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Traces of an H chondrite in the impact-melt rocks from the Lappajärvi impact structure, Finland

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Abstract–Here we present the results of a geochemical study of the projectile component in impact-melt rocks from the Lappajärvi impact structure, Finland. Main- and trace-element analyses, including platinum group elements (PGEs), were carried out on twenty impact-melt rock samples from different locations and on two shocked granite fragments. The results clearly illustrate that all the impact melt rocks are contaminated with an extraterrestrial component. An identification of the projectile type was performed by determining the projectile elemental ratios and comparing the corresponding element ratios in chondrites. The projectile elemental ratios suggest an H chondrite as the most likely projectile type for the Lappajärvi impact structure. The PGE composition of the highly diluted projectile component (~0.05 and 0.7 wt% in the impact-melt rocks) is similar to the recent meteorite population of H chondrites reaching Earth. The relative abundance of ordinary chondrites, including H, L, and LL chondrites, as projectiles at terrestrial impact structures is most likely related to the position of their parent bodies relative to the main resonance positions. This relative abundance of ordinary chondrites suggests a strong bias of the impactor population toward inner Main Belt objects.

INTRODUCTION

Impact craters are formed through collision with interplanetary bodies, including asteroids and comets. Most impactors originate from the Main Belt, spread across ~2 AU between the orbits of Mars and Jupiter. Recent estimates suggest that this zone may contain over 670,000 asteroids larger than 1 km (Ivezic et al. 2001). The orbits of these asteroids are affected by a variety of resonances with Jupiter and Saturn, which are mainly responsible for the transport of asteroidal material into the inner solar system (Morbidelli et al. 2002). The number of known meteorite parent bodies (asteroids) is estimated between 100 and 150; the majority of them related to iron meteorites (Burbine et al. 2002). Taking into consideration the large number of asteroids and the relatively young terrestrial ages of most meteorites <1 Myr (Jull 2001), the question arises whether these meteorites really represent the average asteroid population or whether the current meteorite population is overrepresented by discrete large events responsible for the formation of a large number of meteorites. The interpretation is supported by the large number of L-chondrite specimens (35% of the meteorites in the world's collections; Grady 2000), and the cosmic exposure ages of L chondrites suggesting a collision ~40 Ma ago (Marti and Graf 1992; Morbidelli and Gladman 1998). The characterization of the projectiles responsible for the formation of impact craters on the Earth and Moon makes it possible to study the ancient flux of material, providing further insight into the composition of the asteroid belt objects. Analytical improvements over the last ten years have allowed the identification of traces of projectile remaining in impact craters and the ability to tie them to a specific type of meteorite on an unprecedented level of detail (McDonald et al. 2001; Tagle and Claeys 2005). The projectile identification relies on the measurement of the concentrations of certain elements in the crater lithologies (e.g., impact melt rocks). These elements are present in elevated concentrations in meteorites compared to the impacted target rocks. The platinum group elements ([PGE] Os, Ir, Ru, Pt, Rh, Pd), together with Ni, Co, Cr, and Au are most useful for projectile identification. The projectile type can, in principle, be identified using the projectile elemental ratios according to the method described in detail by Tagle and Hecht (2006), and by comparing the results to the characteristic element ratios of

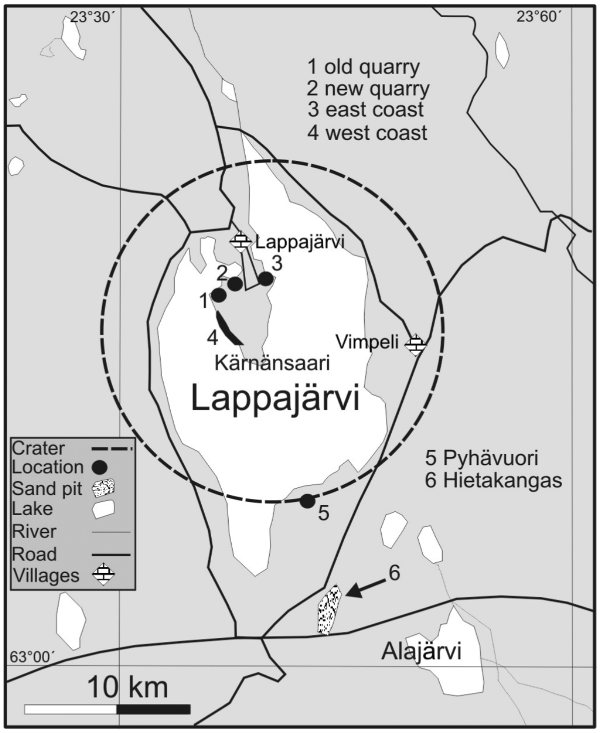

Fig. 1. Map of the Lappajärvi Lake showing the crater size as estimated by Abels (2003) and the sample localities. Numbers 1 through 6 and the respective names represent the sample locations. The numbers for the sample locations match those used in the tables.

the different meteorites in a database (Tagle 2004; Tagle and Berlin, Forthcoming). This approach has recently shown to be reliable, as the recent discovery of a projectile fragment in the Morokweng impact melt (Maier et al. 2006) confirmed the ordinary chondrite identification previously proposed by McDonald et al. (2001), which was based on the analysis of PGE ratios in the impact melt rocks of this crater. The goal of this study is to identify the projectile responsible for the Lappajärvi cratering event using PGE elemental ratios.

Geological Setting and Target Rock Composition

The Lappajärvi impact structure (63°12′N, 23°42′E) is located in the eastern part of the Palaeoproterozoic (Svecofennian) Bothnian schist belt of Finland, and has an age of 73.3 ± 5.3 Ma (ion probe U-Pb on zircons; 2 sigma) (Mänttäri and Koivisto 2001). The average original diameter of Lappajärvi was estimated by Abels (2003) to be about 22 km. The target rocks of the Lappajärvi impact structure are about 1.9 Ga old and consisted mainly of meta-graywacke, mica-schist, and mica-gneiss of amphibolite facies, along with pegmatitic granite, granodiorite, tonalite, and skarn (Vaarma and Pipping 1997 and references therein). Although minor mafic and intermediate metavolcanic rocks are present immediately to the southeast of the impact structure (Vaarma and Pipping 1997), no fragments of mafic target rocks were observed in impact melts (the so-called "kärnäite") or in suevites (Lehtinen 1976, 1991). Target lithologies also included younger Mesoproterozoic (~1.2 Ga) sedimentary rocks, preserved in a graben on the eastern side of the crater (Uutela 1990), and possibly also forming fragments in impactites (Lehtinen 1991). Cambrian to Ordovician siltstones were apparently present at the time of the impact event, but have so far only been discovered as fracture fillings in the impactites (Uutela 1993, cited by Vaarma and Pipping 1997). The total thickness of the sedimentary sequence covering the crystalline basement was calculated to be less than 200 m (Abels 2003).

Petrology of the Melt Rocks

The impact melt rocks (kärnäite) are divided into two types based on the abundance and crystal shape of the pyroxene in the matrix, clast content, level of alteration, and homogeneity (Lehtinen 1970, 1976; Reimold 1982). However, the two types grade into each other and consequently this division is regarded as somewhat arbitrary. This is emphasized by the fact that the kärnäite melt sheet is geochemically extremely homogenous with respect to both major and trace elements, and that this extends both laterally (Reimold 1982) and vertically (Lehtinen 1990, 1991; Pipping and Lehtinen 1992). This is also valid for Rb/Sr- and Sm/Nd-isotope signatures (Hölker and Deutsch 1996). The composition of this melt rock can be produced by mixing mica schist (79%) with granite-pegmatite (11%) and amphibolite (10%) (Reimold 1982; see also Eskola 1921). Small impact diamonds are also reported to occur in the impact-melt rock (Langenhorst et al. 1999). Another characteristic feature of the Lappajärvi impact-melt rocks is the ubiquitous presence of small Fe-Ni and pyrrhotite particles. Their origin, whether as contamination by the meteoritic projectile (Fregerslev and Carstens 1976) or as target rock components (Badjukov et al. 1999; Badjukov and Raitala 2000) is still under debate. Studies of siderophile elements of the Lappajärvi impact-melt rocks by Göbel et al. (1980) pointed toward a chondritic source for the projectile component. More recently, Cr-isotope studies of the Lappajärvi impact melt suggested that the projectile composition was compatible with an ordinary chondrite (Shukolyukov and Lugmair 2000; Koeberl et al. 2007).

SAMPLES AND ANALYTICAL METHODS

Sample Origin and Description

Twenty samples of Lappajärvi impact-melt rocks collected from different locations and two shocked granite fragments found in the impact-melt rocks from the new quarry (Fig. 1) were studied for major- and trace-element composition, including PGE. The impact-melt rock samples were collected from the old and new quarries (11 samples) and outcrops on the northeastern shore of Kärnänsaari island (5 samples), as well as from glaciofluvial deposits south to the Lappajärvi Lake (4 samples). Sample localities are given in Fig. 1.

Sample Preparation and Analytical Methods

The 22 samples were first cut into slices 5–8 mm thick using a diamond saw. The slices were broken into smaller fragments by hand using a corundum mortar after removing clasts larger than 2 mm, and then finely powdered in a corundum ball mill. This procedure adds no detectable PGE contamination to the samples (Tagle and Claeys 2005). The total amount of powder obtained for each sample was between 100 g and 200 g. These powders were used for all subsequent analytical measurements. The samples were first analyzed for major- and trace-element concentrations. The measurements were carried out by X-ray fluorescence spectroscopy (XRF) on glass beads with a SIEMENS SRS 3000 instrument at the Museum of Natural History in Berlin. The glass beads were prepared using 0.6 g of dried sample powder (105 °C for 4 h) and 3.6 g of Di-lithiumtetraborate (BRA A10 Specflux). For measurement and data analysis, a modified GEOQUANT program (SIEMENS) based on international rock standards and internal reference samples was used. For more details, see Schmitt et al. (2004).

Additionally, the elements Ni, Co, and Cr were measured by ICP-MS (Fisions VG-Plasma Quad XS) at the GeoForschungsZentrum (GFZ) in Potsdam after acid sample digestion, due to the lower detection limit of this method compared to XRF analysis. The acid sample digestion was performed by using 250 mg sample powder dried at 105 °C. Sample powder was placed in a Savillex Teflon bomb together with 4 ml concentrated HF and 4 ml aqua regia. The Savillex Teflon bomb was closed and placed on a hot plate over night at 160 °C. Then, 1 ml of concentrated $HClO_4$ was added, and the solution was heated to dryness at 180–190 °C. Two ml of bidistilled H_2O and 1 ml HNO_3 were added and again heated almost to dryness. The Savillex Teflon bomb was again left closed overnight on the hot plate at 100 °C with 1 ml of concentrated HNO_3 and 5 ml bidistilled H_2O. If needed, the procedure was repeated again until the obtained solution was clear. The clear solutions were diluted with bidistilled H_2O up to 50 ml. These solutions were measured on two different days by ICP-MS using external calibration solutions prepared from pure element standards. The accuracy of the method was tested by comparison with standard reference material digested parallel to each sample set. The average concentration values for 16 analyses of the reference sample TB (clay shale) (Cr = 97 ± 12 µg/g; Ni = 47 ± 6 µg/g; Co = 14 ± 1 µg/g) are in good agreement with the values recommended by Govindaraju (1994) (Cr = 82 µg/g; Ni = 40 µg/g; Co = 14 µg/g). The PGE concentrations were determined after nickel-sulfide fire assay preconcentration combined with ICP-MS according to the procedure described in Plessen and Erzinger (1998). The determination limits for the PGE and Au are 0.06 ng/g Ru, 0.01 ng/g Rh, 0.14 ng/g Pd, 0.06 ng/g Ir, 0.1 ng/g Pt, and 0.13 ng/g Au. The solution obtained after preconcentration of PGE from the sample was measured twice by ICP-MS on two different days to reduce the possible effects of machine instability. The concentrations used in this paper were obtained by averaging the two measurements. The uncertainties of the analytical procedure were estimated using the range of all independently analyzed aliquots from each sample according to the method of Doerffel (1990). The standard deviation of a number (n) of related samples of similar composition is determined as the square root of the square sum of the range of duplicated analyses divided by 2n.

Projectile Identification

Projectile component identification is carried out following the procedure used by Tagle and Claeys (2005) to identify the Popigai projectile component and, more recently, described in detail by Tagle and Hecht (2006). The PGE enrichment reflects the incorporation of small but variable amounts of projectile component into the melt pool formed by melting the various target rocks. The projectile elemental ratios for the different PGE combination were obtained from the slope of the mixing lines formed between the target and the projectile composition. All parameters of the linear regressions such as slopes, y-axis interceptions, and correlation coefficients (r) used in this work were obtained using the Origin 7.0 (Microcal Origin, Version 7.0) software program. The algorithms used by this program for the calculation of the linear regression only include uncertainties in the y-axis. However, this has no influence on the slope. Because all samples have the same uncertainty (one for each element) due to the method used for the estimation of the standard deviation, all points are weighted equally during linear fitting calculation.

RESULTS

Main and Trace Elements

Results obtained from XRF analyses for major and trace elements (Table 1) confirm the homogeneity of the impact melt, as previously reported by Reimold (1982). Impact-melt samples Lap 28 and Lap 24 diverge from the average composition of the impact melt due to the presence of a small carbonate component, as indicated by higher CaO concentrations combined with higher LOI (Table 1). Besides this, the impact melt rocks from different regions of the crater are remarkably homogeneous in major- and trace-element compositions. This homogeneity argues for a strong mixing

Table 1. Results from the XRF data of major and trace elements of two granites from the target and the Lappajärvi impact melt rocks, including ICP-MS determination of Ni, Co, and Cr concentrations. The samples location numbers 1 through 6 represent the locations shown in Fig. 1.

	Target granite		Impact-melt rocks										
	Lap 3	Lap 2	Lap Q1	TÖ-L1C	TSÖ-L1B	TÖ-K1,4	TÖ-K1,2	TÖ-K2,6	TÖ-K2,2	TÖ-K2,5	Lap 1	Lap Q2-1	Lap Q2-2
Sample loc. no.	2	2	1	1	1	1	1	2	2	2	2	2	2
XRF													
wt%													
SiO_2	73.0	73.4	66.5	65.9	66.0	66.5	67.1	65.3	66.0	65.7	68.1	66.2	66.0
TiO_2	0.31	0.06	0.54	0.49	0.50	0.50	0.49	0.52	0.50	0.52	0.45	0.53	0.51
Al_2O_3	13.6	13.0	15.5	15.7	15.0	15.3	15.0	15.5	15.4	15.2	14.7	15.9	15.4
$Fe_2O_{3(total)}$	2.2	2.9	5.1	5.5	5.7	5.3	5.2	5.8	5.5	5.8	4.1	5.0	5.3
MnO	0.02	0.01	0.05	0.04	0.05	0.04	0.04	0.04	0.05	0.05	0.04	0.05	0.06
MgO	0.8	1.0	2.1	1.9	1.9	2.0	1.9	2.3	2.0	2.0	1.6	2.0	1.9
CaO	1.8	1.6	2.6	2.7	2.6	2.7	2.6	2.7	2.6	2.7	2.0	2.7	2.6
Na_2O	2.6	2.8	2.8	2.9	2.9	2.9	2.8	2.8	2.8	2.8	2.4	2.9	2.8
K_2O	3.3	3.7	3.6	3.9	4.0	3.9	3.8	3.7	3.8	3.9	3.8	3.7	3.8
P_2O_5	0.03	0.03	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07
SO_3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
LOI	1.9	1.3	0.7	0.6	0.7	0.5	0.6	0.6	0.8	0.8	2.3	0.7	1.2
Total	99.4	99.7	99.5	99.7	99.5	99.7	99.6	99.3	99.5	99.4	99.4	99.7	99.7
µg/g													
Ba	1704	852	933	1118	1114	1106	1030	972	1080	1115	1442	989	1074
Ce	69	<30	64	73	61	86	66	73	77	46	65	62	63
Cu	<30	<30	<30	35	38	41	34	<30	40	36	<30	<30	<30
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Nb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Pb	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
Rb	66	70	111	105	104	99	98	102	102	107	93	114	102
Sr	286	170	239	228	226	228	223	228	221	230	245	233	238
Th	12	11	17	12	<10	14	10	<10	13	<10	12	13	15
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
V	43	16	129	107	115	120	110	120	111	130	89	114	116
Y	<10	<10	21	20	21	23	18	21	23	22	20	24	20
Zn	78	51	86	74	79	79	74	68	73	85	96	82	79
Zr	332	<15	154	159	207	200	178	155	162	206	290	160	152
ICP-MS													
µg/g													
Cr	23[a]	11	112	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	66	113	117
Co	7[a]	2	19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	16	21	21
Ni	85[a]	11	152	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	81	179	206

[a]Granite possibly contaminated by projectile material of the surrounding melt.

Table 1. *Continued.* Results from the XRF data of major and trace element of two granites from the target and the Lappajärvi impact melt rocks including ICP-MS determination of Ni, Co, and Cr concentrations. The samples loc. numbers 1 to 6 represent the locations shown in Fig. 1.

	Target granite			Impact melt rocks									
	Lap 34	Lap 34[b]	Lap 36	Lap 31	Lap 38	Lap 10	Lap 40	Lap 26	Lap 28[c]	Lap 24[c]	Avg. n = 19	σ	s%
Sample loc. no.	3	3	3	3	3	4	5	6	6	6			
XRF													
wt%													
SiO_2	66.5	65.1	68.0	65.4	62.5	66.3	67.7	66.1	55.7	63.5	66.2	1.2	2
TiO_2	0.50	0.52	0.48	0.52	0.56	0.51	0.46	0.51	0.46	0.52	0.51	0.03	5
Al_2O_3	15.4	15.1	15.3	15.7	16.5	15.8	15.4	15.4	13.0	14.1	15.4	0.4	3
$Fe_2O_{3\,(total)}$	5.1	5.8	3.9	5.4	6.6	4.7	4.3	5.1	5.4	4.5	5.2	0.6	12
MnO	0.05	0.17	0.02	0.05	0.10	0.02	0.04	0.03	0.16	0.08	0.05	0.03	64
MgO	1.4	1.3	0.7	2.4	2.5	0.9	1.6	1.4	1.5	1.2	1.8	0.5	27
CaO	2.7	2.9	2.4	2.6	2.4	2.6	2.4	2.8	10.0	5.3	2.6	0.2	8
Na_2O	2.8	2.8	2.8	2.8	2.5	2.8	2.9	2.9	1.5	1.7	2.8	0.1	5
K_2O	3.9	3.8	4.0	3.3	3.1	3.8	3.9	3.9	3.6	4.0	3.8	0.2	6
P_2O_5	0.08	0.08	0.08	0.08	0.14	0.08	0.08	0.08	0.12	0.09	0.1	0.0	21
SO_3	<0.1	0.1	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.1	40
LOI	1.3	1.9	1.7	1.3	2.5	2.0	0.8	1.5	8.9	4.8	1.2	0.6	53
Total	99.7	99.5	99.6	99.7	99.3	99.6	99.6	99.8	100.2	99.8	99.6	0.1	0
µg/g													
Ba	1165	1151	1243	1161	1263	2235	1093	1071	880	955	1161	271	23
Ce	43	87	40	84	80	63	93	79	48	70	68	15	22
Cu	<30	<30	35	<30	<30	35	<30	<30	33	37	37	3	7
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10		
Nb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10		
Pb	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<10		
Rb	105	100	103	92	73	100	104	104	93	109	101	8	8
Sr	236	236	224	228	223	238	221	239	189	196	231	7	3
Th	13	15	15	10	18	16	14	15	<10	<10	14	2	16
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10		
V	117	113	118	121	127	119	103	109	94	94	115	9	8
Y	18	17	22	20	13	21	20	21	27	25	20	2	12
Zn	79	81	80	90	118	114	77	79	108	85	84	12	15
Zr	172	169	177	176	178	156	153	150	108	166	174	32	18
ICP-MS													
µg/g													
Cr	146	125	115	144	154	124	121	108	79	83	121	23	19
Co	26	22	18	21	12	31	25	20	17	14	21	5	24
Ni	253	240	169	178	44	191	210	179	155	99	173	60	34

[b]Different powder aliquot.

[c]Sample excluded from the average calculation because of carbonate content.

LOI = loss on ignition; total Fe as Fe_2O_3; n.a. = not analyzed; σ = 1 standard deviation.

of the different target rock components during the impact event. One of the granites of Lap 3 has relatively high concentrations of Cr (23 μg/g) and Ni (85 μg/g) compared to Lap 2. Values for Lap 2 are closer to those published by Reimold (1982) for the granite (9 μg/g for Ni and 7 μg/g for Cr). The higher concentrations in Lap 3 sample might result from the projectile component of the surrounding impact-melt rock in which the samples were found, and are not representative for the granite.

Impactor Relevant Elements (PGE, Ni, Co, and Cr)

Results obtained by inductively coupled plasma mass spectrometry (ICP-MS) analyses for the elements Ni, Co, and Cr show that the values are higher in the impact-melt rocks than in the two granite samples (Table 1) and the additional target rocks previously studied by Reimold (1982). Terrestrial rocks usually display higher Cr than Ni concentrations, while in the Lappajärvi impact-melt rocks, Ni is systematically higher than Cr. This enrichment can be interpreted as the result of the admixture of a component with significantly more Ni than Cr, as it would be the case for chondritic material, which contains usually over three times more Ni than Cr (Wasson and Kallemeyn 1980). The PGE concentrations obtained from the 37 analyses of 20 impact melt-rock samples and the two target granites are presented in Table 2. The variations between the results from multiple analyses of single powder aliquots are usually small. These differences in the concentrations measured should not be interpreted as analytical error. Rather, they represent the real variation of the PGE content within the sample fractions analyzed, mainly as a result of the so-called "nugget effect." The PGE concentrations of multiple analyses of the same powder aliquot are shown on Table 2 with the same sample names but different sample numbers. The analysis of PGE reveals that all impact-melt rocks have higher PGE concentrations than the two target-rock granite samples analyzed and the other target rocks analyzed by Reimold (1982). The iridium concentrations reported by Reimold for mica schist, amphibolite, and granodiorite are <0.5 ng/g. Furthermore, the Cr, Co, and Ni concentrations measured by Reimold (1982) for the amphibolites (60 μg/g, 37 μg/g, and 52 μg/g, respectively) are below the average composition of the Lappajärvi impact-melt rock (Table 1). The measured values for the impact-melt rocks are significantly above the concentrations expected for average continental crust (Table 2). The PGE enrichments indicate the presence of a meteoritic component in the Lappajärvi impact melt rocks. As shown in Fig. 2, the Cr/Ir ratios support this interpretation, as the range of the Cr-Ir concentrations of the Lappajärvi impact melt differs from the values found in terrestrial rocks. The values obtained from the different samples plot in a field representing the mixing of average continental crust with chondrites.

This is further supported by the relatively flat CI-normalized PGE pattern (Fig. 3), which confirms the previous assumption of a chondritic projectile for the Lappajärvi impact structure (Göbel et al. 1980; Shukolyukov and Lugmair 2000; Koeberl et al. 2007).

A closer look at the element patterns of each sample reveals that five of the 34 impact-melt rock aliquots analyzed (212, 211, 315, 327, and 329) differ from the average pattern. Samples with this peculiar element pattern are plotted and compared to the Lappajärvi average pattern in Fig. 4. Aliquots 212 and 329 from sample Lap Q2-1 show Rh and Au enrichment compared to the average composition (Fig. 4). These Rh values were excluded from the calculations to derive the elemental ratios used to characterize the type of projectile. The PGE patterns found for the aliquots 315 and 327 of sample Lap 36 and one of sample Q2-2 (211) indicate a relative Pd enrichment (Fig. 4). This enrichment was not reproduced in a second analysis of aliquot 330 of sample Q2-2; hence, these Pd values were also excluded from further calculations. The unusual patterns are not a property of samples with high PGE concentrations, as could be inferred from Fig. 4, where the average element pattern of the Lappajärvi impact melt rocks is lower than the samples with the aberrant pattern. For example, the samples Lap 10, Lap 40, and Lap 34, which also have high PGE concentrations (Table 2), do not show the relative enrichment in Rh or Pd. Small-scale mineralizations involving some PGE-rich phases could be responsible for these deviations from the mean.

Projectile Identification

The projectile elemental ratios are determined by calculating the slope of the concentration of elements relevant for impactor identification, as previously done by McDonald et al. (2001) and Tagle and Claeys (2005). The advantages of this procedure are discussed in detail by Tagle and Hecht (2006). Figures 5a–c illustrate the results for Ni, Co, and Cr. The Cr/Co projectile elemental ratio of 5.7 is well within the range of the ratios found in chondrites. However, ratios including Ni (e.g., Ni/Co and Ni/Cr) are slightly below the range in chondrites. Because of the higher concentration of these elements (Ni, Co, and Cr) in the target rock compared to PGE, and because of the small variations in the ratios of these elements in different chondrites, the projectile's element ratios obtained from Ni, Co, and Cr correlations are less precise than those calculated from PGE. Nonetheless, these elements are relevant for the projectile identification, as they allow recognizing (as in this case) or even ruling out the presence of traces of a chondritic projectile. A refined projectile identification can only be achieved by using the PGE.

Figures 6a–f show some PGE combinations and the respective regression analyses. The correlations are

Table 2. PGE and Au concentrations of two granites from the target and the Lappajärvi impact-melt rock samples analyzed by NiS fire assay and ICP-MS.

Sample number	Sample name	Sample location no.[a]	Ir (ng/g)	Ru (ng/g)	Pt (ng/g)	Rh (ng/g)	Pd (ng/g)	Au (ng/g)	Sample weight (g)
	l.d.[b]		0.04	0.06	0.04	0.01	0.13	0.09	
	Uncertainty		0.04	0.09	0.04	0.04	0.07	0.04	
	Continental crust		0.02	0.21	0.51	0.06	0.52	2.50	
	Target rocks								
320	Lap 3	2	<0.04	<0.06	<0.4	0.02	0.27	0.18	70
323	Lap 3	2	<0.04	<0.06	0.16	0.04	0.45	0.24	70
318	Lap 2	2	0.07	0.11	<0.4	0.07	0.46	0.35	70
312	Lap 2	2	0.20	0.16	0.49	0.13	0.53	0.23	70
	Impact melt								
331	Lap Q1	1	1.87	2.90	4.41	0.79	2.74	0.13	70
332	Lap Q1	1	0.69	1.13	1.53	0.30	0.47	<0.13	70
210	Lap Q1	1	2.32	4.02	5.95	1.03	3.96	0.47	51
437	TÖ-L1C	1	2.90	4.19	6.99	1.14	4.35	0.32	80
436	TSÖ-L1B	1	2.41	3.32	5.69	0.93	3.39	0.28	80
442	TÖ-K1,4	1	2.05	2.92	5.26	0.85	3.20	0.25	80
441	TÖ-K1,2	1	2.32	3.10	6.59	1.02	4.05	0.35	81
311	Lap 1	2	0.41	0.71	1.20	0.22	1.13	0.12	70
317	Lap 1	2	0.42	0.82	1.18	0.24	1.30	0.25	70
329	Lap Q2-1	2	1.88	3.12	4.60	0.89[c]	3.10	0.56	70
212	Lap Q2-1	2	3.59	6.25	9.10	1.71[c]	6.19	1.24	40
330	Lap Q2-2	2	2.69	4.59	6.10	0.99	3.61	0.27	70
211	Lap Q2-2	2	4.15	7.35	10.46	1.62	6.78[c]	0.72	55
440	TÖ-K2,6	2	1.99	2.60	5.25	0.77	2.75	0.21	73
439	TÖ-K2,2	2	2.07	2.76	5.21	0.87	2.79	0.14	65
438	TÖ-K2,5	2	2.65	3.88	6.28	1.07	4.01	0.34	80
314	Lap 34	3	2.24	3.50	5.17	0.82	2.94	0.17	70
326	Lap 34	3	5.36	7.78	12.46	1.78	6.34	0.75	70
369	Lap 34[d]	3	3.34	5.08	7.30	1.09	4.28	0.28	70
315	Lap 36	3	4.09	6.58	9.29	1.39	6.18[c]	0.42	70
327	Lap 36	3	3.60	5.77	8.33	1.23	5.70[c]	0.37	70
389	Lap 31	3	3.42	5.19	7.62	1.10	4.21	0.49	50
414	Lap 31	3	3.61	5.23	7.53	1.19	4.24	0.31	44
370	Lap 38	3	3.28	4.92	7.23	1.09	4.47	0.27	50
415	Lap 38	3	2.27	2.93	3.72	0.61	2.12	0.11	39
322	Lap 10	4	5.04	6.99	10.68	1.57	5.64	0.47	70
325	Lap 10	4	5.33	7.60	12.05	1.74	6.18	0.51	70
390	Lap 40	5	3.75	4.93	7.04	0.98	3.71	0.24	50
413	Lap 40	5	2.48	4.00	5.65	0.93	3.62	0.32	52
313	Lap 28	6	0.83	1.32	2.46	0.34	1.77	0.22	70
319	Lap 28	6	0.76	1.21	2.04	0.30	1.50	0.29	70
316	Lap 26	6	2.67	4.58	6.55	1.06	3.99	0.21	70
328	Lap 26	6	2.92	5.03	7.06	1.11	4.26	0.31	70
321	Lap 24	6	0.44	0.70	1.28	0.20	0.91	<0.09	70
324	Lap 24	6	0.38	0.60	1.27	0.19	1.11	<0.09	70
Avg.			2.58	3.93	6.01	0.93	3.36	0.36	

[a]Sample locations: 1 = old quarry; 2 = new quarry; 3 = Kärnänsaari island east coast; 4 = Kärnänsaari island west coast; 5 = Pyhävuori; 6 = Hietakangas (cf. Fig. 1).

[b]l.d. = detection limit; (blank + 3 sigma).

[c]Excluded from avg. calculation and projectile determination continental crust values from Peucker-Ehrenbrink and Jahn (2001); Rh values from Wedepohl (1995).

[d]Different powder aliquot.

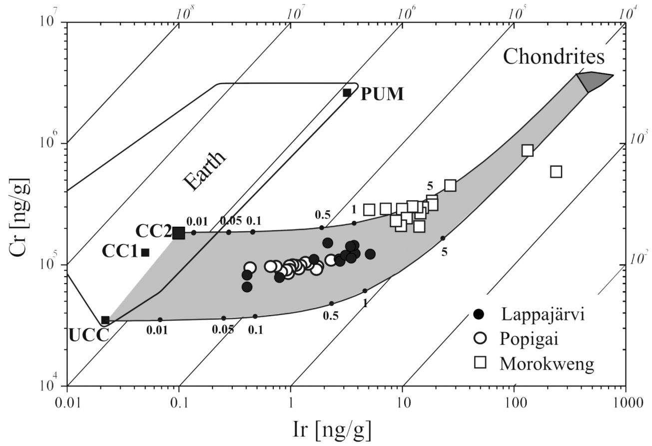

Fig. 2. Double logarithmic plot of the concentrations of Cr versus Ir of various terrestrial lithologies compared to the concentrations in the Lappajärvi impact-melt rocks. Values obtained for the Popigai crater (Tagle and Claeys 2005) and Morokweng (McDonald et al. 2001) are presented for comparison. The gray field indicates the most likely mixing zones between chondritic projectiles and common terrestrial targets. UCC = upper continental crust; CC = continental crust; CC1 = Wedepohl (1995); CC2 = Taylor and McLennan (1985); PUM = primitive upper mantle (McDonough and Sun 1995). A detailed description of the composition data for terrestrial rocks used for this plot is given in a compilation of literature data by Tagle and Hecht (2006).

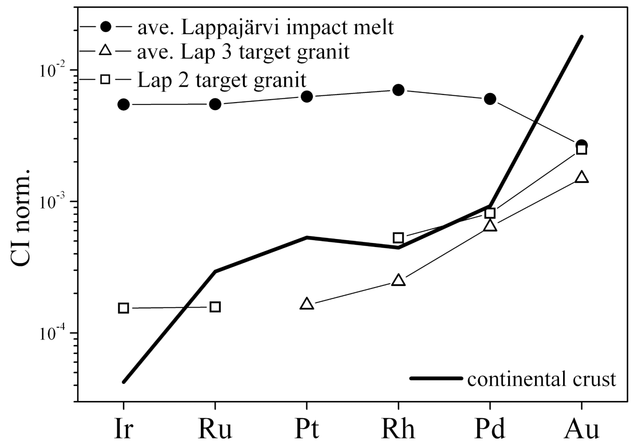

Fig. 3. CI-normalized mean composition of PGE and Au concentrations in the Lappajärvi impact melt rocks and the two granite samples from the target compared to the average composition of the continental crust (after Wedepohl 1995; Rh values from Peucker-Ehrenbrink and Jahn 2001). CI values from Palme and Jones (2003). The impact-melt rocks are enriched in PGE compared to the continental crust and show a flat PGE pattern.

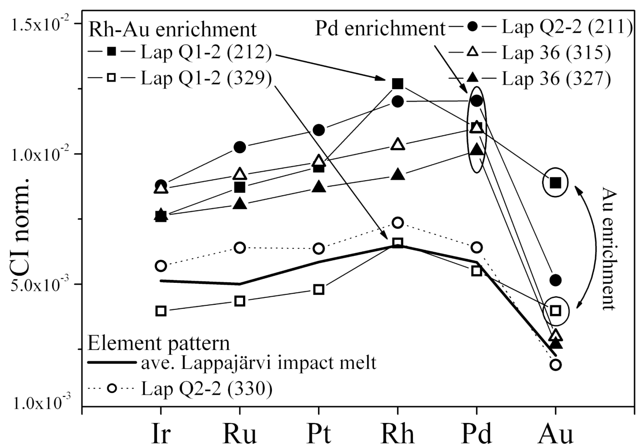

Fig. 4. CI-normalized PGE and Au concentrations in the five unusual sample aliquots (212, 211, 315, 327, 329) that show Rh-Au and Pd enrichment compared to aliquot 330 (dotted line) of sample Lap Q2-2 and the average composition of the Lappajärvi impact-melt rocks representing the pattern of the PGE in the Lappajärvi impact melt. CI values from Palme and Jones (2003).

remarkable, as can be seen from the correlation coefficients (r). Additionally, the variation in the proportion of extraterrestrial contamination in the different samples (e.g., Ir concentrations vary between 0.38 and 5.36 ng/g) ensures a higher confidence in the calculated slope. The results of the linear regression are summarized on Table 3.

To refine identification, the chondritic projectile component suggested from the Ni, Cr, and Co correlations (Fig. 5) and also the projectile elemental ratio of the PGE obtained from the linear regressions (Fig. 6) were compared with the element ratios in chondrites (Fig. 7; Tagle 2004; Tagle and Berlin, Forthcoming). Figure 7 shows different combinations of these element ratios. The highest resolution for the identification of chondritic projectiles is usually obtained by combining elements with large differences in condensation temperatures within a gas of solar nebula composition (e.g., highly refractory Os, Ir, and Ru combined with less refractory Pt, Rh, and Pd; see Table 4). Ratios including these elements show the largest fractionation among chondrites, as condensation is a main process influencing the formation of early solar material (Horan et al. 2003; Lodders et al. 2003; Palme and Jones 2003). The projectile elemental ratios of the Lappajärvi impact-melt rocks show a consistent overlap with the element ratios of H chondrites (Figs. 7a–c). The plots of Figs. 7d–f appear to illustrate a slight shift in the position of Lappajärvi projectile elemental ratios compared to the ratios obtained for H chondrites. This deviation is also observed for the projectile elemental ratios of the Popigai and Morokweng impact craters, formed by the impact of an L and LL chondrite, respectively (Tagle and Claeys 2005; McDonald et al. 2001). The deviations have a similar magnitude and direction for the ratios obtained from these three impact structures compared to their respective projectile type suggested from Figs. 7a–c. The geochemical identification of the Morokweng projectile is in fact supported by the recognition of an LL chondrite meteorite fragment in the impact melt by Maier et al. (2006). However, based on small differences in the ferrosilite content of orthopyroxene versus the fayalite content of olivine in the fragment compared to the LL chondrites, these authors suggested that the Morokweng

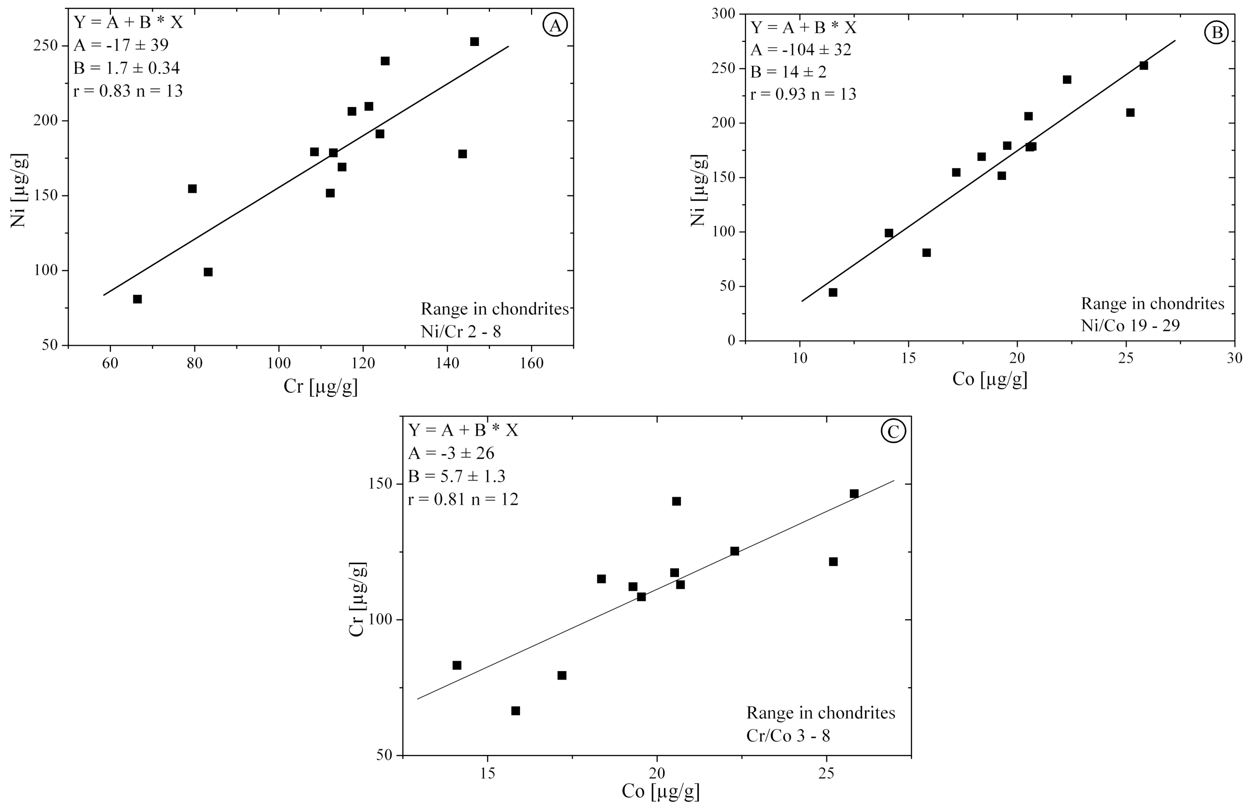

Fig. 5. Linear correlation of Ni, Co, and Cr concentrations in the impact melt of the Lappajärvi impact structure. The projectile elemental ratios calculated from the slope of the mixing line (b) are compared to the range of the ratios of the respective elements in chondrites (Tagle and Berlin, Forthcoming).

meteorite sampled a different portion of the LL chondrite parent body compared with the known population of small LL-chondrite meteorites. This could be a possible explanation for the deviations. Still, the composition of the Lappajärvi projectile is consistent with an H chondrite because the small deviations could be due either to a mobilization of PGE by hydrothermal processes or to small compositional differences in the chondrite population.

DISCUSSION

Lappajärvi and H Chondrites

The results obtained from the Lappajärvi impact-melt rocks are in agreement with previous studies by Reimold (1980), Göbel et al. (1980), Shukolyukov and Lugmair (2000), and Koeberl et al. (2007). They confirm the presence of a chondritic projectile component in the Lappajärvi impact melt rocks. The PGE ratios in the projectile that formed the Lappajärvi impact melt are similar to those obtained for the current population of H ordinary chondrites reaching Earth. This identification agrees well with the type of projectile suggested by Shukolyukov and Lugmair (2000) and Koeberl et al. (2007) based on ^{53}Cr excesses detected in the Lappajärvi impact-melt rocks. It is noteworthy that a positive ε ^{53}Cr rules out a carbonaceous chondritic projectile because this type of chondrite has negative ε values (Shukolyukov and Lugmair 1998; Trinquier et al. 2006). The Lappajärvi projectile originates from an asteroid parent body with a composition similar to that of actual H-chondrite meteorites and a diameter of approximately 1 km. This projectile size was computed using the freeware provided by http://www.lpl.arizona.edu/tekton/crater_p.html (Melosh and Beyer 1999) using the most common 45° impact angle and the average speed for asteroidal collisions with the Earth of 17 km/s, and a original crater size of 22 km (Abels 2003). Assuming an H-chondrite projectile, the proportion of extraterrestrial material within the analyzed impact-melt rock samples varies between 0.05 and 0.7% (considering an average Ir content in H chondrites of 760 ng/g (Wasson and Kallemeyn 1980). If the analyzed samples are considered representative of the whole crater in terms of projectile proportion, the projectile contribution to the impactite lithologies can be estimated. Using ~0.34 wt% as the average projectile proportion, a total melt volume of ~11 km^3 (Abels 2003), and a projectile diameter of 1 km, the total proportion of the original projectile material retained in the crater is ~7%, while the main mass is ejected out of the crater as vapor, solid, or melt during the impact event, as suggested by Pierazzo and Melosh (2000).

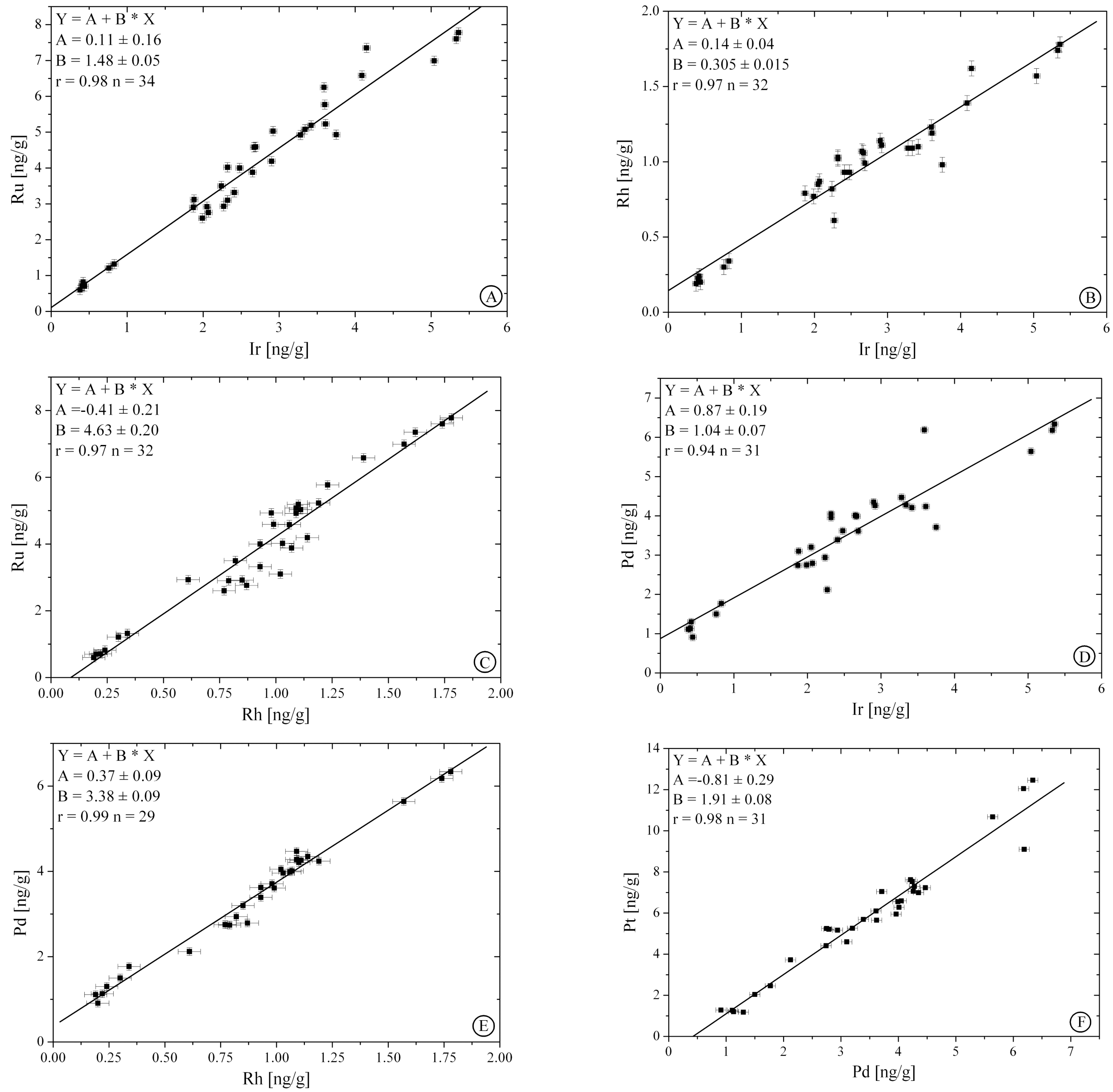

Fig. 6. a–f) Linear correlations of the PGE concentrations in the impact melt rocks of the Lappajärvi impact structure. The projectile elemental ratios are calculated from the slope of the mixing line (b). Error bars represent 1 sigma uncertainty.

Ordinary Chondrites as Impactors

The identification of an ordinary chondrite (OC) as an impactor for the Lappajärvi impact structure offers further support for the hypothesis of McDonald et al. (2001) and Tagle and Claeys (2005) that OC represent the main fraction of extraterrestrial material reaching Earth not only as meteorites, but also as crater-forming projectiles. Small craters must be excluded from these statistics due to bias introduced by interferences with the atmosphere; the small craters are usually produced by iron projectiles (e.g., Bland and Artemieva 2003). The vast majority of craters larger than 1.5 km, for which a chondritic projectile has been identified, were produced by ordinary chondrites (see Table 5). So far, the only impact structure with a carbonaceous chondritic projectile is the Cretaceous-Tertiary boundary crater Chicxulub (Kyte 1998; Shukolyukov and Lugmair 1998; Trinquier et al. 2006). Additionally, material linked to carbonaceous chondrites were found in the 3.5 to 3.2 Ga old Barberton spherule beds in South Africa (Shukolyukov and Lugmair 2000).

Ordinary Chondrites as Meteorites and Asteroids

Around 80% of the meteorites falling to Earth are ordinary chondrites (Grady 2000). The geochemical homogeneity, the oxygen isotopic composition, and the

Table 3. Linear regression data. The slope represents the element ratios in the projectile; the uncertainty is calculated as 1 sigma. Excluded sample aliquots are given for each ratio.

y-axis	x-axis	Slope + 1 sigma	Intercept + 1 sigma	n	r	Excluded analyses
Ru	Ir	1.48 ± 0.05	0.11 ± 0.16	34	0.98	–
Pt	Ir	2.15 ± 0.07	0.48 ± 0.22	34	0.98	–
Rh	Ir	0.305 ± 0.015	0.14 ± 0.04	32	0.97	212, 329
Pd	Ir	1.04 ± 0.07	0.87 ± 0.19	31	0.94	212, 211, 315, 327
Ru	Rh	4.63 ± 0.20	−0.41 ± 0.21	32	0.97	212, 329
Ru	Pd	1.27 ± 0.06	−0.66 ± 0.24	31	0.97	212, 211, 315, 327
Pt	Rh	6.86 ± 0.16	−0.37 ± 0.17	32	0.99	212, 329
Pt	Pd	1.91 ± 0.08	−0.81 ± 0.29	31	0.98	212, 211, 315, 327
Pd	Rh	3.38 ± 0.09	0.37 ± 0.09	29	0.99	212, 329, 211,315,327
Pt	Ru	1.42 ± 0.05	0.45 ± 0.23	34	0.98	–

Table 4. Element ratios in chondrites used for the plots in Fig. 7.

	Pd/Ir	Rh/Ir	Pt/Rh	Pd/Rh	Pt/Pd	Ru/Rh	Ru/Pd
CI	1.19 ± 0.10	0.29 ± 0.01	7.36 ± 0.17	4.18 ± 0.21	1.69 ± 0.23	4.95 ± 0.25	1.15 ± 0.01
CO	0.94 ± 0.11	n.d.	n.d.	n.d.	1.80 ± 0.06	n.d.	1.46 ± 0.13
CM	1.07 ± 0.09	0.26 ± 0.01	7.18 ± 0.36	4.08 ± 0.20	1.70 ± 0.13	5.08 ± 0.25	1.45 ± 0.22
CV	0.93 ± 0.07	0.28 ± 0.01	6.93 ± 0.35	3.38 ± 0.17	2.10 ± 0.15	5.01 ± 0.25	1.65 ± 0.08
CK	0.97 ± 0.05	0.28 ± 0.01	7.51 ± 0.38	3.52 ± 0.18	1.82 ± 0.09	n.d.	1.41 ± 0.07
CR	1.18 ± 0.17	n.d.	n.d.	n.d.	1.69 ± 0.24	n.d.	1.30 ± 0.20
CH	0.90 ± 0.05	n.d.	n.d.	n.d.	2.00 ± 0.10	n.d.	n.d.
H	1.10 ± 0.10	0.31 ± 0.00	6.77 ± 0.14	3.63 ± 0.09	1.86 ± 0.07	4.73 ± 0.12	1.33 ± 0.06
L	1.22 ± 0.14	0.33 ± 0.01	6.54 ± 0.12	4.08 ± 0.16	1.70 ± 0.19	4.43 ± 0.17	1.16 ± 0.10
LL	1.49 ± 0.21	0.34 ± 0.01	6.46 ± 0.21	4.70 ± 0.24	1.40 ± 0.17	4.40 ± 0.16	1.04 ± 0.16
EH	1.62 ± 0.09	0.33 ± 0.02	6.39 ± 0.32	5.04 ± 0.25	1.27 ± 0.05	4.94 ± 0.25	0.96 ± 0.03
EL	1.31 ± 0.07	0.33 ± 0.02	6.25 ± 0.40	4.11 ± 0.28	1.53 ± 0.09	4.98 ± 0.02	1.16 ± 0.10

n.d. = not determined.

Table 5. Summary of terrestrial impact structures where a chondritic projectile component has been identified, down to level of the chondrite type.

Crater name	Location	Age (Ma)	Diameter (km)	Projectile	Evidence[a]	References[b]
New Quebec	Canada	1.4 ± 0.1	3.4	OC, type L?[c]	S	1
Brent	Canada	450 ± 30	3.8	OC, type L or LL	S	1
Wanapitei	Canada	37 ± 2	7	OC, type L or LL	S	2
Lappajärvi	Finland	73.3 ± 5.3	23	OC, type H	S, Cr*	3, 10, this work
Clearwater East	Canada	290 ± 20	26	OC, type LL	S, Cr*	4, 10*
Morokweng	South Africa	145.0 ± 0.8	70	OC, type LL	S, Cr*, M	5, 6
Popigai	Russia	35.7 ± 0.2	100	OC, type L	S, Cr*	7
Chicxulub[d]	Mexico	64.98 ± 0.05	170	CC	M, S, Os*, Cr*	1, 8, 9

[a]S = siderophile elements (PGE, Ni, Au); Cr* = chromium isotopes; Os* = Os isotopes; M = meteorite fragment; OC = ordinary chondrites; CC = carbonaceous chondrites.

[b]1 = Koeberl (1998); 2 = Wolf et al. (1980); 3 = Shukolyukov and Lugmair (2000); 4 = McDonald (2002); 5 = McDonald et al. (2001); 6 = Maier et al. (2006); 7 = Tagle and Claeys (2005); 8 = Shukolyukov and Lugmair (1998); 9 = Kyte (1998); 10 = Koeberl et al. (2007).

[c]? = questionable.

[d]Enrichment in ejecta layer.

Size and age of the impact structures were obtained from the Earth Impact Database (2007).

cosmic exposure ages of the ordinary chondrite groups (H, L, and LL) justify the existence of one parent body per group (Meibom and Clark 1999 and references therein). Further, it has been even suggested that OC asteroids are rather uncommon in the Main Belt (e.g., Meibom and Clark 1999). In contrast, current interpretations of the asteroidal spectra suggest that OC asteroids are relatively common within Main Belt and near-Earth objects (e.g., Pieters and McFadden 1994; Binzel et al. 2004). This interpretation is based on linking the relatively abundant S-type spectra asteroids to ordinary chondrites. However, the spectra of a large number of S-type asteroids do not fit to those obtained in the laboratories from OC because asteroids spectra are "more reddish" and have much shallower olivine/pyroxene absorption band at 1 µm (e.g., Chapman and Salisbury 1973; Chapman 1996). These discrepancies may be explained by the influence of "space

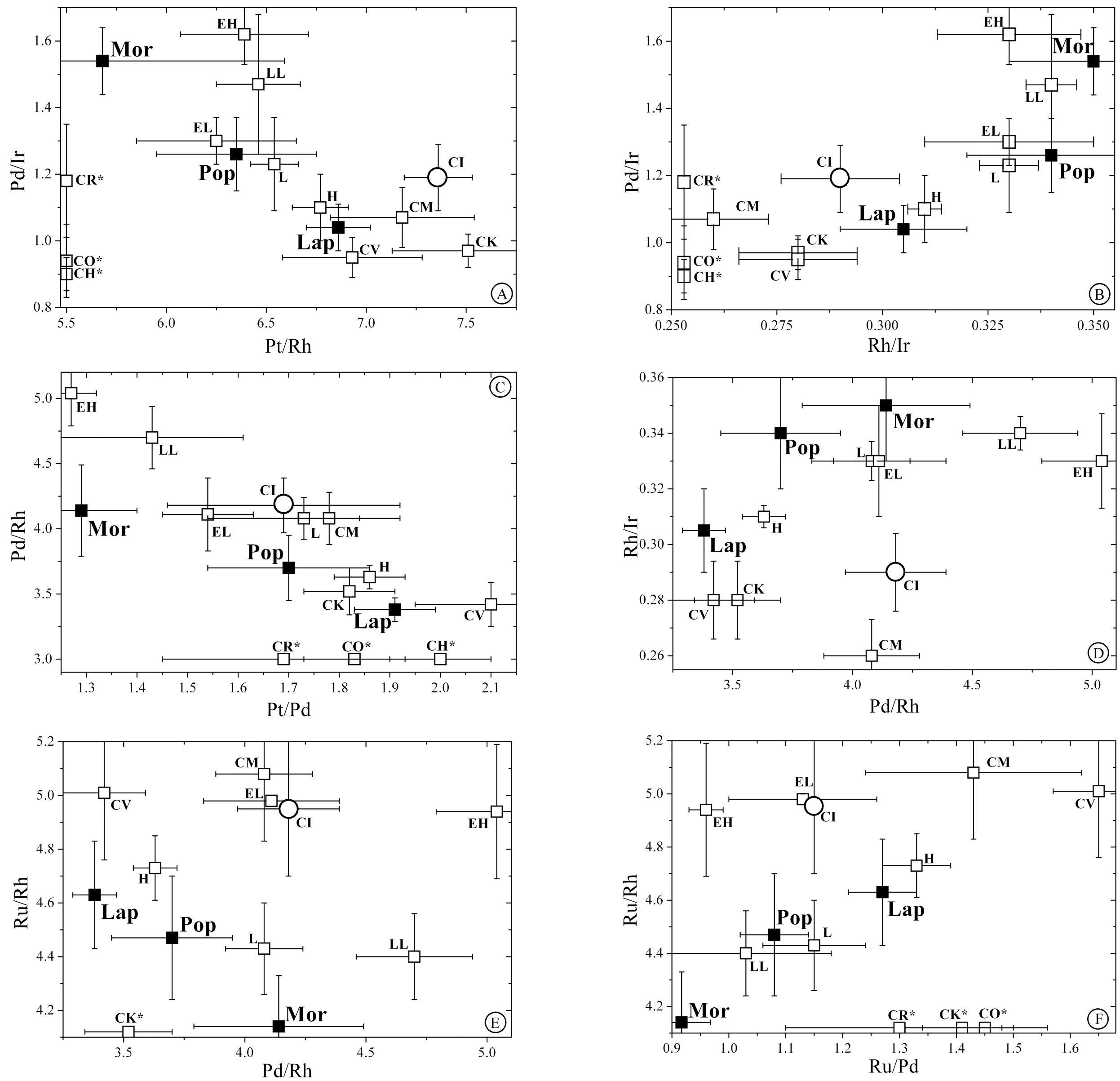

Fig. 7. The projectile elemental ratios obtained for the impact melt rocks of the Lappajärvi impact structure compared to the element ratios in different chondrite types. Included for comparison are the projectile elemental ratios previously determined for the Morokweng and the Popigai impact structures by McDonald et al. (2001) and Tagle and Claeys (2005), respectively. The ratios for the different chondrites (uncertainty corresponds to 1 sigma) have been compiled by Tagle and Berlin (Forthcoming). * = only one ratio known.

weathering." This weathering is supposed to change the surface mineral composition of the asteroids (e.g., iron is reduced to Fe metal) by interaction with cosmic rays (Chapman 1996; Binzel et al. 2004; Nesvorný et al. 2005). Chapman (1996) suggested that between 25 and 50% of S-type asteroids could be made of OC-like material. However, the abundance of OC projectiles (see Table 5) is not necessarily evidence for the abundance of OC asteroids. Ordinary chondrite asteroids are most likely clustered in the inner part of the Main Belt between 1.9 and 2.8 AU (Gaffey et al. 1993; Farinella et al. 1993). This area of the Main Belt is affected by the strongest resonances: the v6 secular resonance at the inner edge of the asteroid belt (2.06 AU) and the mean motion resonances with Jupiter 3:1 and 5:2 at 2.5 and 2.8 AU, respectively. These resonances are responsible for the transfer of asteroidal material into the inner solar system (Morbidelli et al. 2002). Numerical simulations have shown that most of the material injected from these positions becomes Earth-crossing within less than 10 Myr (Gladman et al. 1997). Hence, the relative position of OC parent bodies within the Main Belt should strongly bias the type of material transported into the inner solar system. Thus, inner belt asteroid dynamics and especially collision events between such bodies are probably a dominant factor for the projectile flux in the Earth-Moon system. Additionally, the bias toward inner belt objects would also imply that projectiles striking Earth through time do not provide significant information on the composition of the outer belt objects. Nonetheless, they provide a good overview of the inner belt objects, and may thus help to solve the S-type asteroid conundrum.

SUMMARY AND CONCLUSIONS

All Lappajärvi impact-melt rock samples analyzed are contaminated by an extraterrestrial component. The correlation of the PGE, similarities in the element patterns, and the fact that the projectiles' elemental ratios are consistent with a certain type of chondrite all suggest that the PGE are not fractionated in the impact melt. Nevertheless, possible small-scale variations related to Rh, Au, or Pd enrichment may have led to the different patterns found for these three elements in five out of the 34 analyses. The projectile elemental ratios identified in the impact-melt rocks suggest an H-chondritic projectile type for the Lappajärvi impact structure. The amount of extraterrestrial components admixed to melt rocks varies between 0.05–0.7 wt%, and the proportion of projectile matter remaining in the crater is estimated to be about 7 wt%. Ordinary chondrites as projectiles are responsible for a significant number of terrestrial impact craters compared to other chondrites. As suggested by McDonald et al. (2001) and Tagle and Claeys (2005), this abundance could be directly related to the position of their parent bodies close to the main resonance position in the asteroid belt, implying a bias of the impactor population towards inner belt objects.

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