The Meteoritical Society

Meteoritics & Planetary Science 43, Nr 3, 541–559 (2008)
Abstract available online at http://meteoritics.org

A database of chondrite analyses including platinum group elements, Ni, Co, Au, and Cr: Implications for the identification of chondritic projectiles

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(Tables A1–A18 are available as an online supplement at http://meteoritics.org/online supplements.htm)

(Received 4 August 2006; revision accepted 16 July 2007)

Abstract–Siderophile elements have been used to constrain projectile compositions in terrestrial and lunar impact melt rocks. To obtain a better knowledge of compositional differences between potential chondritic projectile types, meteorite analyses of the elements Ru, Rh, Pd, Os, Ir, Pt, Cr, Co, Ni, and Au were gathered into a database. The presented compilation comprises 806 analyses of 278 chondrites including new ICP-MS analyses of Allende and two ordinary chondrites. Each data set was evaluated by comparing element ratios of meteorites from the same chondrite group. Characteristic element abundances and ratios were determined for each group. Features observed in the element abundance patterns can be linked directly to the presence of certain components, such as the abundance of refractory elements Os, Ir, and Ru correlating with the occurrence of refractory inclusions in CV, CO, CK, and CM chondrites. The refined characteristic element ratios appear to be representative not only for meteorites, but also for related asteroidal bodies. Chondrite element ratios were compared to previously published values from impact melt rocks of the Popigai and Morokweng impact structures confirming that an identification of the specific type of projectile (L and LL chondrite, respectively) is possible. The assessment for Morokweng is supported by the recent discovery of an LL chondrite fragment in the impact melt rocks. Ultimately, the database provides valuable information for understanding processes in the solar nebula as they are recorded in chondrites. A new type of complementarity between element patterns of CK and EH chondrites is suggested to be the result of condensation, redox, and transportation processes in the solar nebula.

INTRODUCTION

Impact craters are the most common topographic feature of solid bodies in the solar system (with exception of geologically highly active bodies like Earth and Io) and are thought to be formed by the collision with interplanetary bodies, such as comets and asteroids. The majority of impactors originate in the main asteroid belt as fragments of either primitive or differentiated asteroids (e.g., Ivanov et al. 2002; Morbidelli et al. 2002; Chapman 2004). The identification of projectiles responsible for impact craters on Earth and Moon will permit a determination of the frequency distribution of projectile types and will provide insights into the dynamics of asteroids and the formation of near-Earth objects (NEOs). Until samples from asteroids are returned to Earth (e.g., by the Japanese Hayabusa space probe from the Itokawa asteroid), the major composition of asteroids can be implied by comparison of their reflectance spectra with those of meteorites (e.g., Burbine et al. 2002; Gaffey et al. 2002), but their minor and trace element composition can only be inferred by chemical analysis of meteorite samples.

The identification of asteroid fragments impacting Earth and Moon is based on the fact that most projectiles have higher abundances of certain elements (e.g., highly siderophile elements) than terrestrial and lunar crustal rocks (e.g., Ganapathy et al. 1970; Anders et al. 1973; Morgan et al. 1974, 1975a; Grieve 1978; Palme et al. 1978; Palme 1982; Koeberl 1998; Tagle and Hecht 2006). First attempts to identify the nature of projectiles responsible for impact craters were carried out on Apollo samples (Ganapathy et al. 1970; Anders et al. 1973; Morgan et al. 1974) and were followed closely by studies characterizing projectiles that formed impact craters on Earth (e.g., Morgan et al. 1975b; Grieve 1978; Palme et al. 1978). Patterns and ratios of elements such as Ir, Re, Ni, Au, Ge, Sb, and Bi were initially used for the identification, because it was possible to accurately analyze them at low concentration levels using radiochemical neutron activation analysis. At this time, an analysis of all platinum group elements (PGE) was usually not done, mainly because of the difficulties in the determination of some of the elements, especially Ru, Rh, and Pt, at such low concentration levels. However, with improvements in the analytical techniques, the number of elements used for impactor identification steadily increased (e.g., Schmidt et al. 1997; McDonald et al. 2001; Norman et al. 2002; Tagle and Claeys 2005) highlighting the relevance of a precise knowledge of the composition of possible projectiles. The most relevant elements are the platinum group elements (Os, Ir, Ru, Pt, Rh, and Pd) as well as Cr, Co, Ni, and Au (refer to the Element Ratios of the Different Chondrite Groups section for a detailed explanation why these elements were chosen). Here, an up-to-date data collection of analyses of these elements in chondritic meteorites is presented.

Chondrites comprise over 85% of all observed meteorite falls (Grady 2000). Therefore, it is very likely that chondritic material also constitutes a substantial fraction of the population of larger projectiles within the inner solar system. The less common type of extraterrestrial material reaching Earth are fragments of differentiated asteroids, including achondrites, iron, and stony-iron meteorites (e.g., Grady 2000; Burbine et al. 2002, and references therein). These materials will not be discussed in this paper.

Chondrites are fragments of undifferentiated asteroids and represent some of the most primitive material in the solar system. So far, 14 chondrite groups (EH, EL, H, L, LL, R, CV, CK, CO, CM, CR, CH, CB, CI) and one grouplet (K) have been classified based on oxygen isotopic compositions, characteristic element abundances, petrographic features, mineralogy, and oxidation state (e.g., Krot et al. 2003). There are also a number of ungrouped chondritic meteorites (e.g., Meibom and Clark 1999; Krot et al. 2003), most of which are related to carbonaceous chondrites. The bulk compositional variations of chondrites probably reflect the conditions at the time and place of the formation of their components (refractory inclusions, metal/sulfides, chondrules, matrix) as well as the abundance of each of these components. Because they have never been subject to processes of planetary differentiation, the composition of small fragments, such as meteorites, should be representative for the composition of the parent body.

The database presented in this paper is a refined and updated version of Tagle (2004), which was used by Tagle and Claeys (2004, 2005) for the identification of an L chondrite component in the impact melt of the Popigai impact structure, Siberia. The main purpose of this database is (1) to compile analytical data sets of chondritic meteorites for elements most relevant for impactor identification, (2) to evaluate the data in order to obtain characteristic element ratios and more precise element patterns for the different chondrite groups, as well as (3) to improve the geochemical criteria used for the identification of impactors. Nevertheless, it also provides interesting constraints on the earliest processes in the solar nebula.

THE DATABASE

The presented data include 806 analyses of 278 chondritic meteorites published over the past 40 years. Tables A3–A18 (Tables A1–A18 are available online at http://meteoritics.org/online supplements.htm) list all meteorite data sets that were used for the calculation of characteristic element ratios for the different chondrite groups (the supplemental data tables are meant for the reader to review and if found necessary to apply their own statistical treatment—the filtering procedure described below is a prototype). The degree of weathering and shock stage of the meteorites are listed if the information was available through MetBase (Koblitz 2003). The meteorites Bjurböle, Cynthiana, Holbrook, Knyahinya, and Sultanpur, which have been categorized as L/LL chondrites (Kallemeyn et al. 1989; Friedrich et al. 2003, and references therein), were handled separately from L and LL chondrites (see the Ordinary Chondrites section and Table A16). Data from the compilation of “Composition of chondrites” published by Wasson and Kallemeyn (1988) were not included in the calculations presented here, because raw data and the procedure applied to obtain the composition of each chondrite group (at that time only: CI, CM, CO, CV, H, L, LL, EH, and EL) were not sufficiently documented in this publication.

Despite the fact that the data compilation reflects the recent advances in analytical techniques, sample inhomogeneity remains a major challenge in the analysis of highly siderophile elements in geological materials (e.g., Morgan et al. 1985; McDonald et al. 2001; Meisel et al. 2001; Walker et al. 2002; Horan et al. 2003). Different aliquots of the same chondrite may not contain the same abundance of components rich in highly siderophile elements, such as metals/sulfides and/or refractory inclusions. Moss et al. (1967) indicated that such inhomogeneities could not be resolved when samples of 10–15 g were used. Haas and Haskin (1991) concluded that sample masses of 200 g might even be necessary to obtain representative analyses. However, such large amounts of sample are rarely available from most meteorites. A minimum amount of meteorite required to obtain reproducible results appears to be in the order of a few grams, as can be seen by comparing meteorite data of different authors (e.g., Jochum 1996; McDonald et al. 2001; Friedrich et al. 2003; Horan et al. 2003). Homogeneous sampling also strongly depends on the meteorite type (see later discussion for CB chondrites, section The CR Clan (CR, CH, CB), Rumuruti (R), and Kakangari (K) Chondrites) and uncertainties introduced during sample preparation and/or by the actual acquisition should be taken into account as well (e.g., Meisel et al. 2001).

As a result of sample inhomogeneities, absolute element abundances are not as reproducible as element ratios, the latter of which usually exhibit relatively small variations within a given meteorite group (Morgan et al. 1985; McDonald et al. 2001; Horan et al. 2003). The data recently published by Walker et al. (2002) suggest that the "real" variations in PGE ratios, as shown especially for Re/Os, are quite small within each chondrite group and most of the scatter reported in earlier studies is due to analytical difficulties rather than chemical variations. Therefore, we assume that most of the element ratios calculated for every analysis in the database varies around a "true" ratio for each meteorite group. The collected data were carefully evaluated and filtered, taking possible analytical uncertainties into account as well as problems due to sample inhomogeneities (as a result of small sample masses analyzed), and element loss as a consequence of weathering. The compiled data were filtered based on element ratios (refer to the Data Reduction and Filtering section), not only because element ratios can be determined more precisely than absolute values, but also because almost every single data set is incomplete (i.e., only selected elements were measured). Thus, simple averaging of absolute abundances would lead to significant uncertainties.

Data Reduction and Filtering

Data reduction was carried out in two steps. In the first step, element/Ir ratios were calculated from each data set. Ir was chosen because it is the most commonly analyzed among the relevant elements. Aberrant element/Ir ratios occur in a few cases (marked bold in Tables A3–A18) and were excluded from further calculations. Such atypical values were assumed to be due to sample preparation and/or analytical errors. An increased number of aberrant element/Ir ratios within a data set led to the exclusion of the entire analysis (e.g., Crocket et al. 1967; Hintenberger et al. 1973). In such cases, the ratios as well as the reference are marked bold. Besides analyses of fresh meteorite falls, the database contains analyses of meteorites that have experienced different degrees of weathering. For example, Kallemeyn and Wasson (1991) reported a strong loss of Ni and Co in the CK chondrites Maralinga and Lewis Cliff (LEW) 86258 due to weathering, while Cr values remained relatively unaffected (refer to Table A7). The 3 available INAA data sets of LEW 86258 (Kallemeyn and Wasson 1991) also show other atypical element/Ir ratios and were therefore excluded from further calculations. However, in meteorites with similar depletions in Ni and Co (e.g., Maralinga and R chondrite Yamato (Y-) 793575), PGE do not seem to be affected (Table A12). Analyses of weathered meteorites were checked for depletions in Ni and Co. The fact that such depletions were only found in CK and R chondrites (which have abundant sulfides and no Fe,Ni-metal), but not in ordinary chondrites, is related to decreasing modal abundances of sulfides with increasing degree of terrestrial weathering (Rubin and Huber 2005). Abnormal low values were excluded from further calculations (marked bold and gray underlayed in Tables A3–A18).

In the second step, mean and standard deviation (σ) of the element ratios were calculated for each chondrite group. Thereafter, a 2σ filter (which includes 95.5% of all analyses) was applied and only values between the mean and $\pm 2\sigma$ were used for further computation. Values above or below the mean $\pm 2\sigma$ were excluded (marked in Tables A3–A18 bold and underlined).

The mean concentrations (used for determining the CI-normalized element patterns in the Characteristic Element Patterns of the Different Chondrite Groups section) were obtained by multiplying the respective element/Ir ratio with the mean Ir concentration of each group (Table 1). The higher number of Ir analyses available should guarantee that the resulting element concentrations are representative for the "true" concentration of the given meteorite group.

Finally, characteristic element ratios were calculated for each chondrite group from the ratios that passed the 2σ-filter. The uncertainties of these final element ratios were calculated as 1σ of all values that passed the filter. In some rare cases, it was only possible to provide "provisional" element ratios (underlined in Table A1), because the two elements of interest (i.e., Pd and Rh in CM chondrites) were never determined in the same aliquot. Such ratios were calculated from the mean composition of the chondrite in question (Table 1). These provisional ratios need to be considered less precise than those obtained from analyses where both elements were measured. If fewer than 3 element ratios were available for one chondrite group, an uncertainty was estimated assuming that the unknown uncertainty is similar to the average uncertainty (~5%) found for the other PGE ratios in the database. These "provisional" uncertainties are calculated as 5% of the ratio and are underlined and italic in Tables 3 and A1.

Data Correction

An important data set that includes analyses of 47 ordinary chondrites (L, LL, and L/LL) and some carbonaceous chondrites (CM and CO) was published by Friedrich et al. (2002, 2003). When compared to results published by other authors, significant deviations were found for the concentrations of Ru. Friedrich (personal communication) acknowledged that an error occurred in the compilation of element abundances for the Allende meteorite, which was used as an external calibration standard. The reported Ru concentration of Allende was ~1.5 times higher than previously published values (e.g., Kallemeyn and Wasson 1981; Jochum 1996; Kong et al. 1999b; Horan et al. 2003), whereas the deviations for the other PGE were smaller. Using more accurate values for the element concentrations of Allende (Table A2), the element abundances published by Friedrich et al. (2002,

Table 1. Mean element concentrations of the different chondrite groups.

	Os (ng/g)	Ir (ng/g)	Ru (ng/g)	Pt (ng/g)	Rh (ng/g)	Co (µg/g)	Au (ng/g)	Pd (ng/g)	Ni (µg/g)	Cr (µg/g)
CI	502	472	717	959	135	521	139	563	10863	2796
CO	784	725	1081	1206		688	187	685	13562	3502
CM	675	605	909	1112	159	583	165	649	12393	3058
CV	807	758	1150	1443	209	641	143	707	13629	3557
CK	825	772	1121	1560	213	647	121	749	12518	3627
CR	655	622	926	1208		666	123	734	13794	3810
CH	1155	1066	1566	1596		1125	249	964	25716	3393
CB[a]	2850	2635	4120			2360	278		51750	2825
CB[b]	3523	3235	4609	5838	1084	2983	511	3277	66431	2058
CB[c]		480				555	109		11600	4110
K	673	628	961			786	212		17172	2575
R	648	609	904			700	137		14366	3563
H	805	749	1135	1559	230	763	210	825	16846	3470
L	537	500	745	1028	166	570	152	613	12930	3648
LL	364	336	522	707	115	452	119	500	9581	3519
L/LL	490	438	662	847		514	148	634	12766	3765
EH	647	573	927	1183	191	856	326	928	18006	3076
EL	629	566	866	1140	185	727	245	741	14676	3148

[a] Bulk.
[b] Metal fraction.
[c] Silicate fraction.

2003) were corrected by multiplication with the obtained correction factors (Table A2). Only the recalculated values are given in the database (Tables A3–A18).

NEW ANALYSES

The database also contains new analyses (Ir, Ru, Pt, Rh, and Pd) of the CV chondrite Allende (Table A6), and duplicate analyses of previously published data (Tagle and Claeys 2005) for Acfer 132 (H chondrite, Table A13) and Acfer 120 (LL chondrite, Table A15). The data were obtained by inductively coupled mass spectrometry (ICP-MS) following Ni-sulfide fire assay pre-concentration and separation steps. Samples of ~20 g (5 g for Allende) were crushed in a corundum mortar and aliquots of ~5 g (1 g for Allende) were used for the Ni-sulfide fire assay. The use of external calibration solutions allowed a quantification of Rh, which is supported by the fact that Rh/Ir ratios obtained for Allende are very similar to previously published values (Table A6). For a detailed description of the method see Plessen and Erzinger (1998). Measurement uncertainties were discussed by Tagle and Claeys (2005).

RESULTS

Element Abundances in CI Chondrites

Element abundances of CI chondrites are widely used for normalization in geo- and cosmochemistry. In Fig. 1 and Table 2, previously published average element abundances of CI chondrites are compared to the values that were obtained with the filtering procedure described above. It has to be noted that only two Rh measurements of CI chondrites (Ivuna and Orgueil) have been published so far (Jochum 1996, Table A3). The Rh concentrations for CI chondrites given by Palme (1988), Wasson and Kallemeyn (1988), Anders and Grevesse (1989), and McDonough and Sun (1995) were recommended values based mainly on Rh analyses of H chondrites from Schindewolf and Wahlgren (1960) and CI/H chondrite ratios of Os, Ir, Ru, Pt, and Pd.

The averaged Rh concentrations of Ivuna and Orgueil measured by Jochum (1996) and given in Lodders (2003) are slightly higher than the value obtained here by calculating element ratios. These deviations result from averaging analyses of small inhomogeneous samples. Unfortunately, Jochum (1996) did not measure Ir in Ivuna (Table A3), therefore it was not possible to determine the Rh/Ir ratio directly for this analysis with the ratio method. However, if the Os concentration (498 ng/g) of Ivuna measured together with Rh (Jochum 1996) is used to calculate the Ir concentration using the ratio (Os/Ir = 1.06) for CI chondrites (Table A3), a Rh/Ir ratio of 0.30 is obtained, which is quite similar to the ratio (Rh/Ir = 0.29) found for Orgueil (Table A3). The same value is obtained if, instead of the Os/Ir ratio, the average Ir composition of CI chondrites is used for the calculation. This strongly supports the value for the Rh/Ir ratio given in Table 3.

The Cr concentration for CI chondrites obtained here is higher than values given by other authors (Table 2, Fig. 1). The small number of CI chondrite analyses where Ir and Cr were measured (Table A3) might introduce a bias towards such a higher value for Cr. Conversely, our method might

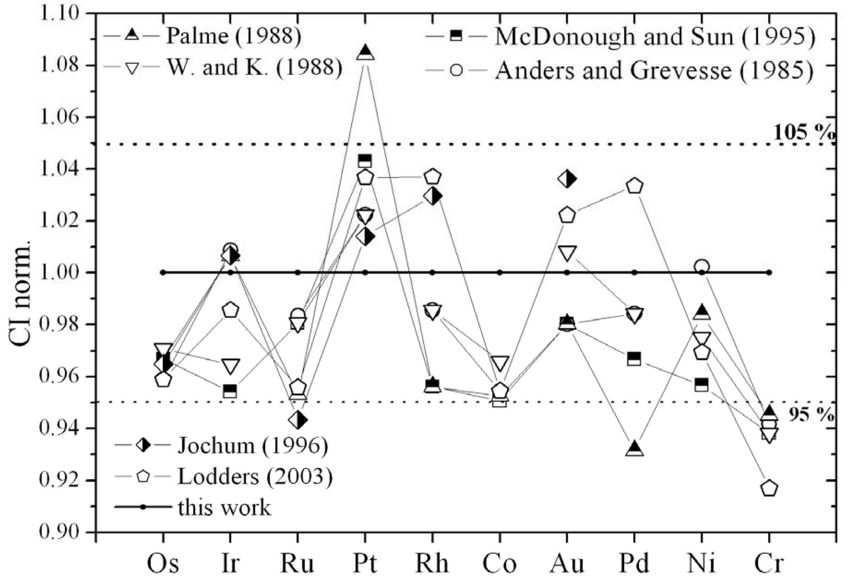

Fig. 1. Comparison of element abundances of CI chondrites published by several authors. Data are normalized to CI values obtained in this work. Note that in this work siderophile elements are always plotted with decreasing condensation temperature (Lodders 2003) and that Cr as lithophile element is plotted last. W. and K. (1988) = Wasson and Kallemeyn (1988).

Table 2. Element abundances of CI chondrites.

Os (ng/g)	Ir (ng/g)	Ru (ng/g)	Pt (ng/g)	Rh (ng/g)	Co (µg/g)	Au (ng/g)	Pd (ng/g)	Ni (µg/g)	Cr (µg/g)	References
490	455	710	1010	130	500	140	550	10,500	2650	McDonough and Sun (1995)
486	481	712	990	134	502	140	560	11,000	2660	Anders and Grevesse (1989)
490	480	690	1050	130	501	140	530	10,800	2670	Palme (1988)
492	460	710	990	134	508	144	560	10,700	2650	Wasson and Kallemeyn (1988)
489	480	683	982	140[a]	n.a.	148	n.a.	n.a.	n.a.	Jochum (1996)
486	470	692	1004	141	502	146	588	10,640	2590	Lodders (2003)
506	480	683	982	140	506	148	556	10,770	2646	Palme and Jones (2003)
502	472	717	959	135	521	139	563	10,863	2796	This work

[a] The only Rh concentration directly measured in CI chondrites (Ivuna and Orgueil).
n.a. = not analyzed.

bring the element abundances closer to the "true" composition of CI chondrites. For example, the value for Pt obtained here is lower than published values because data sets from Hintenberger et al. (1973) and Crocket et al. (1967) were omitted (refer to the Data Reduction and Filtering section, where possible systematic errors are discussed). Our suggested value for Pt is supported by recently published analyses of CI chondrites (e.g., Horan et al. 2003) also yielding lower Pt abundances.

In general, element/Ir ratios (Table A3) show only small variations between the different CI chondrites (usually <10%). However, some variations appear to affect the element Au. This has been reported by Ebihara et al. (1982) and was attributed to hydrothermal processes within the CI parent body which resulted in Au migration and inhomogeneous distribution within different aliquots. The element abundances determined for CI chondrites within this work (Table 2) are used for normalizing the data obtained for the different chondrite groups (section Characteristic Element Patterns of the Different Chondrite Groups).

Characteristic Element Patterns of the Different Chondrite Groups

Carbonaceous Chondrites (CC) with High CAI Abundances (CO, CV, CM, and CK)

The characteristic CI-normalized element patterns of CO, CV, CM, and CK chondrites (Fig. 2) show a significant enrichment in highly refractory PGE (Os, Ir, Ru). The high abundances of these elements are certainly related to the presence of refractory inclusions (e.g., El Goresy et al. 1978; Bischoff and Palme 1987; Sylvester et al. 1990; Palme et al. 1994). Ca-Al-rich inclusions [CAIs] and amoeboid olivine aggregates [AOAs] constitute 13 vol% in CO, 10 vol% in CV, 5 vol% in CM, and 4 vol% in CK chondrites (Brearley and Jones 1998). Most of our knowledge of CAIs stems

Table 3. Selected element ratios of the different chondrite groups.

	Os/Ir	Ru/Ir	Pt/Ir	Rh/Ir	Ni/Ir	Co/Ir	Pd/Ir	Au/Ir	Cr/Ir	Ni/Cr
CI	1.06 ± 0.04	1.52 ± 0.07	2.03 ± 0.15	0.29 ± *0.014*	23.02 ± 1.15	1.10 ± 0.07	1.19 ± 0.10	0.30 ± 0.04	5.92 ± 0.20	3.87 ± 0.25
CO	1.08 ± 0.05	1.49 ± 0.08	1.66 ± 0.23		18.70 ± 1.64	0.95 ± 0.03	0.94 ± 0.11	0.26 ± 0.01	4.83 ± 0.38	3.96 ± 0.09
CM	1.12 ± 0.09	1.50 ± 0.10	1.84 ± 0.09	0.26 ± *0.013*	20.48 ± 1.29	0.96 ± 0.05	1.07 ± 0.09	0.27 ± 0.02	5.06 ± 0.34	4.01 ± 0.30
CV	1.06 ± 0.03	1.52 ± 0.08	1.90 ± 0.12	0.28 ± *0.014*	17.97 ± 1.13	0.85 ± 0.02	0.93 ± 0.07	0.19 ± 0.02	4.69 ± 0.20	3.76 ± 0.12
CK	1.07 ± 0.05	1.45 ± 0.14	2.02 ± 0.07	0.28 ± *0.000*	16.21 ± 1.97	0.84 ± 0.09	0.97 ± 0.05	0.16 ± 0.05	4.70 ± 0.36	3.45 ± 0.40
CR	1.05 ± 0.04	1.49 ± 0.07	1.94 ± 0.16		22.18 ± 2.02	1.07 ± 0.09	1.18 ± 0.17	0.20 ± 0.05	6.13 ± 0.63	3.72 ± 0.39
CH	1.08 ± 0.04	1.47 ± 0.05	1.50 ± 0.27		24.13 ± 1.23	1.06 ± 0.12	0.90 ± *0.05*	0.23 ± 0.07	3.18 ± 0.42	7.65 ± 0.69
CB[a]	1.09 ± 0.08	1.42 ± 0.16	1.80 ± 0.12	0.34 ± 0.032	20.54 ± 4.80	0.92 ± 0.19	1.01 ± 0.18	0.16 ± 0.07	0.64 ± 0.17	31.22 ± 7.61
K	1.07 ± 0.02	1.53 ± 0.02			27.34 ± 4.86	1.25 ± 0.19		0.34 ± 0.09	4.10 ± 3.50	9.72 ± 5.01
R	1.06 ± 0.05	1.48 ± 0.07			23.58 ± 1.03	1.15 ± 0.03		0.23 ± 0.09	5.85 ± 0.23	3.99 ± 0.19
H	1.07 ± 0.04	1.51 ± 0.07	2.08 ± 0.06	0.31 ± 0.004	22.48 ± 2.20	1.02 ± 0.10	1.10 ± 0.10	0.28 ± 0.03	4.63 ± 0.45	4.38 ± 0.42
L	1.07 ± 0.04	1.49 ± 0.09	2.05 ± 0.12	0.33 ± 0.007	25.84 ± 2.83	1.14 ± 0.11	1.22 ± 0.14	0.30 ± 0.03	7.29 ± 0.42	3.22 ± 0.19
LL	1.08 ± 0.04	1.55 ± 0.07	2.10 ± 0.12	0.34 ± 0.006	28.50 ± 2.41	1.35 ± 0.16	1.49 ± 0.21	0.35 ± 0.03	10.47 ± 0.84	2.64 ± 0.21
EH	1.13 ± 0.04	1.62 ± 0.16	2.06 ± 0.04	0.33 ± *0.017*	31.41 ± 2.42	1.49 ± 0.08	1.62 ± 0.09	0.57 ± 0.05	5.37 ± 0.40	5.79 ± 0.36
EL	1.11 ± 0.08	1.53 ± 0.14	2.01 ± 0.04	0.33 ± 0.020	25.92 ± 3.02	1.28 ± 0.10	1.31 ± 0.07	0.43 ± 0.04	5.56 ± 0.98	4.77 ± 1.03

[a] Values for the metallic fraction. Error values 1σ; error values (italic and underlined) calculated as 5% of the ratios. PGE in ng/g; Co, Ni and Cr in µg/g.

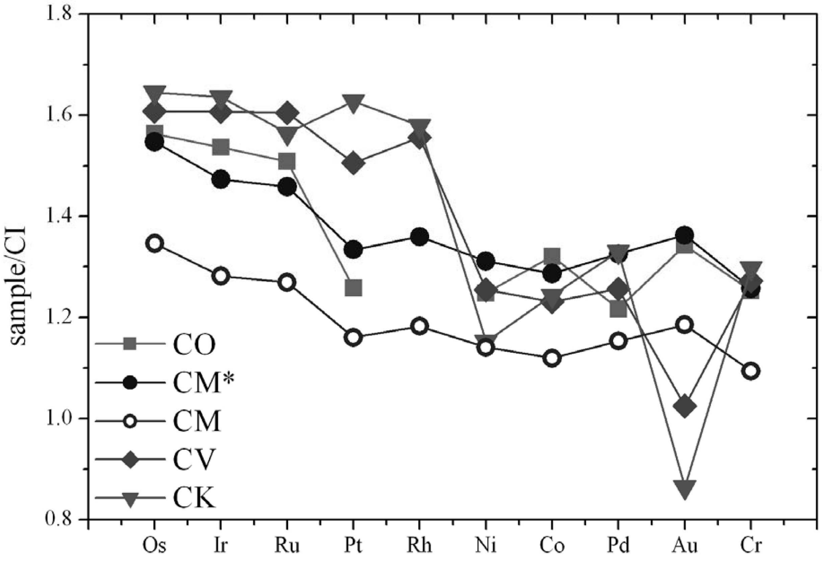

Fig. 2. CI-normalized element patterns of CV, CK, CO, and CM chondrites. Highly refractory PGE are enriched compared to later condensing elements, which is probably related to the high abundance of refractory inclusions in these meteorites. Element abundances in the original CM chondrite pattern seem low compared to the other groups. This is probably due to the high volatile content of these meteorites which dilutes their element abundances. For the CM* pattern, 13% volatiles were deduced from the CM pattern which moves the element abundances up into a range that is comparable with the other three chondrite groups.

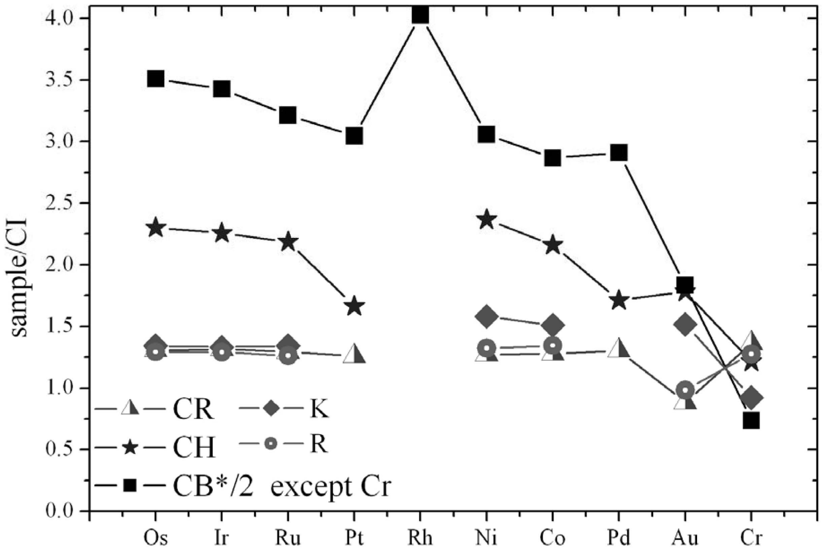

Fig. 3. CI-normalized element patterns of CR, CH, K, and R chondrites as well as for the metal fraction of CB chondrites (CB*). The element pattern for CB metal was divided by 2 (except for the element Cr) in order to present all patterns within one diagram.

from studies of the CV chondrite Allende. Small, µm-sized nuggets of PGE alloys have been found in melilite, fassaite, spinel and perovskite in type A CAIs (e.g., Wark and Lovering 1978; El Goresy et al. 1978), whereas type B CAIs contain so-called "Fremdlinge," which are PGE-rich phases associated with Fe,Ni-metal, sulfides, and oxides (e.g., El Goresy et al. 1978).

Interestingly, CK chondrites show a higher abundance of Pt than the other carbonaceous chondrites, but so far data are quite rare (Table A7). However, in contrast to CM, CV, and CO chondrites, CK chondrites contain various PGE-rich mineral grains that are found outside of CAIs (PGE-rich sulfides/arsenides and other minerals rich in Pt), often associated with magnetite and/or sulfides (Geiger and Bischoff 1989, 1995). Their occurrence has been explained by the high oxidation state of CK chondrites and the absence of Fe,Ni-metal (Geiger and Bischoff 1989, 1995).

As discussed before for CI chondrites, Au concentrations show a much stronger variation than the other elements (Tables A4–A7). CV and CK chondrites even show a Au

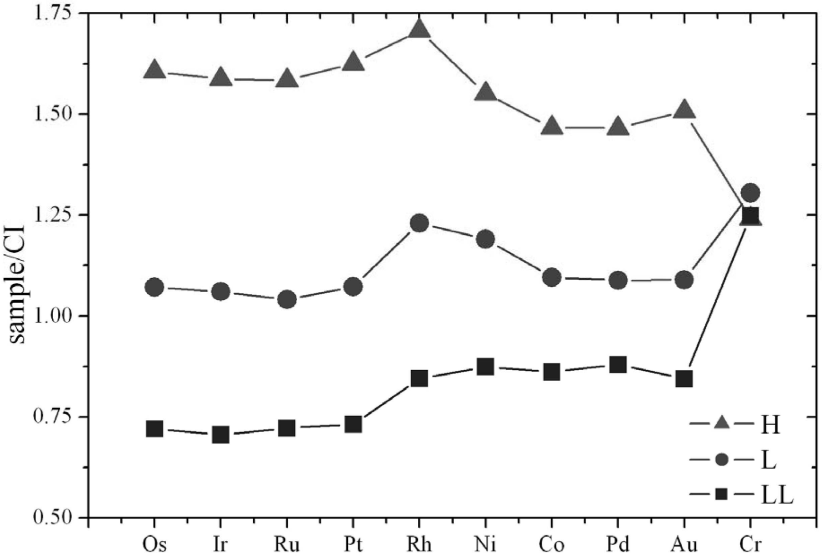

Fig. 4. CI-normalized element patterns of H, L, and LL chondrites. Element abundances correlate with the metal content of each group, decreasing from H > L > LL.

depletion (Fig. 2). This depletion does not seem to correlate with terrestrial weathering, as it is clearly present in Allende (CV) and Karoonda (CK), which are both fresh falls. Therefore, this depletion may represent a "real" deficit of Au in these chondrites.

Horan et al. (2003) pointed out that relatively low abundances of siderophile elements in CI chondrites probably result from the dilution of all their components by the high concentration of volatiles (H_2O, C, S). The same should be true for CM chondrites as they contain about 13% volatiles (Wood 2005 and references therein). Deducting such an amount of volatiles from the element pattern of CM chondrites (CM^* in Fig. 2) yields not only a Cr abundance that is very similar to CO, CV and CK chondrites, but also similar abundances for more refractory PGEs.

The modal abundances of refractory inclusions in these 4 chondrite groups (CO > CV > CM > CK) do not seem to correlate with the sequence of decreasing abundances of highly refractory PGE (CK > CV > CO > CM). However, the latter sequence does support the fact that PGE minerals are present outside CAIs in CK chondrites. Furthermore, this sequence plus the overall trends seen in the element patterns support the observation that CV and CK chondrites are closely related to each other (e.g., Greenwood et al. 2004; Krot et al. 2003) as are CO and CM chondrites (e.g., Clayton and Mayeda 1999; Krot et al. 2003). In contrast to the element patterns of CO and CM chondrites, which show a rapid decrease in concentrations for elements condensing after Ru, the patterns for CV and CK chondrites show a significant decrease after Rh. This may imply that certain phases such as those found in CK chondrites (Geiger and Bischoff 1995) which contain significant amounts of Pt (and Rh?) may also be present in CV chondrites, but not in CO and CM chondrites.

The CR Clan (CR, CH, CB), Rumuruti (R) and Kakangari (K) Chondrites

Despite significant petrographic and chemical differences, the element patterns of CR, CH, CB, Rumuruti (R), and Kakangari (K) chondrites are quite similar (Fig. 3). Therefore, they will be discussed here in one section. The main reason for the similarity of the element patterns is probably the scarcity of refractory inclusions, which appears to be one of the major sources of highly refractory PGE in chondrites. According to Krot et al. (2003), CR chondrites contain 0.5 vol%, CH chondrites 0.1 vol%, and CB, R, and K chondrites have less than 0.1 vol% refractory inclusions. As of today, the amount of available data for these chondrite groups is quite limited (Tables A8–A12). More analytical work is needed in order to resolve characteristic differences between these different chondrite groups.

The CR Clan. The CR clan includes CR, CH, and CB chondrites as well as the unique chondrite LEW 85332 (Krot et al. 2002, 2003). A CH-like grouplet was proposed by Krot et al. (2002) consisting of Hammadah al Hamra 237 and QUE 94411/94627, however, for the database we follow the classification of Krot et al. (2003) and assign these meteorites to the group of CB chondrites. The relative element abundances in CR, CH, and CB chondrites (Fig. 3) are in accordance with their Fe,Ni-metal contents, increasing from CR (5–8 vol%) < CH (20 vol%) < CB (60–70 vol%) (Krot et al. 2003). The significant abundance of metal, especially in CB chondrites, hampers a precise determination of the bulk composition for the relevant elements. Most CB chondrite analyses included in the database (Table A10) are not bulk meteorite analyses, but were obtained on metal nodules (e.g., Campbell et al. 2002). Nevertheless, the element pattern for CB metal is very similar to the other meteorite groups of the CR-clan.

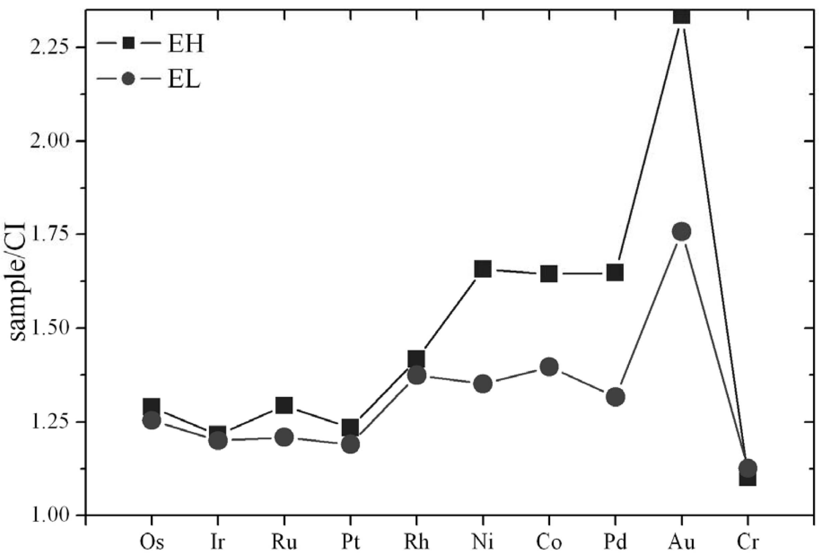

Fig. 5. CI-normalized element patterns of EH and EL chondrites. Similar abundances of highly refractory PGE indicate a common evolution during the early stages of condensation. EH and EL reservoirs might have been separated when temperatures dropped as EH chondrites are more enriched in later condensing elements than EL chondrites.

A peculiar feature in the CB chondrite element pattern is Rh (Fig. 3). However, it was only measured in the metallic fraction of CB chondrites (Campbell et al. 2002) and has not yet been analyzed in CH, CR, R, or Kakangari chondrites. A relative enrichment of Rh compared to highly refractory PGE is a feature that is also found in OC and EC (Figs. 4 and 5). As yet, the significance of this Rh enrichment is unknown.

Rumuruti Chondrites. The element pattern of Rumuruti (R) chondrites (Fig. 3) is astonishingly similar to that of CR chondrites even including the relative Au depletion. However, so far there are no data for Pt, Rh, and Pd. In contrast to CR chondrites, which contain 5–8 vol% metal (Krot et al. 2003), R chondrites are highly oxidized and contain very little Fe,Ni-metal (<0.1 vol%, Schulze et al. 1994). Nevertheless, tiny PGE-rich phases have been found (Schulze 1998, 1999; Berlin et al. 2001) which are similar to those found in CK chondrites (Geiger and Bischoff 1989, 1995). On the other hand, R chondrites have a close relationship to ordinary chondrites, especially in their oxygen isotopic composition ($\Delta^{17}O \approx +2.7‰$). If R chondrites would have been plotted within the diagram for ordinary chondrites (Fig. 4), it would have become obvious that the abundances of the selected elements fall between H and L chondrites. This correlates well with Fe/Si ratios (Lodders and Fegley 1998): H (0.80) > R (0.68) > L (0.59) > LL (0.53), indicating that PGE abundances were initially associated with Fe,Ni metal. Furthermore, it supports the suggestion that the metal-silicate fractionation was independent of the degree of oxidation (Schulze et al. 1994).

Kakangari Chondrites. The grouplet of Kakangari (K) chondrites comprises only 2 meteorites: Kakangari and LEW 87232 (Krot et al. 2003). Lea County 002 was originally classified as a Kakangari-like chondrite (Weisberg et al. 1996), but Krot et al. (2003) suggested that it should be categorized as a CR chondrite instead. Although no data are yet available for Pt, Rh, and Pd, it was possible to resolve an element pattern (Fig. 3) that is similar to those of CR and R chondrites. However, it does not show the Au-depletion observed in the CR and R chondrite element patterns. K chondrites have a bulk oxygen isotopic composition similar to CR, CB, and CH chondrites, but they also exhibit characteristics distinct from carbonaceous chondrites and show affinities to enstatite and H chondrites (Weisberg et al. 1996). The abundance of Cr in K chondrites is somewhat lower than in carbonaceous and ordinary chondrites, but it is comparable with enstatite chondrites.

Ordinary Chondrites (OC)

The element patterns of H, L, and LL chondrites are relatively flat with the exception of Rh, Ni, and Cr (Fig. 4). The rareness of refractory inclusions in ordinary chondrites (< 0.2 vol%, Krot et al. 2003) is reflected in the patterns. LL chondrites even show a relative depletion of highly refractory PGE compared to later condensing elements (e.g., Rh and Pd). The relative element abundances correlate with the metal content of each of the chondrite groups, decreasing from H > L > LL. As would be expected for a lithophile element, the behavior of Cr is clearly independent from the metal content.

The amount of published PGE data for ordinary chondrites is huge compared to CC and EC. Nonetheless, analyses of Rh are rare. A determination of Rh by radiochemical methods (INAA or NAA) is complex because of its short half-life. Moreover, a quantification of the monoisotopic Rh is not possible by standard isotope dilution measurements of PGE. The Rh data included in the database for ordinary chondrites (Tables A13–A15) are from McDonald et al. (2001) and new analyses from this work. The results of our OC analyses are consistent with the concentrations and element ratios determined by McDonald et al. (2001).

The assignment of chondrites to the different ordinary chondrite groups is mainly based on Fe,Ni-metal abundance, Fa-content of olivine and oxygen isotopic composition. However, some ordinary chondrites do not fit the taxonomic classification and are catalogued as intermediate. This is the case for the H/L chondrites Tieschitz and Bremervörde (Koblitz 2003). Element ratios of these two meteorites determined here are in good agreement with those of H chondrites (Table A13), supporting a classification of these meteorites as H chondrites as was suggested by Grady (2000). Another intermediate ordinary chondrite is Xi Ujimgi, which was classified as L6/LL6 by Kallemeyn at al. (1989). Element ratios of this meteorite are consistent with those found for L chondrites (Table A14), again supporting the classification by Grady (2000). Data sets of 5 chondrites that were classified as L/LL chondrites (Kallemeyn et al. 1989; Friedrich et al. 2003, and references therein) are listed in a Table A16, separate from L and LL chondrites. These meteorites do not yield unambiguous element ratios—most of the ratios resemble LL chondrites, but Co/Ir ratios are more consistent with L chondrites. As different analyses of the same meteorites yield quite variable results, further studies are needed to resolve their assignment to either L or LL or even a new group of ordinary chondrites.

Enstatite Chondrites (EC)

As can be seen in the element patterns shown in Fig. 5, the abundances of highly refractory PGE are very similar for EH and EL chondrites. The absolute Ir concentrations derived from the database are 573 ± 67 ng/g for EH chondrites (19 meteorites) and 569 ± 141 ng/g for EL chondrites (17 meteorites); uncertainties represent 1σ. However, enstatite chondrites exhibit an Ir depletion compared to Os and Ru (Fig. 5). This feature, also observed in the compilation of Wasson and Kallemeyn (1988) and by Horan et al. (2003), is small but most likely not an artifact. Both, EH and EL chondrites are significantly enriched in the later condensing elements Rh, Ni, Co, Pd, and Au.

There is some discussion whether EH and EL chondrites originated from the same (e.g., Wasson and Wai 1970; Biswas et al. 1980; Kaczaral et al. 1988; Kong et al. 1997) or two distinct parent bodies (e.g., Sears et al. 1982; Keil 1989). At first, the main evidence favoring a single parent body was that EL chondrites were only found as petrologic type 6, and EH chondrites were only present as type 4 and 5. Sears et al. (1982) and Keil (1989) presented physical and chemical evidence indicating that nebular, not planetary processes must have been responsible for the differences found between EH and EL. The discussion is still ongoing as Kong et al. (1997) found continuity in the chemical composition between EH and EL when considering newly discovered EL3 and EH3 chondrites. Schneider et al. (2002) suggested similar precursor materials for the chondrules of the two groups, which must have formed in similar environments, followed by subsequent size-sorting and rapid incorporation into the bulk rock. After accretion, EL chondrites must have cooled more slowly than EH chondrites.

The element patterns indicate a common evolution of EH and EL chondrites during the early stages of condensation, but a possible separation of EH and EL reservoirs after temperatures dropped below ~1400 K. EH and EL chondrites clearly represent two distinct populations for all siderophile elements condensing after Rh, as the Pd/Ir ratios for EH (1.62 ± 0.09) and for EL (1.30 ± 0.07) are quite different and no meteorite has been found within this compositional gap. However, the similarity of the patterns indicates related environments in which EH and EL must have formed. In contrast, ordinary chondrite parent bodies must have evolved separately from the very beginning, as the abundances of the highly refractory PGE are significantly different for H, L, and LL (refer to Fig. 4) and correlate well with their Fe,Ni-metal content. In fact, EH and EL chondrites have very similar Fe,Ni-metal abundances (EH = 10.1 vol%, EL = 10.2. vol%, Krot et al. 2003), but different bulk Fe abundances and therefore different Fe/Si ratios (e.g., Sears et al. 1982; Lodders and Fegley 1998).

ELEMENT RATIOS OF THE DIFFERENT CHONDRITE GROUPS

Condensation probably played an important role among the different processes that could have been responsible for the fractionation of PGE during chondrite formation (Lodders 2003, and references therein). The cosmochemical classification and condensation temperatures of the elements (50%, at 10^{-4} bar total pressure) used for the interpretation of the results were taken from Lodders (2003). The elements Os and Re, the latter of which was not included in the database (see later discussion in the Projectile Identification in Terrestrial and Lunar Impact Melts section), are among the *ultrarefractory elements* with condensation temperatures above 1650 K. Re/Os ratios are quite uniform within each chondrite group (Walker et al. 2002): 0.0814 ± 0.0031 for CC, 0.0876 ± 0.0052 for OC, and 0.0874 ± 0.0027 for EC (uncertainty given as 1σ standard deviation).

Ir and Ru are *highly refractory elements* with condensation temperatures between 1650 and 1500 K. The variations of Os/Ir and Ru/Ir ratios with averages of 1.08 ± 0.02 and 1.51 ± 0.04 for all chondrites (uncertainty given as 1σ standard deviation) are exceptionally small (Fig. 6). However, enstatite and CM chondrites have a slightly higher

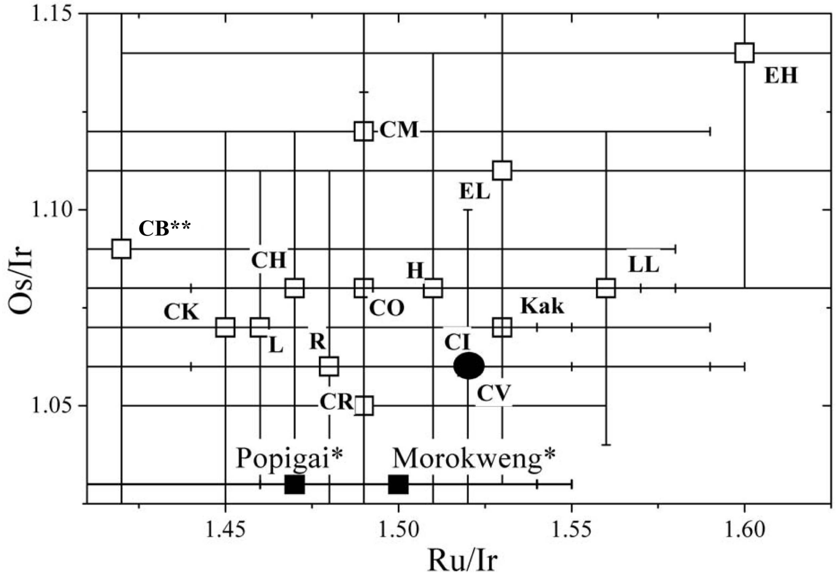

Fig. 6. Illustration of the poor resolution in the discrimination of chondrites by using refractory elements only (with small differences in their condensation temperatures) such as Os, Ir, and Ru. *No Os/Ir ratios were available for the two impact craters. **Metal fraction only.

Os/Ir ratio than other chondrites. The divergence of EC in this case seems "real" as it is related to the observed Ir depletion (refer to the Enstatite Chondrites section). On the contrary, the ratios determined for CM chondrites vary strongly between the meteorite analyses (Table A4), not allowing a conclusive statement.

The Os/Ir versus Ru/Ir diagram in Fig. 6 illustrates that a combination of three elements with similar condensation temperatures does not permit a discrimination between the different chondrite types. The differences are quite small and the uncertainties strongly overlap. However, when Os, Ir, and Ru are instead combined with the *refractory elements* Pt and Rh (condensation temperatures between 1500 and 1360 K) or even with elements that share their condensation temperature with the *common elements* (Si, Mg, Fe) such as Ni, Co, Pd, and Cr (1360 and 1290 K), a much greater spread between the characteristic ratios can be achieved (Table 3). Finally, the differences are largest when Au as a *moderate volatile element* with a condensation temperature of 1060 K is used for the ratios (Table 3). Again, it is therefore obvious that element ratios including one of the ultra- or highly refractory elements and one of those with a lower condensation temperature allow the best separation between the different chondrites types (refer to the Characteristic Element Ratios for Projectile Identification section for further discussion). A set of selected element ratios of the different chondrite groups is shown in Table 3 (all determined ratios are given in Table A1).

The main emphasis of this paper is the selection of characteristic element ratios that permit the best discrimination between the different chondrite types within impact-derived material. Therefore, it is fundamental to consider abundances of the relevant elements in the target material itself, preferably in comparison with chondritic abundances (e.g., as target/meteorite ratio). Elements such as Os, Ir, Ru, Pt, Rh, and Pd are not significantly disturbed by the indigenous concentrations in a terrestrial or a lunar target. This is not the case for Co, Cr, Ni, and Au, which can be present in significant amounts within potential target rocks. The latter elements are therefore less useful for projectile identification, despite the fact that element ratios involving these elements would allow a better discrimination between the different chondrite types because of their lower condensation temperatures (refer to Table 3). The indigenous concentrations of Co, Cr, Ni, and Au can disturb the determination of the projectile element ratios (Tagle and Hecht 2006), but can still be useful when the target concentrations are negligible or can be accounted for. As a final consequence, element ratios that involve Os, Ir or Ru combined with Rh or Pd were found to be most effective in resolving the "finger-prints" of the different chondrite groups in impact-derived rocks. In addition, it proved helpful when Pt is combined with both sets of elements (Os, Ir, Ru versus Rh, Pd), because of its intermediate condensation temperature between Ru and Rh.

Characteristic Element Ratios for Projectile Identification

In this section, diagrams are presented which show the widest spread between the element ratios of the different chondrite groups and which are therefore ideal for impactor identification. Element ratios combining Ir, Ru, or Pt, with Rh and Pd are shown in Fig. 7. It is interesting to note that carbonaceous and non-carbonaceous chondrites clearly occupy separate regions in the diagrams and CI chondrites repeatedly plot intermediate between them. The differences in the Rh/Ir ratio appear to be most indicative for distinguishing between CC and OC/EC (Fig. 7a). Unfortunately, the number of Rh analyses is quite low for all chondrite groups. Nevertheless, all well characterized Rh/Ir ratios for bulk CC are below the value of 0.29 for CI chondrites. The only exception are CB chondrites, however, the data only represent the metal fraction. Currently, no explanation exists for the high abundance of Rh in CB metal as measured by Campbell et al. (2002). The lack of Rh analyses for CH, CR, and CO chondrites does not allow any conclusions whether or not their Rh/Ir ratios are compatible with those of other CC. The differences in the Rh/Ir (Fig. 7a) and Pt/Rh (Fig. 7c) ratios are most significant between CC and OC/EC. For a reasonable distinction between OC and EC other ratios such as Ru/Rh (Fig. 7b) and Pt/Pd (Fig. 7c) are more useful.

The diagram shown in Fig. 8 is less effective in resolving differences between the chondrite groups, however, it illustrates the compositional relationship between CI chondrites and the other chondrite groups very well. CI chondrites plot intermediate between carbonaceous and non-carbonaceous chondrites.

Projectile Identification in Terrestrial and Lunar Impact Melts

The identification of a projectile type has usually been performed by determination of CI-normalized element patterns in the "contaminated" rocks. When flat PGE patterns were found, chondritic impactors were proposed (e.g., Koeberl 1998; Palme 1982; Schmidt et al. 1997). However, element patterns in impactites are often significantly disturbed by the composition of the target. This effect can mask the small differences among chondrites and in the worst case, such as high indigenous PGE concentrations, hamper the recognition of a chondritic pattern for the projectile (Tagle and Hecht 2006). Element patterns should only be used for the rough identification of the projectile type, but are generally not appropriate for a precise projectile identification, especially for chondrites.

Nevertheless, the identification of the projectile type can be achieved, without specifically accounting for the target component. This was discussed in detail by Tagle and Hecht (2006). The final composition of impactites, e.g., impact melt rocks, is the result of a mixture of the different target rocks with a projectile component. Whereas the target rocks are relatively homogeneously distributed within the impact melt, as shown by major and trace element compositions (e.g., Grieve et al. 1977; Dressler and Reimold 2001), the projectile component (frequently below 1 wt%) is often distributed unevenly within the samples. Therefore, a mixing line can be defined by individual samples with variable amounts of the projectile component (Fig. 2 in Tagle and Claeys 2005). The projectile element ratios can be determined by linear regression of such mixing trajectories, even in the case of a PGE-rich target (e.g., containing ultrabasic rocks). The deviation of the slope from the ratio in the projectile is inversely proportional to the projectile/target ratio of the selected elements. The effects of the indigenous component on the projectile element ratios, e.g., for a chondritic projectile in a terrestrial or lunar target, are typically below 1% for PGE and therefore below analytical resolution.

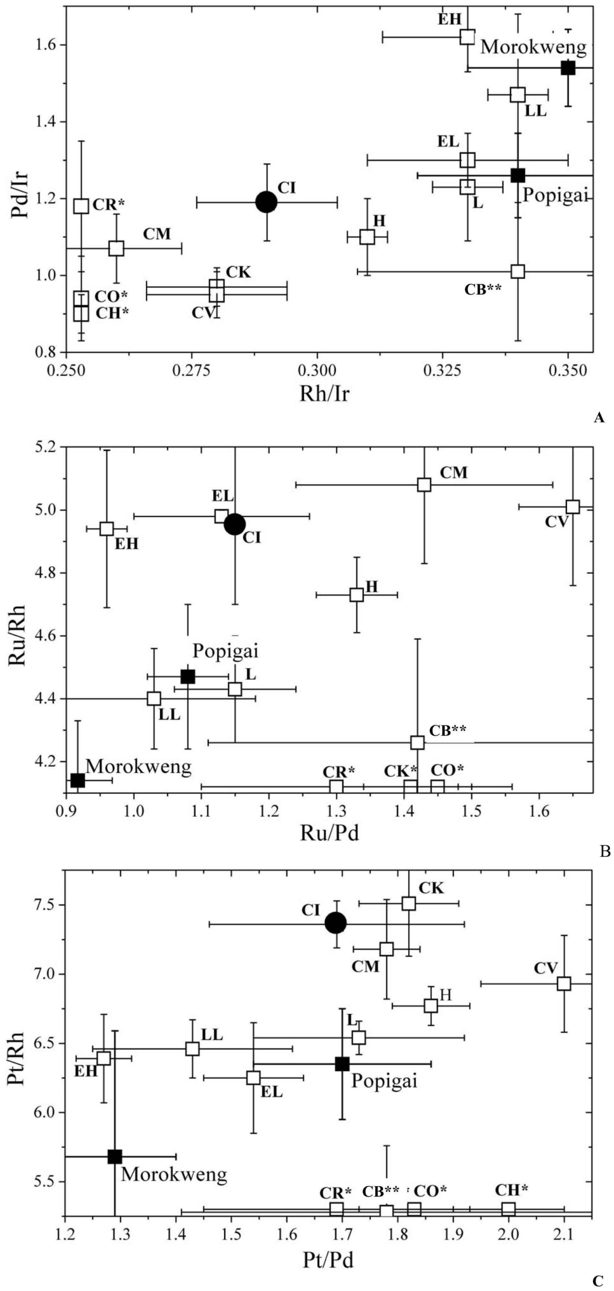

Fig. 7. a) Pd/Ir versus Rh/Ir. Ordinary and enstatite chondrites are clearly separated from carbonaceous chondrites by higher Rh/Ir ratios. b) Ru/Rh versus Ru/Pd. This diagram is helpful to distinguish between the different ordinary and enstatite chondrite groups. c) Pt/Rh versus Pt/Pd. Ordinary and enstatite chondrites have lower Pt/Rh and Pt/Pd ratios than carbonaceous chondrites. *Only one of the two ratios plotted were available. **Metal fraction only.

As previously discussed, elements with a higher indigenous target composition, such as Cr, Ni, or Au, are less appropriate for a precise projectile identification. The values

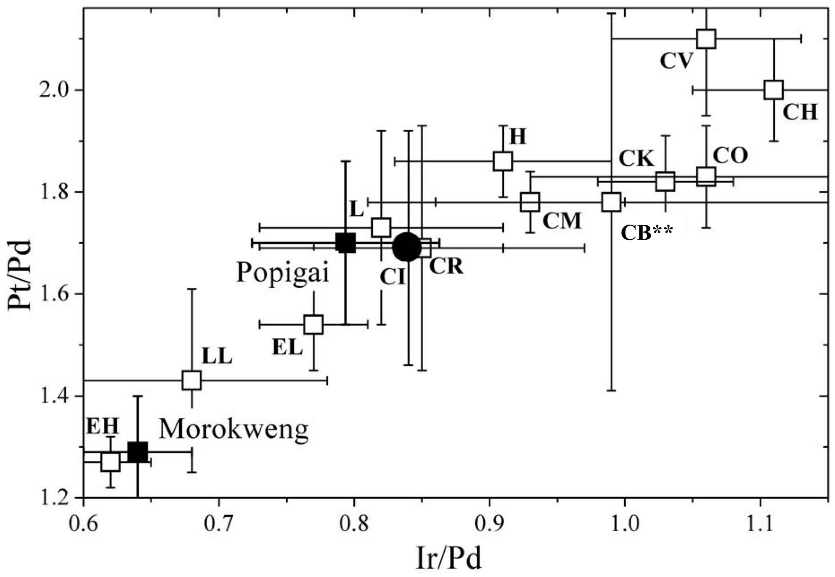

Fig. 8. Diagram showing a less effective discrimination between the chondrite groups, but none the less a remarkable fractionation trend. **Metal fraction only.

for CI/upper continental crust (UCC) ratios are 21 for Cr, 191 for Ni, and 58 for Au, whereas the value for Ir is 9200 (UCC values taken from Wehdepohl 1995). Even though Re is a highly siderophile element, its concentration in chondrites (e.g., CI = 37 ng/g, Wasson and Kallemeyn [1988]) is relatively small compared to continental crust values (0.2 ng/g, Peucker-Ehrenbrink and Jahn [2001]; 0.4 ng/g, Wedepohl [1995]). This fact combined with the highly refractory character of this element, which implies small fractionations among chondrites as shown in Fig. 6 for other refractory elements, makes it less suitable as an element relevant for the identification of projectiles.

There are two main consequences of a low projectile/target ratio for the determination of projectile element ratios: (1) The relative amount of a certain element admixed to the impactite by the projectile becomes quite small compared to the amount present in the target. This fact combined with the small variations that the indigenous elements show within the samples results in a less precise determination of the linear regression parameters. To further illustrate this, an impact of a projectile with CI composition in a target with UCC composition will be discussed as an example. CI concentrations are Ir = 478 ng/g and Cr = 2811 μg/g and for UCC are Ir = 0.05 ng/g and Cr = 126 μg/g (Wehdepohl 1995). Assuming a projectile contamination of 1% (Ir + 4.78 ng/g and Cr + 28.11 μg/g) and a 10% variation in the Ir and Cr concentration in the target rocks (Ir ± 0.005 ng/g and Cr ± 12.6 μg/g), the effect on Ir is negligible, whereas the effect on Cr is significant (almost 50% of the admixed extraterrestrial component). (2) The higher indigenous concentrations can change the slope of the mixing line and therefore affect the values for the projectile element ratios. Using the same example as discussed above, Cr/Ir ratios calculated from the slope would deviate ~5% from the projectile element ratios. Because PGE concentrations are so much lower in target rocks than the concentrations of Cr, Ni, and Au, they are the most adequate elements for projectile identification. Nevertheless, Cr, Ni, and Au can be used after taking the target composition into account.

The most diagnostic plots for the identification of an impactor in an average terrestrial or lunar target were shown in Fig. 7 in combination with previously published projectile element ratios from 2 impact structures. The projectile element ratios used for the Morokweng crater (South Africa) were taken from McDonald et al. (2001) and values for Popigai (Siberia) were published in Tagle and Claeys (2005). These ratios, obtained using the linear regression method described above, allow a reasonably consistent assignment of the projectile type. For Morokweng an LL chondrite appears to be the most likely projectile type as discussed by McDonald et al (2001). PGE in Popigai impactite rocks resemble the composition of L chondrites, an interpretation also supported by Cr-isotopic data suggesting a non-carbonaceous chondrite (Kyte et al. 2004). All element ratios that are not disturbed by the target match the ratios of the determined chondrite groups. The fact that the projectile element ratios of these impact craters (work on the identification of several more impact crater projectiles is currently in progress) overlap with certain chondrite types supports the assumption that chondrite element ratios obtained here are not only representative for the composition of meteorite fragments, but also for the composition of larger bodies. Moreover, the recent discovery of a 25 cm projectile fragment, found almost at the bottom of the impact melt sheet

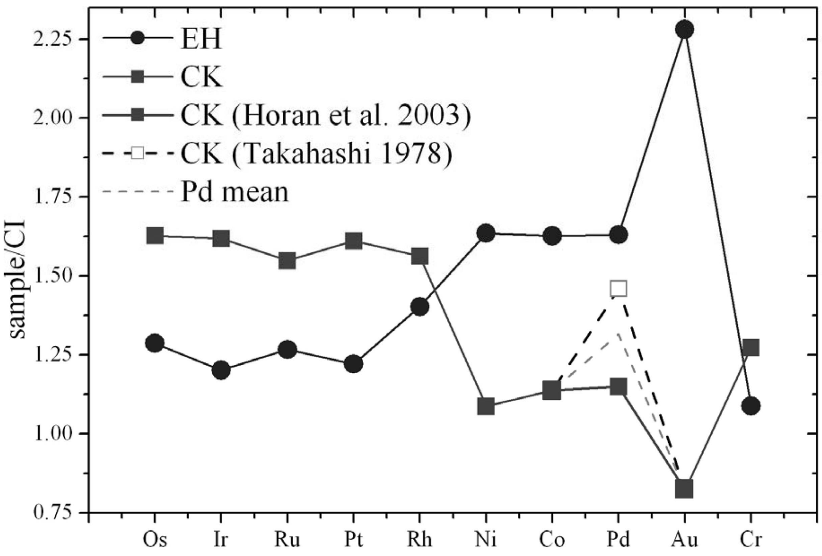

Fig. 9. A new type of complementarity between element patterns of EH and CK chondrites was observed during data analysis. Only 2 Pd analyses of Karoonda are available for CK chondrites (refer to Table A7). The patterns are even more complementary if only the analysis by Horan et al. (2003) is used.

of the Morokweng impact structure (Maier et al. 2006) and its classification as an ordinary chondrite conclusively supports the suggested projectile type (McDonald et al. 2001) and the method presented herein.

DISCUSSION AND CONCLUSIONS

The compiled data clearly reflect the increase of analytical precision over the past years. A significant portion of previous measurements are in good agreement with the newest results. Nevertheless, gaps still exist in the data. For example, Rh, Pd, and Pt analyses are completely missing for R chondrites and the Kakangari grouplet. Rh data are also rare for enstatite and carbonaceous chondrites. However, the results of the compilation presented here show that data are reasonably consistent within each meteorite group, and that chondrite groups that belong to the same clan (e.g., EH and EL belonging to the EC clan) show similar but not identical element patterns. Characteristic features in the element patterns can be linked directly to the presence of certain components, such as the high abundance of highly refractory PGE correlating with the occurrence of refractory inclusions in CV, CO, CK, and CM chondrites. Nonetheless, the results underline the fact that PGE are fractionated in chondritic meteorites and a closer examination of the data reveals surprising findings, such as an apparent complementary relationship in the element patterns of some carbonaceous (e.g., CK and CV) and enstatite chondrites (Fig. 9, see later discussion).

An identification of the projectile component in rocks contaminated by the impact (e.g., impact melt rocks) is, in principle, possible as shown for the cases of Morokweng and Popigai. It can be achieved by calculating the projectile element ratios from the slope of the mixing line formed between target and projectile composition (Tagle and Hecht 2006). A comparison of the projectile element ratios with element ratios obtained from the database confirms that even a specific chondrite type can be assigned. However, it is crucial to select element ratios that permit the best discrimination between the different chondrite types. Ratios that involve one highly refractory PGE (e.g., Os, Ir, Ru, or Pt) and one element with a lower condensation temperature (e.g., Rh, Pd) were found to be most effective in resolving the “fingerprints” of the different chondrite groups.

Ordinary chondrites are the most common material in meteorite collections comprising 82% of all observed falls (Grady 2000). Enstatite chondrites are much less abundant with 1.4%. In contrast to ordinary and enstatite chondrites, which consist only of three and two groups, respectively, carbonaceous chondrites are quite diverse despite their low abundance (~4%). So far, eight distinct groups (Krot et al. 2003) have been identified (CI, CO, CM, CV, CK, CR, CH, CB). CV and CB chondrites are even further divided in subgroups and, moreover, a large number of unclassified or unique meteorites are assigned to the class of carbonaceous chondrites. This variety, the poor amount of data and the fact that the element patterns of the different carbonaceous chondrite groups are very similar to each other makes a precise identification of the exact chondrite group very difficult for this class. However, because most carbonaceous chondrites are enriched in primary condensates, it is relatively straightforward to distinguish them from ordinary and enstatite chondrites by their low Rh/Ir ratios.

As mentioned before, solar nebula processes are clearly recorded in the element patterns of chondrites. A noteworthy observation is the complementary character of CK/CV and EC patterns (as shown for CK versus EH chondrites, Fig. 9), which might suggest a genetic relationship between these chondrite classes. Enstatite chondrites are thought to have formed under reducing conditions in the inner part of the main asteroid belt, whereas carbonaceous chondrites probably originated in the outermost part (e.g., Rubin and Wasson 1995; Wood 2005). A removal of primary condensates from the enstatite chondrite forming region has been suggested by several authors. For example, Hutson and Ruzicka (2000) showed that the mineralogy and chemical characteristics of enstatite chondrites can be explained with a multi-step model, involving the removal of a refractory component, followed by loss of water vapor and partial equilibration of the phases with the remaining vapor at temperatures ranging from ~900–950 K to 700 K. Likewise, Petaev and Wood (1998, 2005) developed models for nebular condensation, evaluating the interplay of processes responsible for the formation of nebular constituents found in primitive chondritic meteorites. They concluded that Ca-, Al-, Ti-rich condensates and olivine were present in the condensation region of enstatite chondrites, but most of these were lost before accretion, resulting in substantial depletion in refractory elements and Mg. The complementary enrichment of these elements in CK/CV chondrites might indicate that the refractory components missing from EC were transported into the CV/CK chondrite forming region before chondrite parent bodies accreted. Ca/Si versus Al/Si (or Mg/Si) diagrams, as published by Wood (2005), show a comparable complementarity for EC and CC as observed in the element patterns presented here and shown in Tagle and Berlin (2007a,b), supporting the chemical imprint of such a mechanism.

With the exception of Cr, which is commonly considered lithophile, the elements included in the presented database are siderophile. For impactor identification, Cr is important to distinguish between chondrites, achondrites and iron meteorites, as it strongly fractionates from the other elements during magmatic processes (e.g., Schmidt et al. 1997 and references therein). However, Cr concentrations are quite similar for all chondrite groups (Figs. 2–5). The CI-normalized values for Cr vary between 1.21 and 1.28 for H, L, LL, CV, CK, CO, CH and R chondrites (the value for CR chondrites (1.35) appears to be just slightly higher). As mentioned in section Carbonaceous Chondrites (CC) with High CAI Abundances (CO, CV, CM, and CK), the relatively low abundances of siderophile elements in CI chondrites probably result from the dilution of all their components by the high concentration of volatiles (H_2O, C, S). Therefore, we consider that the apparent enrichment of Cr compared to CI is most likely an artifact related to dilution. If the element abundances of CI chondrites were recalculated as water-free, taking a value of ~20% H_2O as suggested by Wood (2005 and references therein), the resulting CI-normalized Cr concentrations for chondrites would be ~1. Interestingly, enstatite chondrites would have Cr concentrations significantly below 1, an observation that could be related to the redox conditions under which their components formed in the solar nebula. More data are needed to confirm if the same could be true for Kakangari chondrites.

The presented database provides the most complete compilation of analyses of chondrites, focusing on the determination of characteristic element ratios for projectile identification. Nevertheless, the early evolution of the solar nebula, which led to the formation of the different chondrite types, is recorded in the elements that condense first (especially PGE). Therefore, it will be fundamental to better understand the abundance of these elements in the different components of chondrites which add up to the characteristic bulk patterns. This will assist in comprehending the relationship between the different chondrite types and their formation locations in the solar nebula. The presented database embodies a synopsis of analytical work of almost a generation of scientists, but it also illustrates the need of systematic studies of PGE in chondrites in order to fill the gaps and allow a better comparison of chondrites, moreover, it provides new directions for further investigations.

Acknowledgments—R. T. thanks the Deutsche Akademie der Naturforscher Leopoldina for financial support (BMBF-LPD 9901/8-130). J. B. would like to thank A. J. Brearley and R. H. Jones for their support. We thank Axel Wittmann, Heinz Huber, and Barbara Cohen for helpful comments and suggestions. This manuscript greatly benefited from reviews of A. Hildebrand and T. Meisel.

Editorial Handling—Urs Krähenbühl

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