km and is obtained consistent with the result of [1]. This depth is dependent upon the density contrast used (-0.15 g/cc), however, and all the mass deficiency need not be melt. The derived melt volume is 1.5×10^4 km³, slightly smaller than that of [3], and in agreement with melt volumes estimated by a variety of methods [7]. The modelled width of the collapsed disruption cavity is slightly smaller than that derived from 2D models and/or seismic imaging of the crater's slumped blocks, indicating a slightly smaller impact energy than previously calculated [1], but is only a partial step toward resolving the lack of accord between the calculated impact energy from a scaling relation [8] and indications of the size and composition of the Chicxulub impactor.

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METALLOGRAPHIC COOLING RATES OF H CHONDRITES AND THE STRUCTURE OF THEIR PARENT ASTEROID

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Trieloff et al. [1] demonstrated that the Ar/Ar and Pb/Pb ages of 7–13 H chondrites are concordant with each other and with their Pu fission track cooling rates and that these three thermochronometers record thermal closure in a cooling asteroid at 4.45–4.57 Gyr. From correlations between these parameters and the degree of metamorphism or petrographic type, Trieloff et al. [1] argued that the H chondrite asteroid was heated internally to 1200 K and was then undisturbed as it cooled through 390 K, so that the higher petrographic types cooled slower than lower types. These authors imply that the metallographic cooling rates recorded by H chondrites at 700 K, which appear to be unrelated to the degree of metamorphism or petrographic type [2], are either flawed [3] or compromised by later impact heating and cannot be used to infer the early thermal history of the H asteroid. However, Haack et al. [4], who investigated the validity of the metallographic cooling rates were correlated with Ar-Ar ages and had not been compromised by shock heating.

I have reinvestigated the metallographic cooling rates [2, 3, 5] and shock history of H chondrites [6, 7] and find that metallographic cooling rates are well correlated with the three thermochronometers used by [1]. For 26 H chondrites, metallographic cooling rates are generally higher for lower types, confirming the likely existence of a layered asteroid. However, this larger data set shows that there was considerable mixing of the petrographic types by impact before they cooled below 800 K. Thus, the cooling history of the H chondrite parent body appears to lie between the two extremes: undisturbed cooling of a layered body [1] and thorough scrambling by impact [2].



Fig. 1.

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MINERALOGICAL STUDY OF THE YAMATO-983885 LUNAR METEORITE

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Introduction: Lunar meteorites are of great scientific importance because, in some cases, they are derived from areas of the moon that were not sampled by the Apollo and Luna missions. Yamato-983885 (Y-983885) was recovered by the Japanese Antarctic Research Expedition in 1999 and classified as lunar [1, 2]. Here, we report a mineralogical study of the Y-983885 lunar meteorite.

Sample and Methods: A polished thin section of Y-983885, 71-1 was studied with an optical microscope using transmitted and reflected light. Mineral compositions were determined by quantitative wavelength dispersive X-ray analyses with JEOL JCXA-733 and JXA-8800M electron microprobes at the National Institute of Polar Research, Japan.

Results and Discussion: Y-983885 is a polymict breccia containing abundant lithic, mineral, and melt clasts (up to 1.2 mm in size) with fragments of minor opaque mineral set in a dark brown glassy matrix. Most large clasts are polymineralic and are composed of Ca-rich plagioclase, pyroxene, and olivine. A few large clasts are composed of plagioclase and pyroxene, or only plagioclase. Smaller clasts are commonly mineral fragments of predominant plagioclase, with subordinate proportions of pyroxenes and olivines. Glass spherules, up to 0.3 mm in diameter, are also observed. Electron probe microanalyses indicate a range of pyroxene composition for the whole meteorite of Wo2-40, Fs12-55, En14-85; a plagioclase range of An₈₉₋₉₈; and an olivine range of Fa₃₂₋₃₆, except one grain of Fa₅₅ [2]. One of the lithic clasts with a subophitic texture (~0.4 mm) is a ferroan mafic lithology that may be a mare basalt or has mare basalt components. The select major element compositions of Y-983885 determined by standard wet chemical analysis [3] and lunar highland crust [4] are shown in Table 1. Although Y-983885 is generally a feldspathic regolith breccia, its relatively lower Al2O3 concentration than that of any other feldspathic lunar meteorites and highland crust (>25%) suggests that the meteorite is a mixture of mare and highland materials. Such "mixed" lunar meteorites include Calcalong Creek [5] of which the bulk Al₂O₃ concentration (~21%) is similar to that of Y-983885. Higher FeO and MgO concentrations than those of lunar highland crust (Table 1) also suggest that Y-983885 is basalt-bearing.

Table 1. Bulk chemical composition (select elements) of Y-983885 and lunar highland crust (wt%).

	SiO ₂	TiO ₂	Al_2O_3	FeO	MgO	CaO
Y-983885 [3]	45.59	0.53	21.81	9.41	7.98	14.02
Highland [4]	45	0.56	24.6	6.6	6.8	15.8

References: [1] Kojima H. and Imae N. 2001. *Meteorite Newsletter* 10(2):1. [2] Kaiden H. and Kojima H. 2002. Abstract #1958. 33rd Lunar and Planetary Science Conference. [3] Kaiden H. and Kojima H. 2002. *Antarctic Meteorites* 33:49–51. [4] Taylor S. R. 1982. *Planetary science: A lunar perspective*. Lunar and Planetary Institute. 481 p. [5] Hill D. H. et al. 1991. *Nature* 352:614–617.

S-PROCESS XENON IN PRESOLAR SILICON CARBIDE GRAINS AND AGB MODELS WITH NEW CROSS SECTIONS

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Precise neutron capture cross sections of ^{128, 129, 130}Xe have been measured by Reifarth et al. [1] with 1 σ uncertainties of 2%. This allows a reanalysis of the s-process Xe predicted in asymptotic giant branch (AGB) stars and its comparison with meteoritic Xe-S carried by presolar SiC grains [2]. Stellar evolutionary models have been calculated, and an updated network of neutron captures has been followed [3, 4]. Neutrons are provided by the ²²Ne(α , n)²⁵Mg reaction activated during recurrent convective He-burning thermal pulses and by the ¹³C(α , n)¹⁶O reaction, which operates radiatively in the interpulse phases (¹³C-pocket). ¹²C and s-processed matter from the He shell are mixed with the envelope by third dredge up episodes. The ¹³C-pocket efficiency may be different in different stars according, e.g., with rotational effects [5]. A large spread of ¹³C-pocket efficiencies are needed to reproduce spectroscopic observations of different classes of s-enhanced stars [6].

Fig. 1 shows how the ¹³⁰Xe normalized Xe-S component fits the AGB models. For the s-only isotopes ^{128, 130}Xe, the 10% deficit of ¹²⁸Xe indicates an additional p-process contribution to solar. We recall that the p-only isotopes ^{124, 126}Xe are destroyed by neutron captures. The small s-process contribution to the odd isotopes ^{129, 131}Xe are reproduced, as well as the 32% s-process contribution to solar ¹³²Xe. As to the "r"-only pair ^{134, 136}Xe, a minute s-contribution to ¹³⁴Xe actually derives from the small neutron channel on unstable ¹³³Xe open at the peak neutron density driven by the ²²Ne neutron source.

Since Xe-S is extracted from millions of SiC grains, AGB predictions have been calculated as a grand average: over the low mass AGB range 1.5 to 3 M_{sun} ; over a large spread of ¹³C-pocket efficiencies; over the expected range from solar to half solar metallicity [7]; and finally, for each AGB model over the envelope mass lost by stellar winds with C/O >1 (necessary condition for SiC to form).

¹³⁴Xe is the best indicator of mass and metallicity. For higher AGB initial masses, or lower metallicities, the temperature in the He shell is higher than in low mass AGB stars of about solar metallicity, and the ²²Ne source is more efficient. The ensuing higher peak neutron density makes a much larger production of ¹³⁴Xe, at odds with G-SiC, all other isotopes being unchanged. The same occurs in the alternative scenario where Xe is assumed to be implanted directly from the He-shell on pre-existing SiC grains, in the planetary nebula phase. This is illustrated in Fig. 2.



Fig. 1.

Fig. 2.

References: [1] Reifarth R. et al. 2002. *Physical Review C* 66:1–14. [2] Lewis R. S. et al. 1994. *Geochimica et Cosmochimica Acta* 58:471–494. [3] Straniero O. et al. 1997. *Astrophysical Journal* 478:332–339. [4] Gallino R. et al. 1998. *Astrophysical Journal* 497:388–403. [5] Lugaro M. et al. 2003. *Astrophysical Journal* 586:1305–1319. [6] Busso M. et al. 2001. *Astrophysical Journal* 557:802–821. [7] Lugaro M. et al. 1999. *Astrophysical Journal* 527: 369–394.

ANOMALOUS SPECTRA OF HIGH-CA PYROXENES IN ANGRITE SAMPLES: A POSSIBLE CORRELATION BETWEEN IR AND MÖSSBAUER PATTERNS

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Introduction: For both near-infrared reflectance (NIR) [1] and Mössbauer [2] spectroscopy of high-Ca pyroxenes, interpretation is complicated by anomalous results not yet amenable to easy interpretation. Both methods often seem to show Fe^{2+} in the M1 octahedral site where Ca^{2+} is known to be. A clue may be provided by a possible correlation between laboratory NIR results [3] and Mössbauer spectra [4] of the same samples, 3 angrites (last table entries below).

Table 1. Some anomalous Mössbauer and infared spectra of high	-Ca
pyroxenes compared to low-Ca pyroxene data.	

Sample	Composition	Spectr	oscopy
		Mössbauer	Infrared
		Mean QS	Туре
	Fe	(comment)	(comment)
Low-Ca pyroxene (Pbe	ca)		
Synthetic ferrosilite [2]		
M1	0.54	2.5	
M2	0.46	1.9	
PYX 032 [1]			"B"
M1			
M2	0.797		
High-Ca pyroxene (C2	2/c)		
Low Al and Ti			
Fs ₅₀ [2]			
M1	1.0	2.2 (Almost as	
M2		if Fe ²⁺ in M2)	B (as if Fe ²⁺ in
PYX 018 [1]			M2)
M1	0.932		
M2			
PYX 020 [1]			A ("normal")
M1	0.933		
M2			
Aluminian-titanian hig	sh-Ca pyroxene		
Terrestrial			
Andranondambo [5]		~ 2.4	("normal")
M1	0.070		
M2			
Angrite [6]			
D'Orbigny "clinopy	roxene	"2.41*	A ("normal")*
M1	0.25	("normal")	
M2			
Sahara 99555 "fassa	uite" ⁵	2.33*	A ("normal")*
M1	0.49	("normal")	
M2	0.29		
Angra dos Reis			
"fassaite separate"	5	2.05* (as if	B (as if Fe ²⁺ in
M1	0.205	Fe ²⁺ in M2)	M2)
M2	0.018		

References: [1] Cloutis E. A. and Gaffey M. J. 1999. *Journal of Geophysical Research* 96:22809. [2] Dowty E. and Lindsley D. H. 1973. *American Mineralogist* 58:850. [3] Burbine T. H. et al. 2001. Abstract #1857. 32nd Lunar and Planetary Science Conference. [4] Hoffman E. J. 2002. Abstract #1973. 33rd Lunar and Planetary Science Conference. [5] De Grave E. et al. 2002. *American Mineralogist* 87:132. [6] Mittlefehldt D. et al. 2002. *Meteoritics & Planetary Science* 37:345. Mikouchi T. et al. 2000. 31st Lunar and Planetary Science R. M. and Finger L. W. 1977. *Earth and Planetary Science Letters* 357.
YAMATO-981651, A NEW VARIETY OF THERMALLY UNMETAMORPHOSED EUCRITE: VESICULAR, MAGNESIAN, AND INCOMPATIBLE ELEMENT-POOR

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Yamato-981651 (Y-981651) is a 236 g eucrite that has been briefly described by [1], who established the rock's affinity with eucrites based on pyroxene FeO/MnO and oxygen isotopes. The rock contains vesicles up to 3 mm across. For reasons unstated, Kojima and Imae [1] suggested it is an impact melt rock.

The vast majority of eucrites have had their pyroxene (etc.) brought into tight compositional ranges by thermal metamorphism. Y-981651, however, has remarkably pristine (unmetamorphosed, "unequilibrated") mineralogy. It is also uncommonly magnesian. Based on analyses to date (105), the record of pyroxene crystallization starts at En₇₂Wo_{4.7}, i.e., at an mg ratio several mol% higher than that observed for other unmetamorphosed eucrites such as Bluewing 001 [2]. If Y-981651 is assumed to be an impact melt rock, the origin of its high-mg component is problematical. If it were diogenitic, we might expect the Y-981651 pyroxene trend to be uncommonly Ca-poor in comparison to other unmetamorphosed eucrites. Instead, on a pyroxene quadrilateral, the early Y-981651 pyroxenes plot consistently several mol% higher in Wo than corresponding pyroxenes from Bluewing 001. However, Y-981651 is also an exceptionally fast-cooled lava, almost vitrophyric, and probably as a result of the rapid cooling, its pyroxenes are uncommonly rich in Al and perhaps, thus, in Wo as well. Siderophile elements that are commonly detectable by INAA in polymict eucrites (Ir, Ni) are not detectable in Y-981651. A forthcoming RNAA analysis for these and other siderophile elements will help to further constrain the impact melt hypothesis.

On a plot of pyroxene mg versus Ti/Al ratio [2], Y-981651 gives an indication of crystallization starting with an uncommonly low TiO_2 . Preliminary bulk-rock INAA data likewise indicate uncommonly low concentrations, by noncumulate eucrite standards, of Ti and incompatible trace elements such as Sm.

References: [1] Kojima H. and Imae N. 2001. *Meteorite Newsletter* 10(2). [2] Warren P. H. 2002. 33rd Lunar and Planetary Science Conference.

LU-HF AND SM-ND ISOTOPIC SYSTEMATICS OF CHONDRITES AND IMPLICATIONS FOR EARTH EVOLUTION

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Sm-Nd and Lu-Hf isotopic systems are not affected by volatile loss during planet formation or by core partitioning, so bulk silicate Earth (BSE) composition should be well known. Hf-Nd isotopes of crust and mantle are well correlated, but trends through these data are offset from the current Hf-Nd CHUR values by 3 ϵ_{Hf} units [7]. This has been used to argue for a hidden reservoir to balance the Hf-Nd array with BSE [2]. Implicit in this theory is the assumption that we know BSE Hf-Nd values.

We present Lu-Hf and Sm-Nd isotopes for 6 carbonaceous and 13 ordinary chondrites. Sm-Nd parameters have a narrow range along a 4.55 Ga isochron, centered on the values currently in use ($^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{144}Nd = 0.1966$ with fractionation correction based on $^{146}Nd/^{144}Nd = 0.7219$; [3, 4]). Excluding Bjurböle, the chondrites vary in $^{143}Nd/^{144}Nd$ from 0.512602 to 0.512678 with an average of 0.512639. This is a variation of less than 1.5 ε_{Nd} units and of <2.5% in $^{147}Sm/^{144}Nd$, verifying current CHUR Sm-Nd values.

The chondrites span a large range in $^{176}\text{Hf}^{/177}\text{Hf}$ and $^{176}\text{Lu}^{/177}\text{Hf}$ and fall along a 4.55 Ga isochron (using a decay constant of $1.865.10^{-11};$ [5, 6]) with an intercept of ~ 0.2798 . All chondrites form a trend with $^{176}\text{Hf}^{/177}\text{Hf}$ from 0.282678 to 0.282949 and $^{176}\text{Lu}^{/177}\text{Hf}$ from 0.03014 to 0.03539. This is a range of $\sim 18~\epsilon_{\rm Hf}$ units and a $\sim 17\%$ variation in Lu/Hf. Results are similar to those of [1], except that their data extend to lower and higher Lu/Hf than do ours. There appears to be a difference between carbonaceous and ordinary chondrites. Carbonaceous chondrites have $^{176}\text{Hf}^{/177}\text{Hf}$ and $^{176}\text{Lu}^{/177}\text{Hf}$ values that average 0.282849 and 0.03422, respectively, compared with 0.282678 and 0.03216 for ordinary chondrites. This is a difference between the two chondrite groups of more than 6 $\epsilon_{\rm Hf}$ units and 6.4% in Lu/Hf ratio.

These results have serious implications for the Hf-Nd isotopic composition of BSE. The average of all our Lu-Hf chondrite data is a value close to the current CHUR (176 Hf/ 177 Hf = 0.282772, 176 Lu/ 177 Hf = 0.0332; [2]). However, if we set BSE CHUR values based on carbonaceous chondrites, the BSE point is ~2.7 $\varepsilon_{\rm Hf}$ units higher. Precisely, this adjustment to the CHUR value would place it near the center of the terrestrial array and obviate the need for a hidden reservoir. We will discuss the advantages or otherwise of this approach with other practitioners of Lu-Hf isotope geochemistry.

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