Rhodium - a long ignored element in cosmo- and geochemistry

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Introduction

The cosmochemical origin of the refractory elements Rh, Ru, Ir, Os, there nucleosynthetic origin of the stable isotopes (e.g., Akram, Farouqi, Hallmann & Kratz, 10th European Summer School on Experimental Nuclear Astrophysics, EPJ Web Conf. 227 (2020) 01009), and the identification of projectile types from impact melt samples on Moon and Earth have been fascinating subjects for cosmochemists and astrophysicists for over 50 years. Nebular processes (e.g., condensation, Fig. 1) and fractional crystallization during core formation of planets have produced some compositional variation in the platinum group element (PGE) chemistry of stony meteorites and irons. This compositional variation makes it possible to identify projectile types from impact craters. The 1850-Ma-old Sudbury impact structure is the largest and oldest impact structure in Canada and the site of world-famous nickel, copper, and PGE deposits [1]. Iridium, Rh and Ru are chemically relatively weathering resistant and essentially immobile in the crust compared to other elements. The Ir/Rh, Ru/Rh and Os/Ir mass ratios are particularly suitable for distinguishing different types of projectiles. In this study I review the diagnostic element ratios Ir/Rh, Ru/Rh, Ru/Ir, and Os/Ir for specific impactor compositions of terrestrial impact craters (Table 1).

Table 1. Terrestrial impact structures with diameters >1 km. A reappraisal of impactor types based on Ir/Rh, Ru/Rh, Ru/Ir, and Os/Ir in melt samples and fossil meteorites.

	Locality	age (Ma)*	crater diameter (km)*	type of impactors: Chondrite	Iron	projectile remnants	
1	Popigai Russia	36.63 ± 0.92	100	(b) H or L-chondrite	(a)		(b) Tagle & Claeys (2005); (a) this work
2	Wanapitei Canada	37.7 ± 1.2	7.5	(b) chondrite or iron	(a)		(b) Evans, Gregoire, Grieve et al. (1993); (a) this work
3	Boltysh Ukraine	65.80 ± 0.67	24		iron		Schmidt (1997)
4	Chicxulub Mexico	66.052 ± 0.043	180	carbonaceous chondrite (CV, CM, CO, or CR)		x	Evans, Gregoire, Grieve et al. (1993); Kyte (1998); Goderis et al. (2013)
5	Lappajärvi Finland	77.85 ± 0.78	23	(b) H-chondrite	(a)		(b) Tagle, Öhman, Schmitt et al. (2007); (a) this work
6	Mien Sweden	122.4 ± 2.3	9		iron		Schmidt, Palme & Kratz (1997)
7	Dellen Sweden	140.82 ± 0.51	19		iron		Schmidt, Palme & Kratz (1997)
8	Morokweng South Africa	146.056 ± 0.018	70	LL-chondrite		x	McDonald, Andreoli, Hart & Tredoux (2001); Maier, Andreoli, McDonald et al. (2006)
9	Rochechouart France	206.92 ± 0.32	23		(c) (IIa); (a) (b) non-magmatic IA, IIIC		(c) Janssens, Hertogen, Takahashi, Anders & Lambert (1977); (b) Tagle, Schmitt & Erzinger 2009; (a) this work
10	Brent Canada	458–453	3.8	(b) chondrite or iron	(a)		(b) Evans, Gregoire, Grieve et al. (1993); (a) this work
11	East Clearwater Canada	470–460	22	(e) new chondrite group	(a)		(a) this work or new chondrite group (e) Palme (2019) pers. comm.
12	Gardnos Norway	546 ± 5?	4.8		non-magmatic		Goderis, Kalleson, Tagle et al. (2009)
13	Sääksjärvi Finland	602 ± 17	6		(d) magmatic (b) non-magmatic IA, IIIC		(d) Schmidt, Palme & Kratz (1997); (b) Tagle, Schmitt & Erzinger (2009)
	total			2	10 ± 1		

*Age data and crater diameter compiled by Schmieder and Kring (2020) Astrobiology 20, 91-141, see references therein.

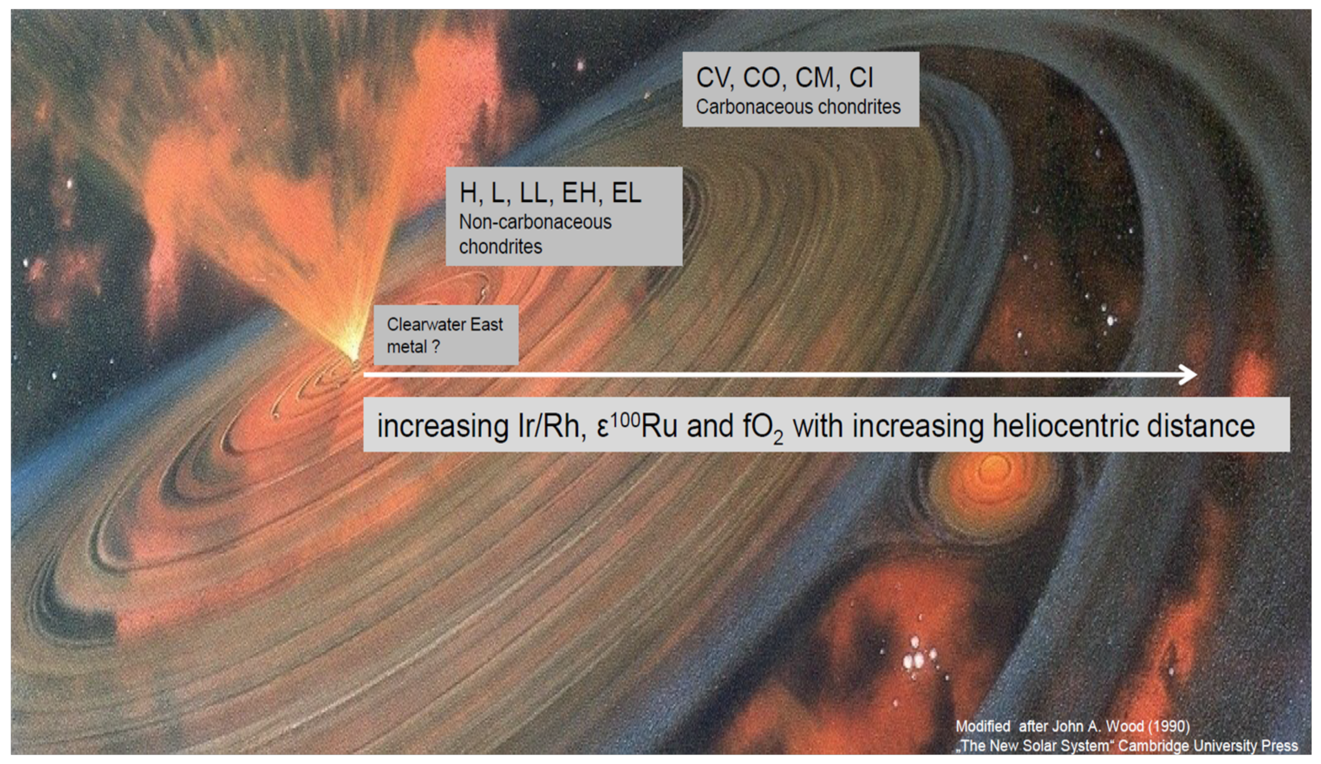

Fig. 1. The Ir/Rh mass ratio as an indicator for the heliocentric distance increases with increasing ε^{100}Ru anomalies and fO2. More reduced materials like enstatite and ordinary chondrites have low values compared to more oxidized and volatile-rich materials such as carbonaceous chondrites that formed at greater heliocentric distance.

Clearwater East, Canada:

Clearwater East has highest PGE contents in melt samples from 204 [2] known terrestrial impact crater. Since the earlier studies by Palme and co-workers 1978 a chondrite has been suggested as impactor based on PGE, Ni, Cr [3-8] and Cr isotopes [9]. However, LA-ICP-MS data on PGE including Ni from iron meteorites [10] allows comparing these data with ICP-MS [6] and neutron activation data from Clearwater East melt samples [7]. Element ratios of iron meteorite IVA Gibeon (Figs. 2-6) agree with Clearwater East samples. Up to ~1.2 wt.% of a IVA Gibeon-like component could be contained in the melt samples. However, a member of an unidentified chondrite group as projectile type, which is not known from meteorite collections, could also be possible (Palme 2019, pers. communication).

Ru/Rh versus Ir/Rh mass ratios of Clearwater East impact crater melt samples compared to meteorites

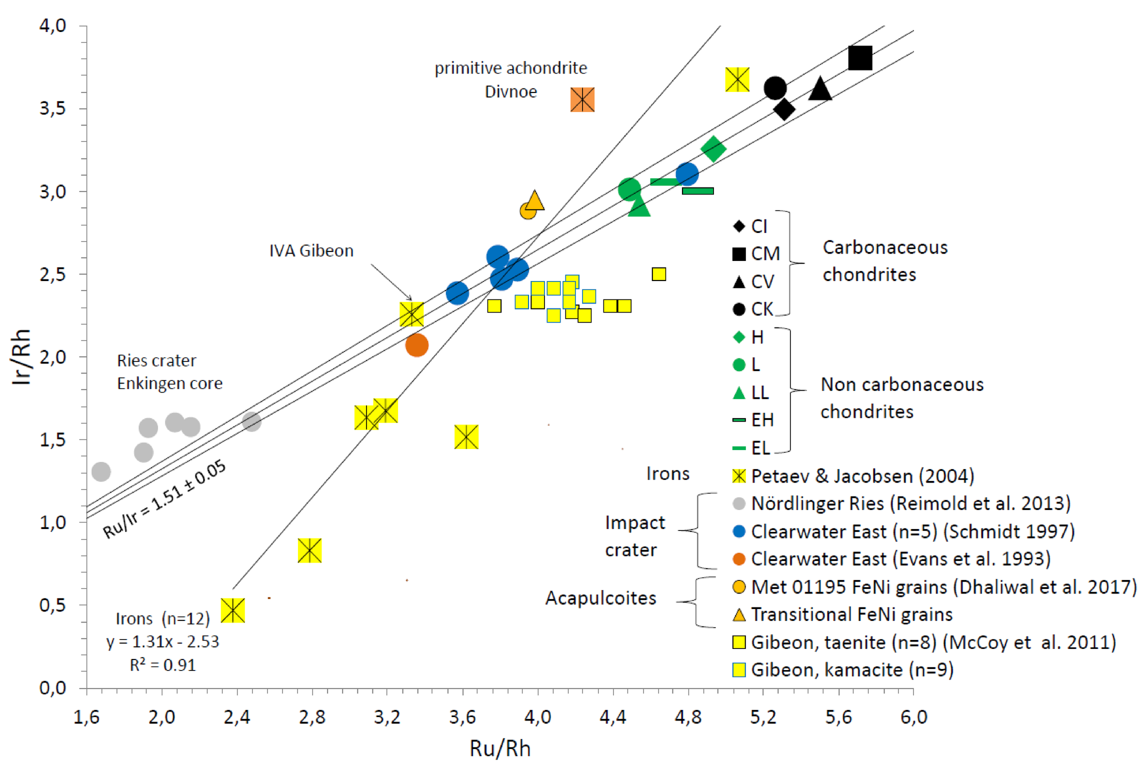

Fig. 2. Ru/Rh versus Ir/Rh mass ratios of Clearwater East impact crater melt samples compared to meteorites. Commas in axis labels represent points.

Ir/Rh mass ratio of chondrites as an indicator for the heliocentric distance of the formation region

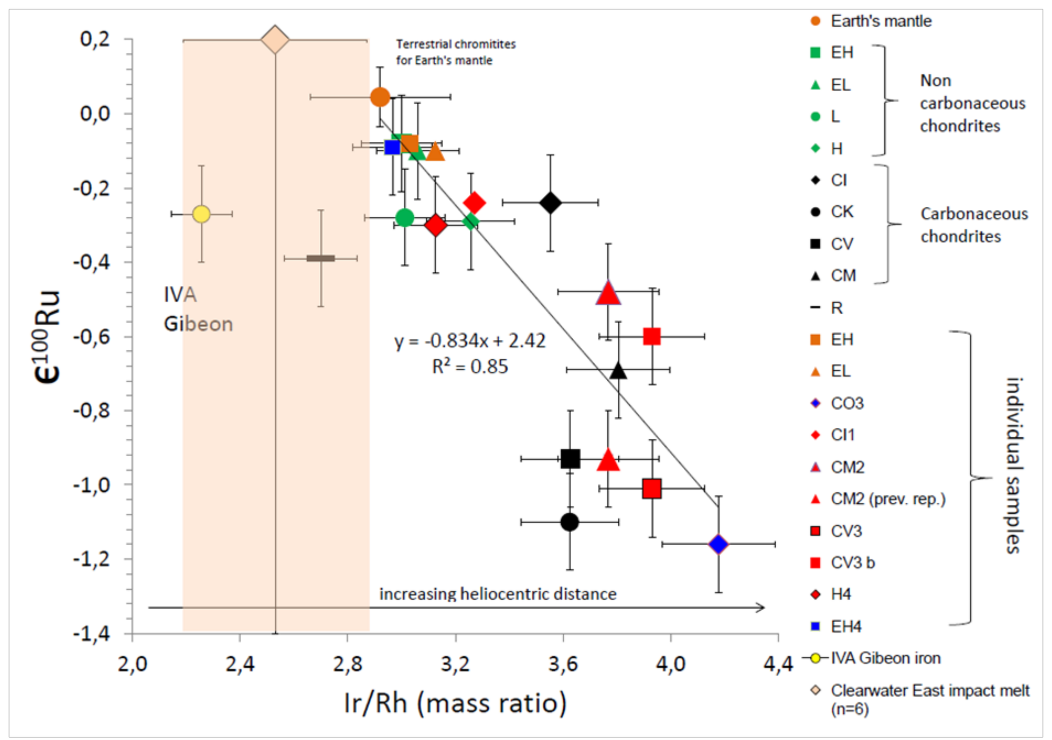

Fig. 3

$\varepsilon^{100}\mathrm{Ru} = [({}^{100}\mathrm{Ru}/{}^{101}\mathrm{Ru})_{sample}/({}^{100}\mathrm{Ru}/{}^{101}\mathrm{Ru})_{standard} - 1] \times 10{,}000$

Fig. 3. ϵ^{100}Ru data from Fischer-Gödde & Kleine (2017) Nature 541. Earth's mantle Ir/Rh (2.92 ± 0.26, 1σ population standard deviation, n=57), Fischer-Gödde, Becker & Wombacher (2011) Chemical Geology 280, 365 - 383. CI abundances from Palme, Lodders & Jones (2014) In Treatise on Geochemistry. Mean chondrite abundance data from Tagle & Berlin (2008) MAPS 43. Ir/Rh data for R, EH, EL chondrites (orange colour) from Fischer-Gödde, Becker & Wombacher (2010) GCA 74. Clearwater East data from Evans, Gregoire, Grieve, Goodfellow & Veizer (1993) GCA 57 and Schmidt (1997) MAPS 32. Gibeon data from Petaev & Jacobsen (2004) MAPS 39 and Fischer-Gödde, Burkhardt, Kruijer & Kleine (2015) GCA 168.

Commas in axis labels represent points.

Impact melt rocks from Earth compared to Moon rocks, iron meteorites (yellow symbols) and chondrite groups (black and green symbols)

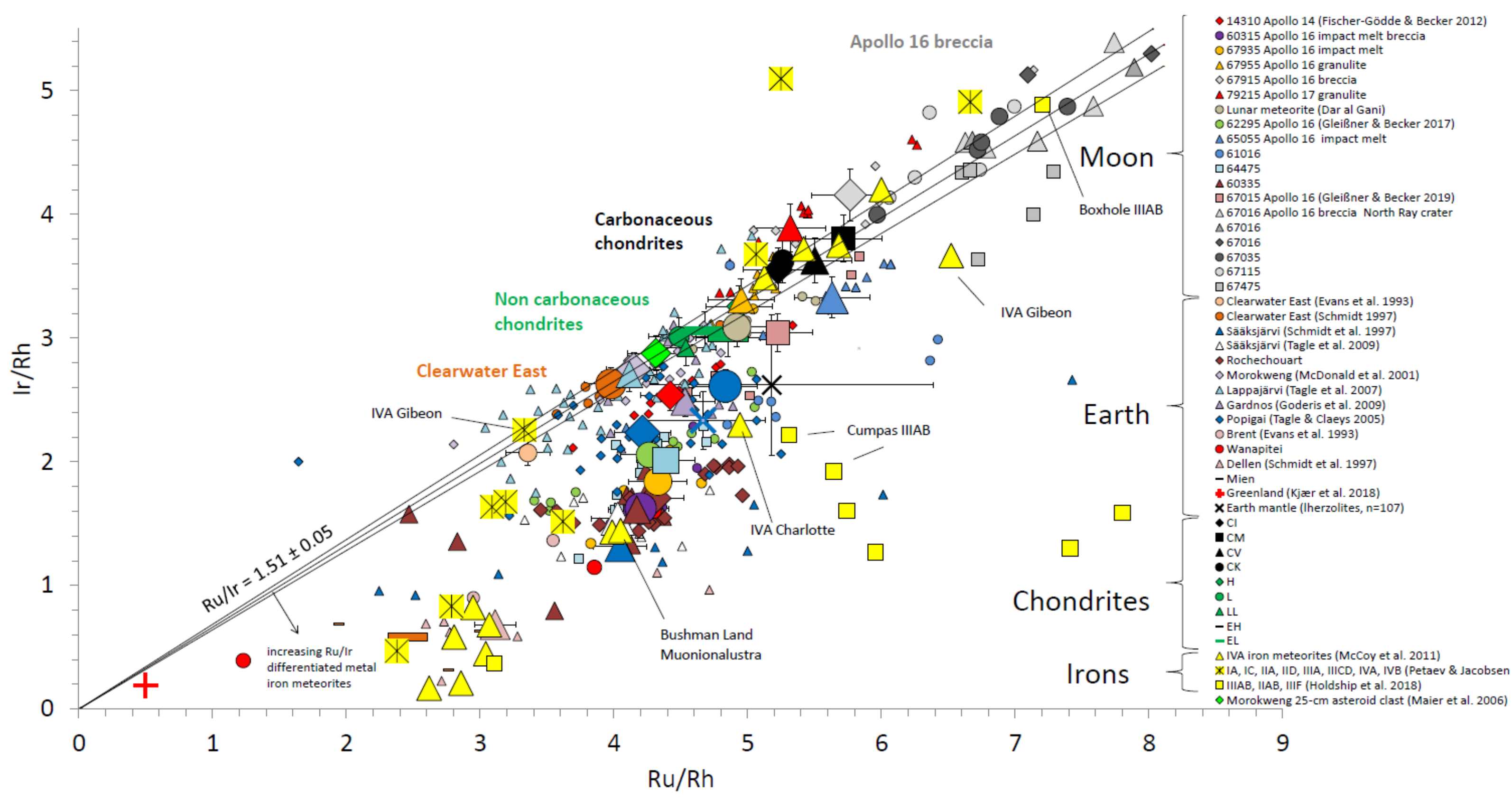

Fig. 4

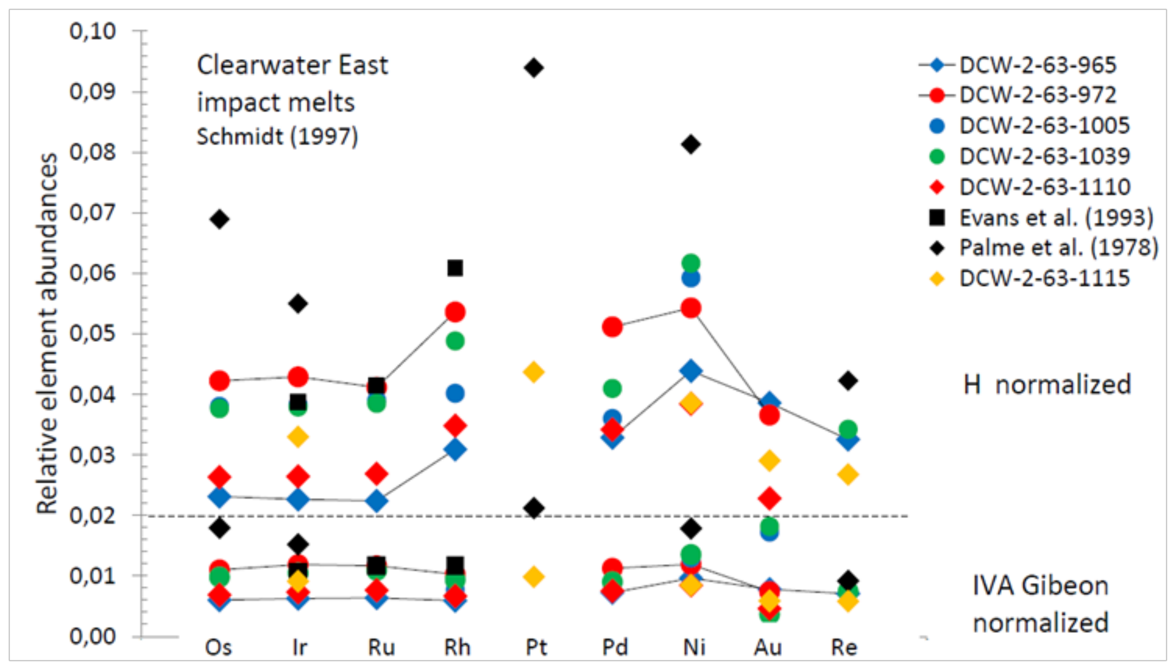

Fig. 5a

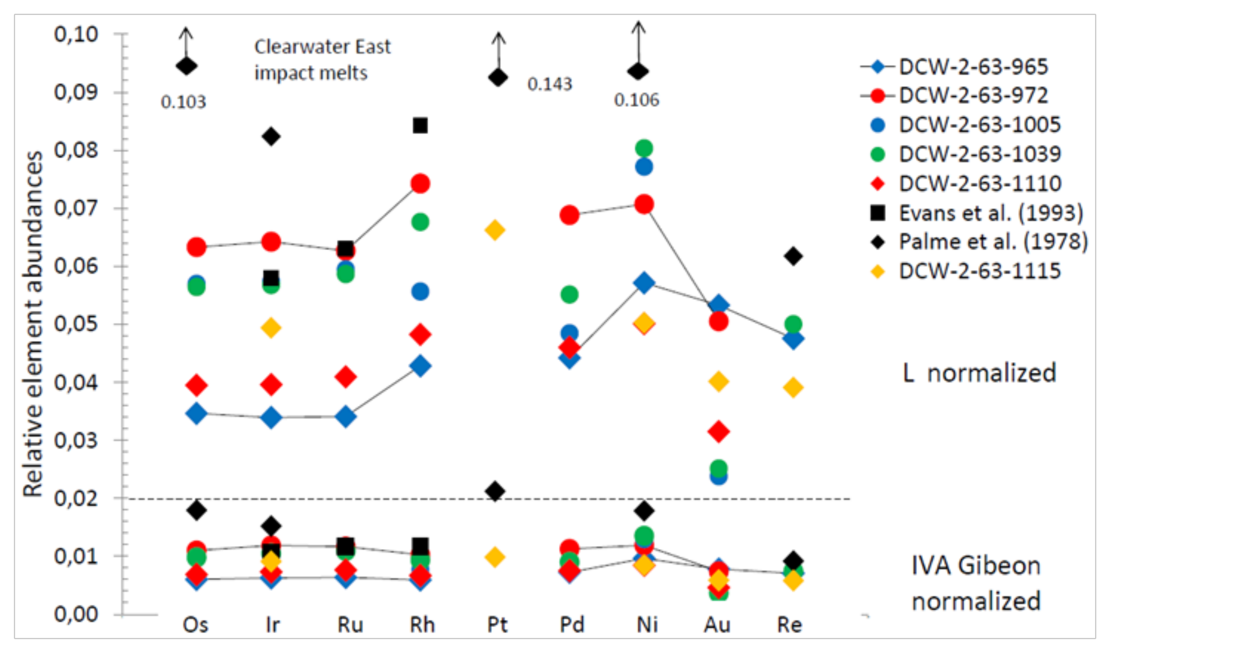

Fig. 5b

Fig. 5. H chondrite (Fig. 5a) and L chondrite (Fig. 5b) normalized element ratios differ significantly from ratios in Clearwater melt samples. Element ratios of iron meteorite Gibeon agree with ratios in melt samples from Clearwater East. All elements shown in the lower part of the figures normalized to Gibeon (linear scale !) plot more or less on a horizontal line. However, Koeberl et al. [9] favour an H or L chondrite as possible Clearwater East projectile. These authors excluded a carbonaceous chondrite based on positive ^{53}Cr excesses in melt samples. Commas in axis labels represent points.

Chemical fingerprints of asteroids in Earth and Moon impact melts, iron meteorites (yellow symbols) and chondrite groups (black and green symbols)

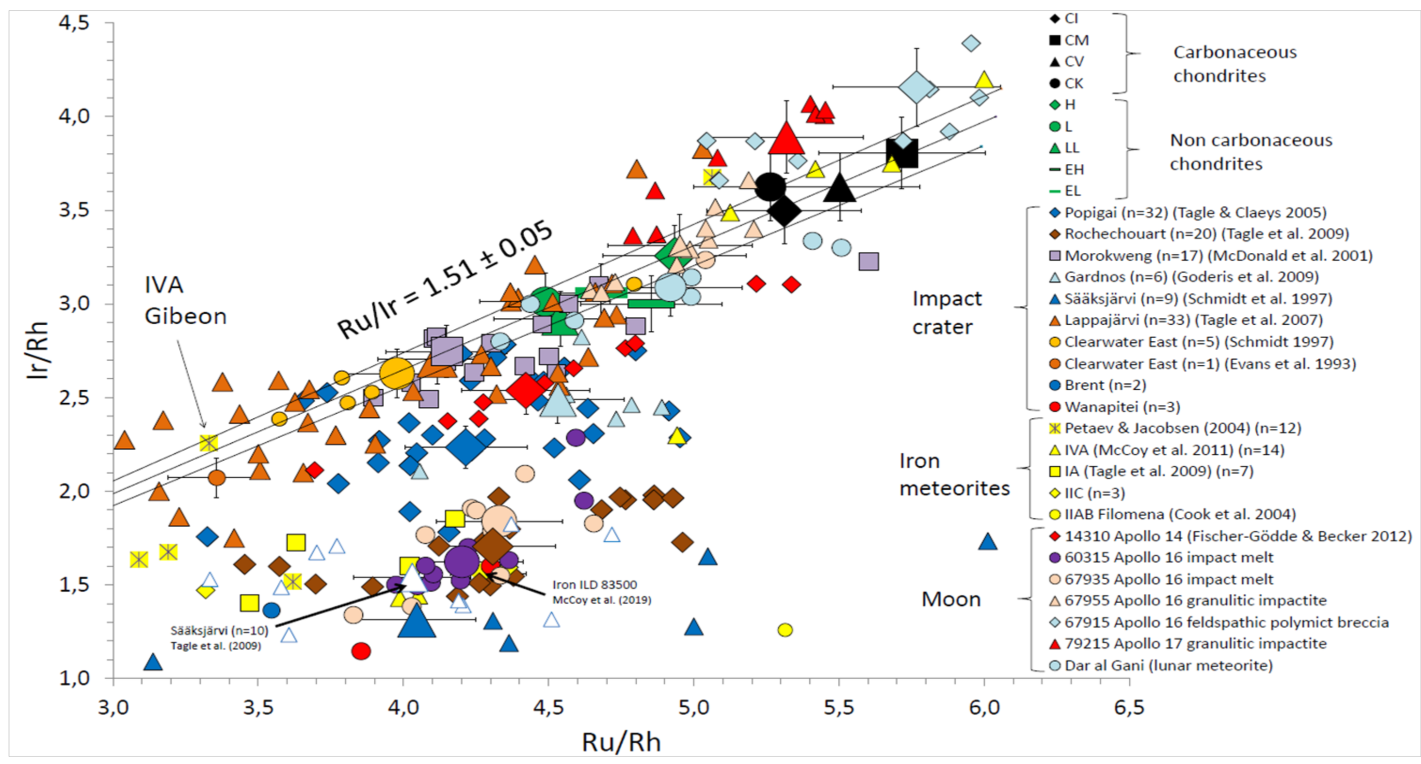

Fig. 6. Impact melt rocks 60315 and 67935 (Apollo 16) are similar in Ru/Rh and Ir/Rh (Fischer-Gödde & Becker 2012) than Rochechouart impactite data (Tagle et al. 2009). IIA or IIIAB magmatic irons are proposed as projectile types for the Rochechouart impact crater in France by Janssens et al. [15]. However, some IVA iron data and ILD83500 (McCoy et al. 2011, 2019) also overlap with some IA irons (compilation of data in Tagle et al. 2009), Rochechouart and Apollo 16 melt rocks.

Results

Clearwater East: Diagnostic ratios of Ir, Rh, Ru and Os in impact melts from Clearwater East crater contradict projectile identification by Cr isotopes (Koeberl et al. [9]). The most likely projectile type based on PGE and Ni appears to be an iron meteorite or a member of an unidentified chondrite group unknown from meteorite collections (Fig. 2,5).

Rochechouart: Based on the abundance of Os, Ir, Ni, and Pd in melt samples and subchondritic Os/Ir ratios a IIA magmatic iron asteroid fragment is favoured as projectile type by Janssens et al. (1977) [15]. Contrary, based on ^{53}Cr excess an ordinary chondrite is favoured by Koeberl et al. [9]. These authors estimated about 3 wt.% of a chondritic component in the melt. However, Rochechouart samples [11] and melt rocks from Apollo 16 landing site [12] match Ru/Rh and Ir/Rh from IA, IIC, IVA and ILD83500 irons (Figs.4,6).

Conclusion

Ir/Rh, Ru/Rh and Os/Ir mass ratios are diagnostic element ratios for specific impactor compositions [13]. High quality data especially of Rh might answer fundamental questions of cosmochemistry [14] and contribute to our understanding of processes involved in the formation and unique composition of planetary bodies. The Ir/Rh mass ratios as an indicator for the heliocentric distance increases with increasing ε^{100}Ru anomalies. Ru isotopes (Ru contents of up to 50 ng/g have been determined in Clearwater East melt samples) could shed light in controversal projectile identifications. However, as shown by Worsham et al. [16] ordinary chondrites and IVA iron meteorites cannot be distinguished by ε^{100}Ru values. A combination of Ir/Rh mass ratios and Ru isotopes in impact melt samples are diagnostic tools for there cosmochemical origin.

References

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