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Collisional modification of the acapulcoite/lodranite parent body revealed by the iodine-xenon system in lodranites

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Abstract–The I-Xe system of three lodranites has been investigated. Samples of Gibson yielded no isochrons, and late model ages are attributed to late addition of iodine. Two metal and one silicate separate from the transitional lodranite Graves Nunataks (GRA) 95209 gave ages that are consistent with each other and with the literature I-Xe age of Acapulco feldspar. These yield a mean closure age 4.19 ± 0.53 Ma after the Shallowater enstatite reference age (4562.3 ± 0.4 Ma). Such identical I-Xe ages from distinct phases imply that the parent material underwent a period of rapid cooling, the absolute age of this event being 4558.1 ± 0.7 Ma. Such rapid cooling indicates an increase in the rate at which heat could be conducted away, requiring a significant modification of the parent body. We suggest the parent body was modified by an impact at or close to the time recorded by the I-Xe system.

An age of 10.4 ± 2.3 Ma after Shallowater has been determined for one whole-rock sample of Lewis Cliff (LEW) 88280. Since the release pattern is similar to that of GRA 95209 this hints that the larger grain size of this sample may reflect slower cooling due to deeper post impact burial.

INTRODUCTION

Lodranites are a class of primitive achondrites, in the same clan as acapulcoites; oxygen isotope systematics (Clayton et al. 2004) and other similarities (McCoy et al. 1996, 1997a) suggest that lodranites and acapulcoites originated from a single parent body. In fact, their cosmic ray exposure ages cluster around 6 Ma (Weigel et al. 1999; Terribilini et al. 2000) and this, combined with their similar abundances of cosmogenic nuclides and similar shielding conditions, suggests that they all originated from a single ejection event. Although this cosmic ray exposure age coincides with the most frequent exposure age of H Chondrites (Marti et al. 1992), oxygen isotope data clearly show that the two groups do not originate from the same parent body (Clayton et al. 2004).

Acapulcoites and lodranites are distinguished from one another primarily by grain size and may in fact represent a continuum (Mittlefehldt et al. 1998a; Floss 2000). In petrological characteristics and bulk chemistries they are very similar to chondrites, but they lack the characteristic chondritic texture. This suggests that they were derived from chondrites by high temperature processing and partial melting (McCoy et al. 1996, 1997a).

Lodranites are coarse-grained (540–700 μm) olivine- and pyroxene-rich rocks, depleted in troilite and plagioclase; acapulcoites are finer-grained (150–230 μm), with approximately chondritic abundances of olivine, pyroxene, plagioclase, metal, and troilite (McCoy et al. 1996; Mittlefehldt et al. 1998b). Rare, relict chondrules have been reported in several acapulcoites, confirming that their precursor material was chondritic (Schultz et al. 1982; McCoy et al. 1996). These differences suggest lodranites reached higher peak temperatures and so experienced higher degrees of partial melting than acapulcoites, with associated loss of some metal/sulfide. The larger grain size implies they cooled more slowly.

In light of the above, it is tempting to view acapulcoites and lodranites as chondritic meteorites in which the continuum of thermal processing represented by variations in petrologic type is extended to the point of melt generation and, in the case of lodranites, partial extraction. However,

among chondrites concentrations of primordial noble gases decrease strongly with increasing petrologic type (Huss et al. 1996), while acapulcoites and lodranites have high concentrations of primordial gases, much higher than those of more evolved achondrites (Nichols Jr. et al. 1994; Busemann et al. 2002). In addition, I-Xe data suggest closure of ordinary chondrites to Xe loss was increasingly late with increasing thermal processing, and as such we might expect acapulcoites and lodranites to have closed even later than type 6 chondrites. However, phosphates in Acapulco closed to xenon loss 34 ± 6 Ma earlier than phosphates in the H6 chondrite Kernouve, 45 ± 4 Ma earlier than phosphates in Walters (L6) and 48 ± 8 Ma earlier than Modoc (L6) phosphates (Brazzle et al. 1999). This is consistent with what is inferred about the thermal histories. The cooling history of the Acapulco meteorite has been traced from the ^{244}Pu fission track density in phosphates (merrillites and apatite) and in orthopyroxenes adjacent to phosphates, in conjunction with ^{40}Ar-^{39}Ar dating (Pellas et al. 1997). Acapulco is estimated to have reached a peak metamorphic temperature of ~1300 K and cooled rapidly (100 ± 40 K/Ma) at high temperature (1300–720 K). Cooling slowed drastically between 720 and 560 K to 3.7 K/Ma, down to a very slow cooling rate of 1.7 ± 0·5 K/Ma from 550 to 360 K. Fast cooling at high temperatures is also inferred in other acapulcoites and lodranites (McCoy et al. 1997b; Rubin 2007). Peak metamorphic temperatures (~1220 K [Ghosh et al. 2003]) of type 6 ordinary chondrites were somewhat lower than those of acapulcoites (Slater-Reynolds et al. 2005) but they cooled much more slowly. Thermochronological data of Trieloff et al. (2003) imply that in the high temperature range (1120–720 K) Kernouve cooled at ~10 K/Ma, markedly slower than Acapulco. At lower temperatures the rate of cooling is comparable to Acapulco: ~3 K/Ma between 720 and 550 K, and ~2 K/Ma from 550 to 390 K.

The iodine-xenon system, which was recently reviewed (Gilmour et al. 2006), relies on decay of ^{129}I to ^{129}Xe, with a half life of 16 Ma. As with other short-lived isotope chronometers, I-Xe dates events in the early solar system with a higher precision that can generally be obtained from chronometers based on long-lived radioisotopes. In this work we present the results of the first I-Xe study of lodranites. In conjunction with previous work on Acapulco, this fine scale chronometry allows us to develop and test models of the evolution of the acapulcoite/lodranite parent body.

I-Xe analyses are similar in principle to those of the Ar-Ar development of the K-Ar system (which was inspired by I-Xe dating). Samples are exposed to a neutron fluence in a reactor. Neutron capture on ^{127}I produces ^{128}I, which β-decays to ^{128}Xe. A correlation is then sought between ^{129}Xe excess (from ^{129}I decay) and ^{128}Xe (produced from iodine in the reactor) across several steps in a step heating experiment. When such a correlation is found, it corresponds to an initial iodine ratio. In the figures presented in this work, points derived from the high temperature steps that define an isochron are shown filled to distinguish them from those (chiefly derived from lower temperature releases) where uncorrelated iodine contributed to the gas release. The points contributing to the isochron are thus similar to those defining a plateau in a conventional Ar-Ar analysis (McDougall et al. 1999). Readers are referred to the recent I-Xe review (Gilmour et al. 2006) for further details on the technique.

Among samples that exhibit such correlated releases between ^{129}Xe* and iodine across a range of temperature steps, relative ages can be inferred on the assumption of isotopic homogeneity of iodine across the relevant region of the solar system. In practice, relative ages are reported as the time intervals that would be required for evolution of the ^{129}I/^{127}I ratio between samples and aliquots of enstatite from the anomalous aubrite Shallowater included in the same irradiation. Shallowater enstatite has a reproducible initial iodine ratio and so is used as an irradiation monitor. For this reason, it defines the zero of the I-Xe relative time scale and calibrations of this time scale are reported as absolute ages of the closure of Shallowater enstatite to xenon loss.

Closure intervals determined from extinct radioisotope chronometers such as the I-Xe system can be converted into absolute ages provided the absolute age associated with closure of the system in one sample is known. As noted, in the case of I-Xe, formation intervals can be converted to absolute ages with reference to the absolute age of the Shallowater standard. Such absolute ages are open to continuous revision, but at present this is taken to correspond to 4562.3 ± 0.4 Ma, based on an observed correlation between absolute Pb-Pb ages and I-Xe formation intervals across a range of samples (Gilmour et al. 2006, 2009). The additional required step of identifying closure of the short lived chronometer with an absolute time necessarily introduces an element of uncertainty beyond that quantified by the experimental error (Gilmour et al. 2009).

EXPERIMENTAL

Samples from three lodranites have been studied: Graves Nunataks (GRA) 95209, Lewis Cliff (LEW) 88280, and Gibson. GRA 95209 shows a number of properties intermediate between acapulcoites and lodranites, and may be termed a transitional lodranite; it contains plagioclase (like acapulcoites) but is depleted in troilite (like lodranites) (Floss 2000). The abundances of the rare earth elements in pyroxenes are an order of magnitude higher than are observed in typical lodranites. It is noteworthy that the smaller average grain size observed for GRA 95209 may indicate faster cooling than typical of lodranites in general. A high ^{129}Xe/^{132}Xe ratio of 15.5 has been previously observed in an Fe-Ni rich separate of GRA 95209 (Busemann et al. 2002), and it was this which provided the initial impetus for this study. LEW 88280 shows a ^{129}Xe/^{132}Xe ratio of 1.114 (Garrison

et al. 1996), and that of Gibson lies in the range 1.12 to 1.27 (McCoy et al. 1997a).

In the first set of analyses, a silicate-rich portion of GRA 95209 from a sample allocated to the University of Bern was coarsely crushed and a magnetic separate produced using a hand magnet. These samples (L3A, L4A, L4B, L4C and L4D) were included in irradiation MN17 at the SAFARI-1 reactor in Pelindaba, South Africa (thermal fluence 8.5×10^{18} n cm^{-2}, fast fluence 2.0×10^{18} n cm^{-2}). The second set of analyses consisted of 4 samples of GRA 95209 (metals separates GRM1 and GRM2, silicate separates GRS2 and GRS3), 5 samples of LEW 88280 (LEW1, LEW_Green, LEW_Brown, LEW_Metal and LEW_Chip), and 2 samples of Gibson. These were also coarsely crushed and a hand-magnet was used again to separate the metal grains from the silicate grains. Silicate grains were selected if they appeared homogenous under a binocular microscope, and, in the case of LEW 88280, separated by color. Metal grains were selected if no inclusions were apparent on the exterior surface. Since large amounts of uncorrelated iodine were observed in the first analyses (detailed below), all of the GRA 95209 samples and any other grains that were noticeably "rusty" in the second set of analyses were treated with a 67% aqueous solution of ethanolamine thioglycolate before irradiation to remove iron oxides (Cornish et al. 1984), which were postulated to be hosts of recently acquired terrestrial iodine. These samples were included in irradiation MN19, again at the SAFARI-1 reactor, Pelindaba, South Africa, (thermal fluence 6.9×10^{18} n cm^{-2}, fast fluence 1.7×10^{18} n cm^{-2}). $^{128}Xe^*/^{129}Xe^*$ ratios for Shallowater were 0.530 ± 0.007 and 0.540 ± 0.023 for MN17 and MN19 respectively (where * denotes xenon produced from iodine).

After irradiation, samples were loaded into the laser port of the refrigerator enhanced laser analyzer for xenon (RELAX) mass spectrometer (Gilmour et al. 1994). These samples were analyzed before the recent instrument upgrades reported by Crowther et al. (2008), though data were reduced to yield isotope ratios by the procedure described therein. Gas was extracted from the samples by heating with a continuous wave Nd:YAG laser ($\lambda = 1064$ nm) for one minute at each of a series of sequentially increasing laser powers. At each step gas evolved from the samples was gettered (SAES, sintered Zr, ~350 °C) for one minute to remove active gases before being admitted to the mass spectrometer. Data were acquired in 30 consecutive ten-second segments. Isotope ratios and the signal intensity of a normalizing isotope were extrapolated from these segments to determine the corresponding quantities at the time of gas inlet. Absolute gas quantities were calculated and a discrimination correction made with reference to interspersed air calibrations. The procedural blank was monitored throughout the analyses but made negligible contribution to the parameters derived from the isotopic data discussed here, so we discuss data that are not blank corrected. All errors discussed in this paper are 1 sigma.

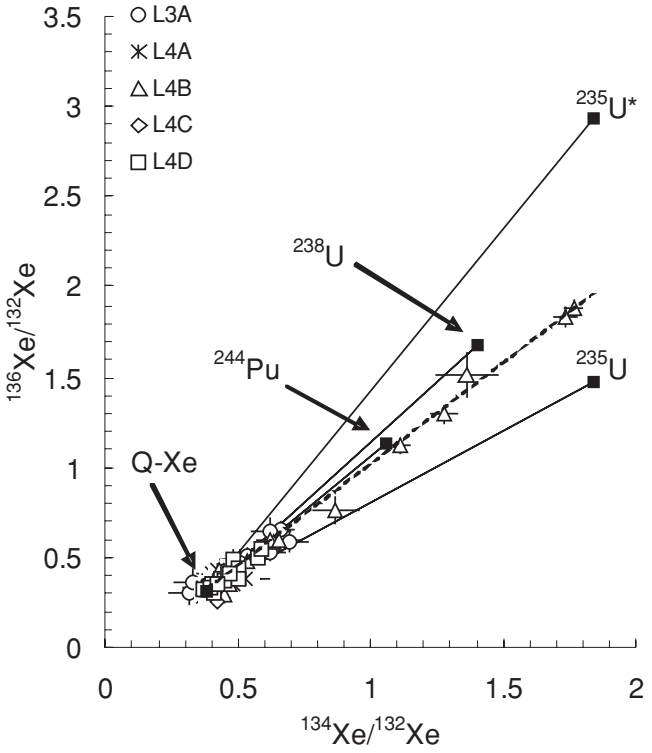

Fig. 1. Fission isotope mixing diagram for 5 irradiated samples of metal from the GRA 95209 lodranite. Data are consistent with mixing between Q-Xe (Busemann et al. 2000) and a fission component. The most fission-rich releases have higher $^{134}Xe/^{132}Xe$ and $^{136}Xe/^{132}Xe$ ratios than can be consistent with spontaneous fission of ^{238}U or ^{244}Pu. They indicate a contribution from neutron-induced fission of ^{235}U, modified by extra production of ^{136}Xe from neutron capture on ^{135}Xe in the reactor (Hohenberg et al. 1981). The composition in which this conversion has gone to completion is indicated by $^{235}U^*$. Compositions of fission endmembers from Ozima and Podosek (1983).

RESULTS

Data from the irradiated GRA 95209, LEW 88280, and Gibson samples are available in supplementary material online. Among the heavy isotopes (Fig. 1) data were found to be a mixture of a component similar to Q-Xe (Busemann et al. 2000) and a fission component, as shown for GRA 95209 in Fig. 1. The most fission-rich releases have higher $^{134}Xe/^{132}Xe$ and $^{136}Xe/^{132}Xe$ ratios than could be produced by spontaneous fission of ^{238}U or ^{244}Pu. This suggests that the major fission contribution is from neutron-induced fission of ^{235}U, with a composition modified by extra production of ^{136}Xe from neutron capture on ^{135}Xe in the reactor (Hohenberg et al. 1981). ^{135}Xe is produced from neutron-induced fission of ^{235}U, along with the other isotopes of Xe. ^{135}Xe has a cross-section of 3×10^6 b, so in irradiations which last more than a

Table 1. Summary of I-Xe chronological data from samples that yielded isochrons. A negative formation interval indicates formation after Shallowater enstatite.

Sample name	Description	Mass	Formation interval (Ma)		Absolute age (Ma)*	
GRA 95209, L4B	Metal	0.2 mg	–4.17	0.73	4558.2	0.8
GRA 95209, L4D	Metal	0.04 mg	–4.11	0.86	4558.3	1.0
GRA 95209, GRS2	Silicate	0.36 mg	–4.6	1.7	4557.7	1.7
LEW 88280 Chip	Whole rock	3.7 mg	–10.4	2.3	4551.9	2.3

*Using Shallowater age of 4562.3 ± 0.4 Ma (Gilmour et al. 2009).

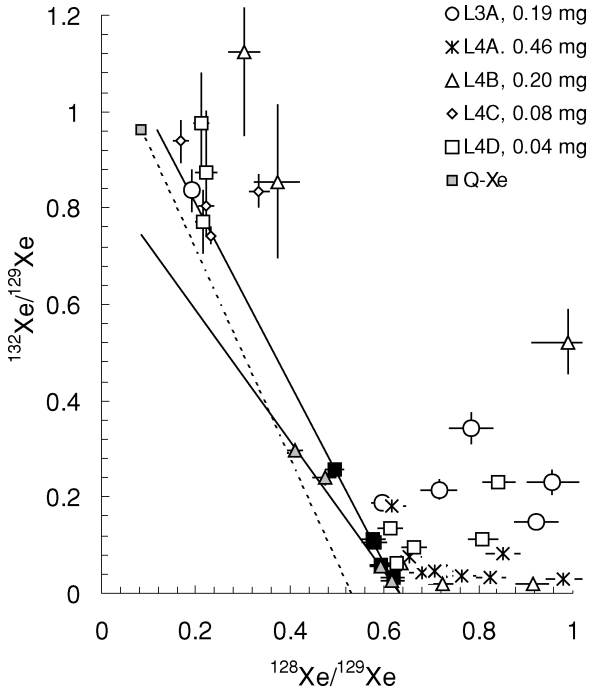

Fig. 2. Accumulated iodine-xenon data for analyses of 5 samples of metal from the GRA 95209 lodranite. All samples had significant amounts of uncorrelated iodine, (some low temperature releases with excess iodine derived ^{128}Xe plot to the right of the region shown) but high temperature isochrons (solid lines) were observed in L4B and L4D (data contributing to the isochrons are shown with solid symbols, for L4B grey is used to make all 4 data on the isochron visible). The two samples had indistinguishable ^{128}Xe*/^{129}Xe* ratios indicating identical initial ^{127}I/^{129}I ratios. Both isochrons indicate the presence of (different) components with mixtures of iodine and trapped/primordial xenon in their failure to pass through the point corresponding to Q-Xe (Busemann et al. 2000). The isochron obtained from Shallowater samples in this irradiation is shown with a dotted line.

few hours (times long enough for decay of fission precursors to produce ^{135}Xe), ^{136}Xe is produced from neutron capture on ^{135}Xe ($T_{1/2}$ ~ 9.1 h), modifying the neutron-induced fission spectrum. All data discussed here have been corrected for a fission contribution based on un-mixing of Q-Xe and neutron-induced fission of ^{235}U using the ^{134}Xe/^{132}Xe ratio.

All the samples released significant amounts of ^{128}Xe* from uncorrelated iodine at low temperatures. The ages of those samples which yielded high temperature isochrons are summarized in Table 1. No sample of Gibson produced a correlation from which an I-Xe age could be extracted. In fact, while some ^{129}Xe* was observed, model formation intervals were uniformly late, suggesting any chronological record from the I-Xe system in this meteorite has been overprinted by late addition of iodine. Bulk ^{128}Xe/^{132}Xe ratios show that both Gibson samples have I/Xe elemental ratios more than 5 times higher than any other sample in this study, suggesting an increased level of terrestrial contamination attributable to some combination of longer residence time at the Earth's surface before retrieval and residence in a distinct terrestrial environment, Western Australia rather than Antarctic (Wlotzka 1992). We do not discuss the Gibson data further here.

Data from 5 samples of GRA 95209 metal included in the first irradiation are presented in Fig. 2. High-temperature isochrons were observed for two of these samples (L4B and L4D) yielding ^{128}Xe*/^{129}Xe* ratios which are identical within error, 0.635 ± 0.018 and 0.633 ± 0.022, respectively. From these values, and the equivalent value derived from the appropriate Shallowater standard, we can determine that L4B closed to xenon loss at –4.17 ± 0.73 Ma and L4D at –4.11 ± 0.86 Ma relative to Shallowater. A negative age implies closure after Shallowater, the absolute age of the sample being given by the sum of its relative age and the absolute age of Shallowater. Therefore these relative ages correspond to absolute ages of 4558.2 ± 0.8 Ma and 4558.3 ± 1.0 Ma, respectively (Table 1) if an absolute age of 4562.3 ± 0.4 Ma is adopted for Shallowater (Gilmour et al. 2009).

The isochrons from each of these samples suggest trapped, pure xenon endmembers that are distinct from Q-Xe (Busemann et al. 2000) in their ^{128}Xe/^{129}Xe/^{132}Xe system. Sample L4B suggests the presence of a pure xenon component that has acquired excess ("parentless") ^{129}Xe, perhaps consistent with a period of isotopic evolution before the setting of the iodine chronometer recorded by the isochron (Kennedy et al. 1988). However, the apparent pure xenon endmember for sample L4D cannot have been produced by evolution of a trapped component since the implied ^{129}Xe/^{132}Xe ratio is lower than that of Q-Xe. Gilmour et al. (2001) noted that such an apparent component could be accounted for as an artefact created by the presence of a phase with a reproducible mixture of xenon and "late" iodine (i.e., with ^{129}I/^{127}I lower than the component implied by the isochron) in the sample. They further demonstrated that such a reproducible mixture of iodine and (Martian atmospheric) xenon is present in Nakhla (where it can be readily identified because the presence of ^{129}Xe from in situ ^{129}I decay can be ruled out). This lends plausibility to the existence of similar

components in other meteorites that can account for the observations subsequently reported from analyses of Allende (Hohenberg et al. 2002; Krot et al. 2002).

The second batch of four GRA 95209 samples was a mixture of metal (GRM1 and GRM2) and silicate samples (GRS2 and GRS3); the data from these samples are shown in Fig. 3. Making the correction necessitated by the slightly different Shallowater values observed in the two irradiations, the high-temperature data from sample GRS2 contribute to an isochron which is identical within uncertainty to the isochron from sample L4B in the first batch of GRA 95209 samples, with an initial iodine ratio corresponding to a formation age of −4.2 ± 1.1 Ma relative to Shallowater (Table 1). Two data points from GRM2 are consistent with the other isochron (L4D) from the previous set of samples. Some of the data from sample GRM1 suggest higher model ages. However, sample L4B indicated the presence of a component with an evolved ^{129}Xe /^{132}Xe ratio in this meteorite, and in the absence of an isochron for GRM1 it is impossible to distinguish elevated $^{129}Xe/^{132}Xe$ ratios produced by in situ decay from those that reflect a trapped component with an elevated $^{129}Xe/^{132}Xe$ ratio.

Five samples of LEW 88280 were analyzed as part of the same set of analyses as the second batch of GRA 95209 samples. These sample contained large amounts of uncorrelated iodine. No isochron was observed in the metallic or silicate separates, however a chip of "whole rock" yielded five consecutive releases that did define an isochron with $^{128}Xe^*/^{129}Xe^* = 0.842 \pm 0.076$, which equates to formation at −10.4 ± 2.3 Ma, or 4551.9 ± 2.3 Ma.

Release patterns for the four samples that yielded isochrons are available in the supplementary online material. In the two metal separates from GRA 95209 (Figs. A1 and A2 in the supplementary online material available at http://meteoritics.org), release of correlated iodine occurred at high temperature as the metal partially and then completely melted. The release came after the release of most of the ^{136}Xe from fission (of uranium) and appeared to be associated with excess ^{131}Xe (produced after neutron capture on ^{130}Te or ^{130}Ba), perhaps indicating production from tellurium associated with a sulfide host phase. The silicate separate from GRA 95209 (Fig. A3) and the whole rock sample from LEW 88280 (Fig. A4) had similar release patterns, with correlated iodine being released in intermediate steps—significant fissiogenic ^{136}Xe and excess ^{131}Xe was released at higher temperatures.

To summarize, high temperature isochrons were observed for three of the samples of the intermediate lodranite GRA 95209 (two metal separates, one silicate separate), and from one sample of the lodranite LEW 88280. Two high temperature steps for a fourth sample of GRA 95209 (GRM2) agreed within error with one of the observed isochrons (L4D). No isochrons were observed from Gibson and $^{129}Xe^*/I$ ratios inferred by assuming each data point was mixture of Q-Xe and an iodine-derived component were consistently low. The three GRA

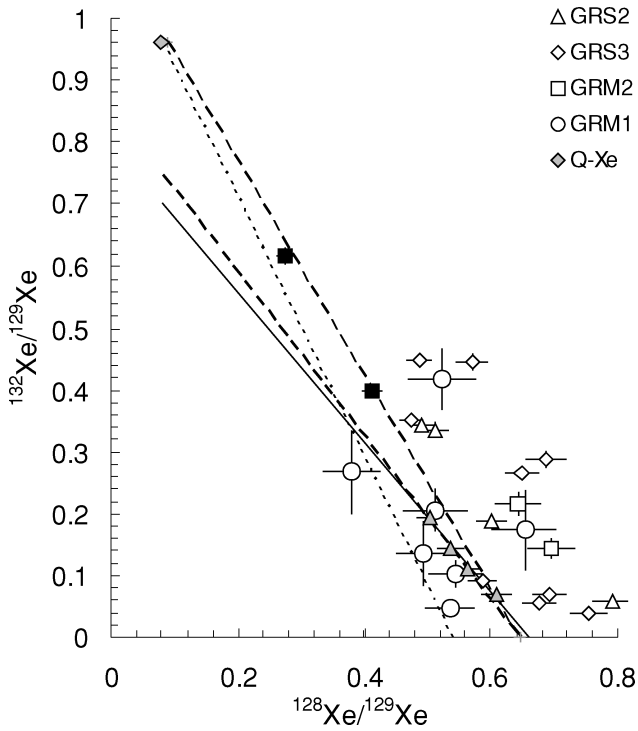

Fig. 3. Accumulated iodine-xenon data for analyses of 4 samples from the GRA 95209 lodranite—2 metal samples (GRM1, GRM2) and 2 silicate samples (GRS2, GRS3). All samples had significant amounts of uncorrelated iodine, but high temperature data (filled grey) from silicate sample GRS2 contribute to a high temperature isochron (solid line) identical within uncertainty to one isochron from the first batch of samples (dashed line—see Fig. 2—allowance has been made for the ~2% difference in conversion efficiency from ^{127}I to ^{128}Xe in the two irradiations). Two points (filled black) from GRM2 are consistent with the other isochron from the previous sample suite. Some data from GRM1 suggest higher model ages, but in the absence of an isochron no chronological significance can be attached. The isochron obtained from Shallowater samples in this irradiation is shown with a dotted line. Q-Xe composition from Busemann et al. (2000).

95209 samples that yielded isochrons suggested identical closure ages within error (Table 1). Taking a weighted mean, closure of these metal and silicate samples in GRA 95209 to xenon loss occurred at −4.19 ± 0.53 Ma relative to closure of Shallowater enstatite, identical within error with the I-Xe age of Acapulco feldspar (Brazzle et al. 1999). This leads to an absolute age of 4558.1 ± 0.7 Ma. Closure of LEW 88280 occurred at −10.4 ± 2.3 Ma (4551.9 ± 2.3 Ma).

DISCUSSION

Our data allow us to address two (linked) issues of importance: the history of the acapulcoite/lodranite parent body and the departure from concordance of the datum derived from Acapulco phosphate in the proposed calibration between the Pb-Pb and I-Xe systems of Gilmour et al. (2006, 2009).

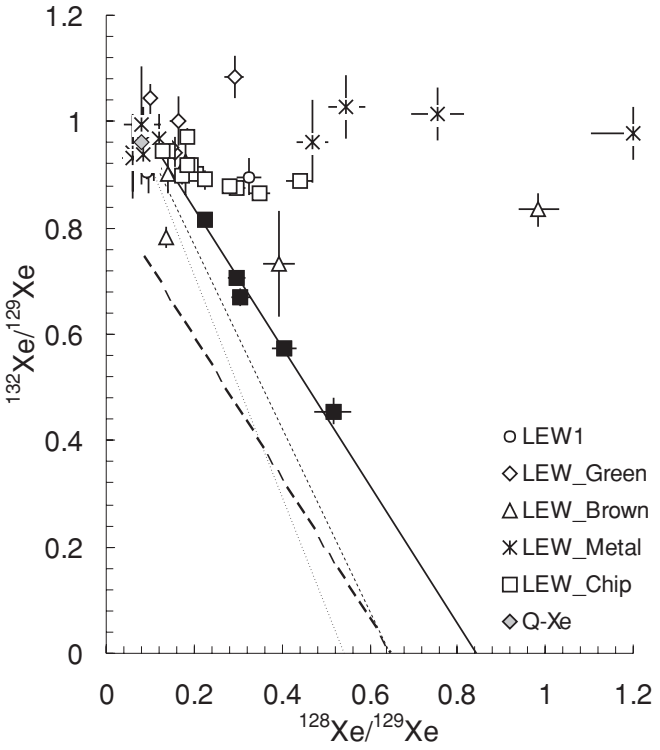

Fig. 4. Mixing diagram showing accumulated iodine-xenon data for LEW 88280 samples. Dashed lines correspond to the isochrons derived from GRA 95209 samples (Fig. 2 and Fig. 3) and the dotted line indicates the Shallowater isochron for this irradiation. Five closely spaced temperature steps from a chip (solid squares) yield an isochron (solid line). Some low temperature releases with excess iodine derived ^{128}Xe plot to the right of the region shown.

Evolution of the Acapulcoite/Lodranite Parent Body

Pellas et al. (1997) proposed a cooling history for the acapulcoite parent body. They assumed that the parent body accreted at 4565 Ma, one million years after the Pb-Pb CAI age accepted at the time (Göpel et al. 1991), and that it took 3 Ma to reach peak temperature, as in the models of Bennett et al. (1996). Combining this with closure of the Pb-Pb system in phosphates as the parent body cooled through ~720 K at 4557 Ma (Göpel et al. 1992) led to a cooling rate of 100 ± 40 K Ma^{-1} from high temperatures, followed by slow cooling below ~720 K for consistency with fission track and Ar-Ar data. Incorporating the present, revised Pb-Pb CAI age of 4568 Myr (Bouvier et al. 2007) would lead to the peak temperature being attained at 4564 Ma, and a revised early average cooling rate of ~80 K Ma^{-1}. Though this cooling rate is relatively rapid, Pellas et al. (1997) noted that even their, higher, estimate was orders of magnitude less than that implied by petrographic and metallographic observations (e.g., McCoy et al. 1996).

There is no inconsistency here, however, since their cooling rate is an average from the time the material achieved peak temperature in a model until the setting of the Pb-Pb system as phosphates cooled through ~720 K. The ~7 Ma over which this took place in acapulcoites is too short to be achieved in a model such as that of Bennett et al. (1996). In such models heat is lost by conduction to the surface of the asteroid, and high peak temperatures can only be attained in deeply buried material where conductive loss is low. This restricts the subsequent cooling rate. For instance, based on the graphical representations in figure 4 of Bennett et al. (1996), type 6 material takes around 60 Ma to reach 700 K from a peak temperature of ~1250 K. Thus an event not incorporated into such models must have occurred on the acapulcoite and lodranite parent body.

Rapid cooling from high temperature such as that observed for the acapulcoites requires a change in the characteristics of conductive cooling to the surface—material must be deeply buried until a high temperature is achieved, then find itself in an environment nearer to the surface to allow rapid cooling. Such a transition might be a consequence of impact removal of overlying layers or of disruption of the parent asteroid, and could have occurred at any point after peak temperature had been achieved up to the time recorded by the closure of the phosphate Pb-Pb system. An average cooling rate based on the modified calculations of Pellas et al. (1997) is thus consistent with a brief period of extremely rapid cooling as required by the petrographic and metallographic data.

Such an interpretation accounts for the I-Xe data. A uniform average cooling rate would require the host phases of correlated iodine in our metal and silicate separates from GRA 95209 and Acapulco feldspar to have closed within the same ~200 K temperature range. They are more easily understood if cooling occurred more rapidly, since this would allow phases with different closure temperatures to record the same time, within error. Thus we conclude that the I-Xe ages of Acapulco feldspar and our GRA 95209 metal and silicate separates record rapid cooling of the parent material that began after an impact removed material from, or fragmented, the parent body, leaving the source region closer to the new surface. In accordance with our data, this occurred at –4.19 ± 0.53 Ma relative to closure of Shallowater enstatite.

In Fig. 5 we present a summary schematic representation of the cooling of the material sampled by Acapulco and GRA 95209 compared to the H6 chondrite Kernouve. The age of the solar system is set at 4568.5 ± 0.5 Ma (Bouvier et al. 2007) and I-Xe intervals are related to the Pb-Pb chronometer using the absolute age of Shallowater. The Pb-Pb ages of the phosphates from the two meteorites are treated as fixed points in time at fixed temperatures of 720 K: 4557 ± 2 Ma for Acapulco (Göpel et al. 1992) and 4521.4 ± 0.5 Ma for Kernouve (Göpel et al. 1994). Following Pellas et al. (1997) we assume each parent body reaches peak temperature 4 Ma after the Pb-Pb age of CAIs, but the acapulcoite/lodranite parent body undergoes a period of rapid cooling constrained by our I-Xe data whereas the H chondrite parent body cools in

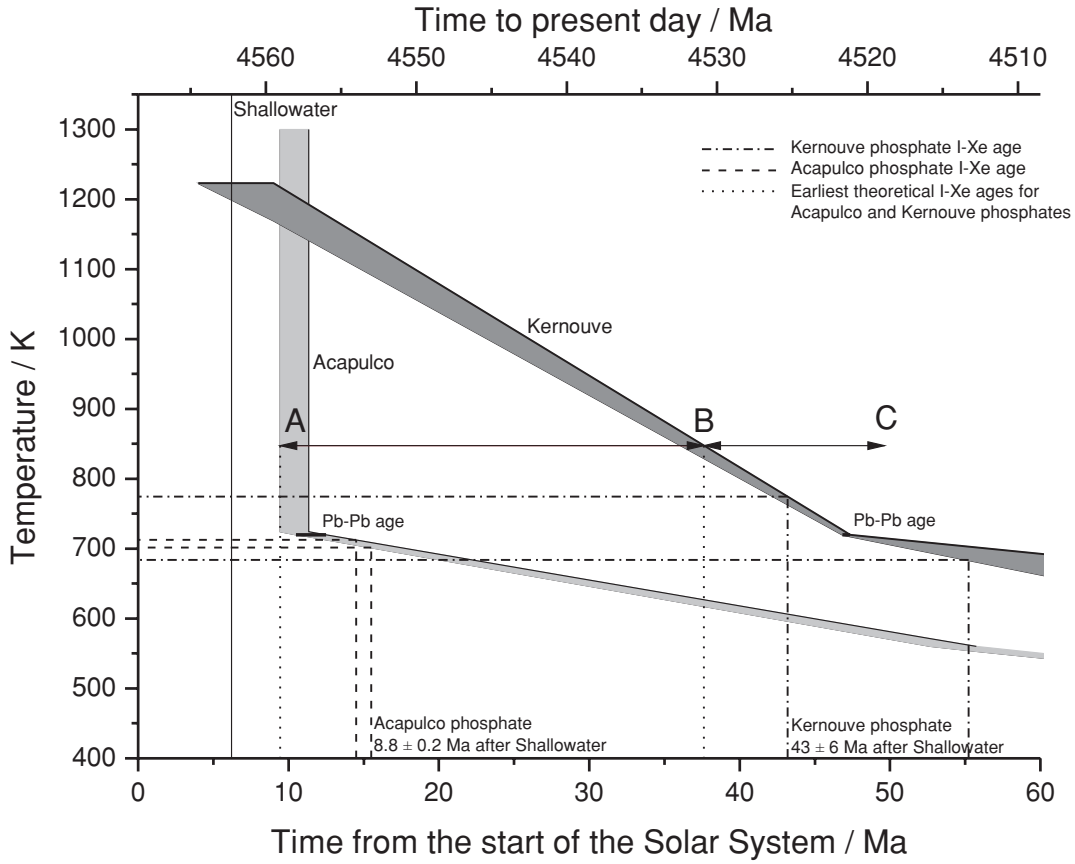

Fig. 5. Approximate cooling rates for Acapulco and Kernouve (H6). The Pb-Pb ages (Göpel et al. 1992, 1994) are taken as fixed points in time and temperature. The I-Xe ages (Brazzle et al. 1999) are related to the Pb-Pb time scale using the absolute age of Shallowater. The parent bodies are assumed to reach peak temperature (1300 K and 1223 K for Acapulco and Kernouve, respectively (Pellas et al. 1997; Ghosh et al. 2003)) 4 Ma after the Pb-Pb age of CAIs (Pellas et al. 1997), and the cooling of the H chondrite parent body is then assumed to be consistent with the models of Bennett et al. (1996). The acapulcoite/lodranite parent body undergoes a period of rapid cooling constrained by our I-Xe data, −4.19 ± 0.53 Ma relative to closure of Shallowater enstatite. The line AB represents the minimum I-Xe age between the closure of the I-Xe system in Acapulco and Kernouve (28.2 Ma), and AC the maximum (40.2 Ma). If point A is constrained to lie within the cooling curve for Acapulco, closure could theoretically occur at any temperature where BC intersects the Kernouve cooling curve. The position of line ABC here depicts the maximum possible temperature where these conditions are satisfied, and hence the oldest theoretical I-Xe age for the Acapulco phosphate: closure at 847 K, 9.4 Ma after the start of the solar system. 1 sigma errors are used throughout this figure.

a manner consistent with the models of Bennett et al. (1996). The peak temperature of Acapulco is assumed to be 1300 K (Pellas et al. 1997), and that of Kernouve 1223 K (Ghosh et al. 2003).

Implications for Calibration of the I-Xe System to the Pb-Pb System

Assuming the I-Xe closure intervals for metal and silicate separates from GRA 95209 and Acapulco feldspar correspond to rapid cooling, the later I-Xe age of Acapulco phosphate requires that it closed to xenon loss during the period of slower cooling through lower temperatures. In examining the absolute calibration of the I-Xe and Pb-Pb chronometers, Gilmour et al. (2009) considered a range of samples in which the Pb-Pb and I-Xe chronometers could be plausibly compared. They employed a method of outlier rejection in which the datum involving an association between the I-Xe and Pb-Pb systems in Acapulco phosphate was rejected. In contrast, the datum produced by associating the Pb-Pb age of phosphates with the I-Xe age of feldspar was part of a data set suggesting a consistent calibration.

Our new I-Xe data yield a significantly higher precision on the age of the proposed rapid cooling event. If this I-Xe interval is associated with the Pb-Pb age of phosphates on the assumption that this too was set during rapid cooling, a procedure similar to that adopted by Gilmour et al. (2009) leads to identification of the same three outliers and an absolute age for Shallowater of 4562.25 ± 0.5 Ma. Relaxing the constraint somewhat and requiring only that the Pb-Pb age of phosphates be bracketed by the I-Xe ages of phosphate and our GRA 95209 separates, the new "best fit" age of Shallowater enstatite is 4562.4 ± 0.4 Ma rather than 4562.3 ± 0.4 Ma (Gilmour et al. 2009)—once again a change that is

insignificant even compared to the quoted errors which quantify only statistical uncertainty and take no account of systematic uncertainty arising from prior assumptions such as the identification of outliers. Accordingly, we see no need to modify the proposed calibration of the I-Xe and Pb-Pb systems, in light of which we determine the time of the rapid cooling event of the acapulcoite and lodranite parent body as 4558.1 ± 0.7 Ma.

An important feature in initially establishing the consistency of the I-Xe chronometer was the observation that the intervals calculated in the I-Xe and Pb-Pb systems between phosphate closure in Acapulco and Kernouve are consistent (Brazzle et al. 1999). With reference to Fig. 5, it is possible to understand how this can be the case even though absolute closure times differ. The line AB represents the minimum possible time difference between closure to I-Xe for Acapulco and Kernouve phosphates—28.2 Ma (Brazzle et al. 1999). Line AC represents the maximum possible time difference—40.2 Ma. If point A is constrained to lie within the cooling envelope for Acapulco, I-Xe closure could occur at any temperature where the cooling curve for Kernouve intersects the line BC. In Fig. 5, line ABC is drawn to illustrate the highest temperature at which this condition is satisfied, and hence gives the highest temperature (847 K) and oldest ages (9.4 Ma and 40.2 Ma after the start of the solar system respectively) at which closure of the Acapulco and Kernouve phosphates could have occurred. At temperatures below 720 K, it is always possible to satisfy the condition that point A lies within the Acapulco envelope and line B-C intersect the Kernouve cooling envelope—thus the agreement between I-Xe and Pb-Pb intervals is met even if the absolute ages are not comparable.

Renne (2000) reported an Ar-Ar isochron for Acapulco feldspar and suggested an adjustment to the half life of ^{40}K that resulted in this coinciding with the Pb-Pb age of Acapulco phosphate. On this basis it was suggested that rapid cooling of the acapulcoites continued to low temperature. Our data demonstrate that there is an offset between the I-Xe age of Acapulco phosphate and the consistent I-Xe ages of Acapulco feldspar and our silicate and metal separates from GRA 95209. We argue that this suggests a period of rapid cooling at high temperature (to account for the consistent ages) followed by slower cooling in the regime over which the system closed in the phosphate, and is thus more consistent with the model proposed by Pellas et al. (1997) as modified here.

The I-Xe isochron age for the chip from LEW 88280 may provide a hint that this sample cooled more slowly than the intermediate lodranite GRA 95209. The release of correlated iodine occurs in a similar relationship to releases of fission xenon and ^{131}Xe by neutron irradiation from either barium or tellurium as is observed in the silicate sample of GRA 95209. This suggests, though not conclusively, that it relates to a similar phase and thus records cooling through a comparable temperature. The larger grain size of this sample may also reflect slower cooling of the end-member lodranites than acapulcoites and intermediate samples such as GRA 95209.

CONCLUSIONS

The I-Xe system has been investigated in three lodranites. Samples of Gibson exhibited excess ^{129}Xe, but did not yield a high temperature isochron and hence no age could be determined. Silicate and metal separates of GRA 95209 contain phases that closed at −4.19 ± 0·53 Ma relative to Shallowater, while a phase in a chip of LEW 88280 closed at −10.4 ± 2.3 Ma. The GRA 95209 data are consistent with the closure age of Acapulco feldspar, and closure of multiple phases from one parent body at the same time is best explained by rapid cooling of the parent material, which is inferred to have occurred at 4558.2 ± 0.7 Ma. This may have been related to an impact that altered the pattern of conductive heat loss to the surface of the parent body. Such impacts, and larger, are expected in the evolution of a precursor solar system debris disk to form the asteroid belt (Petit et al. 2001).

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