ON THE NATURE OF S-TYPE ASTEROIDS AND THE TERRESTRIAL IMPACTOR POPULATION

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Introduction: The main asteroid belt between the orbits of Mars and Jupiter contains over 670 000 asteroids larger than 1km [1]. Their orbits are affected by a variety of resonances, mainly with Saturn and Jupiter responsible for the "production" of Near Earth Objects (NEOs) [2]. Spectroscopic observations indicate that S-type asteroids are the most common objects among the NEOs (Figure 1).

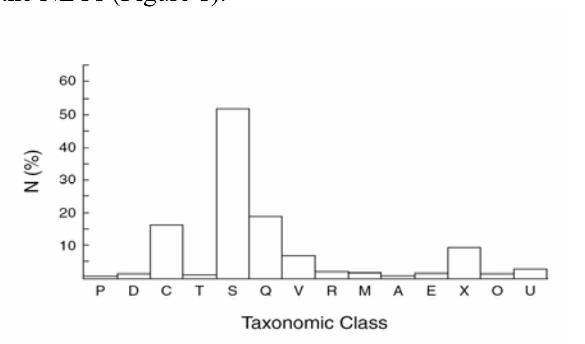

Fig. 1. Abundance of S-type asteroids among ~ 300 NEOs data compiled by [3].

The meteorite type represented by S-type asteroids is still controversial; the most common idea is that they are related to ordinary chondrites (OC). Ordinary chondrites represent ~80 % of the meteorites in collections [4]. However, they may only represent samples from 3 asteroid parent bodies. Some authors suggested that OC-asteroids are rather uncommon in the Main Belt (MB) [5]. This contradicts the current interpretations of asteroidal spectra suggesting that OC-asteroids are relatively common within the MB and among NEOs [6; 7]. This 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 on OC in the laboratories. Asteroid spectra are 'redder' and have much shallower olivine/pyroxene absorption bands at 1 µm [7; 8]. These discrepancies could be explained by the influence of "space weathering", which is supposed to change the surface mineral composition of the asteroids, (e.g., iron is reduced to Fe-metal) by interaction with cosmic-rays [8; 3 and 9]. It has been suggested that between 25 and 50 % of S-type asteroids could be made of OC-like material [8]. The question is thus: what are the remaining S-type asteroids made of?

S-Type asteroids as impactors: S-type asteroids are abundant in the actual NEOs population, consequently they should also represent a significant fraction of the Phanerozoic population, as the processes responsible for their production most likely did not change over time. The identification of the projectiles responsible for the formation of terrestrial craters sheds some light on the the nature of this other fraction of S-type asteroids.

Projectiles in terrestrial craters: Based on the results of the projectile identification in large terrestrial craters (over 1,5 km), ordinary chondrites appear to be the most common type of projectile (Fig. 2 and Table 1). Non-magmatic irons represent the second most abundant group of projectiles recognized (Table 1). Other types of projectiles, such as carbonaceous chondrites, (probably also abundant as asteroids [5]) are so far only represented by the Chicxulub projectile [10; 11].

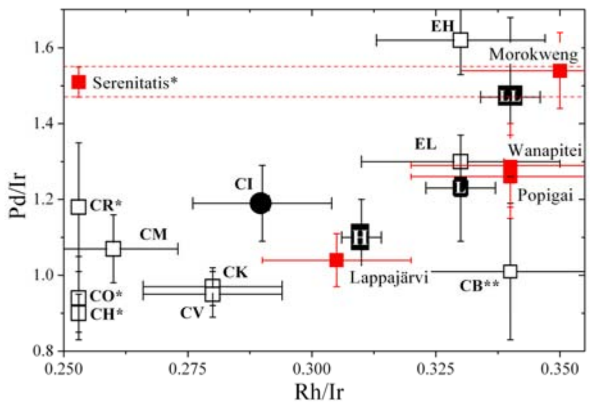

Fig. 2. The diagram illustrates the abundance of OC among projectiles hitting Earth. The element ratio in the impact melt of Morokweng [12], Popigai [13], Wanapitei [14], Lappajärvi [15], and Seranitatis (poikilitic apollo 17 impact melt) [16], are compared to the element ratios in chondrites [17].

What are non-magmatic iron (NMI) meteorites? NMI meteorites are a group of iron meteorite that were not formed by the magmatic segregation of their asteroid parent body, but through poorly understood processes (e.g., [18; 19]). They are composed of iron and may contain up to 90% of silicate inclusion [20]. Among iron meteorites reaching Earth, they represent the second largest group, composed of apparently genetically linked IA, IB, IIIC, IIID, and IIE, the latter being probably not related to the previous four. So far only 3 of the 9 craters smaller than 1.5 km in diameter and formed by iron meteorites, are produced by IIIA´s, the most common type of magmatic iron meteorite reaching Earth. One crater is formed by a IIIB, a less common magmatic iron [21 and ref. therein]. The projectile of the remaining 5 craters are all NMI meteorites, including the Barringer in Arizona (Table 1).

This suggests that NMI's are relatively abundant among the extraterrestrial material reaching Earth and the second most abundant projectile type for large craters.

Table 1. *Projectile types identified in terrestrial craters, data from [21] and references therein, Gardnos [22].*

Crater	Size (km)	Age (Myr)	Projectile
Morasko	0.10	<0.01	NMI (IIIC)
Kaalijärvi	0.11	0.004	NMI (IA)
Odessa	0.17	0.006	NMI (IA)
Monturaqui	0.46	<0.005	NMI (IA?)
Baringer	1.19	<0.05	NMI (IA)
New Quebec	3.4	1.4	OC-(L?)
Brent	3.8	450	OC-(L-LL?)
Sääksjärvi	6	~560	NMI
Wanapitei	7.5	37.2	OC-L
Gardnos	5	~ 650	NMI
Lappajärvi	23	77.3	OC-H
Rochechouart	23	214	NMI
Clearwater East	26	290	OC-LL
Morokweng	70	145	OC-LL
Popigai	100	35	OC-L

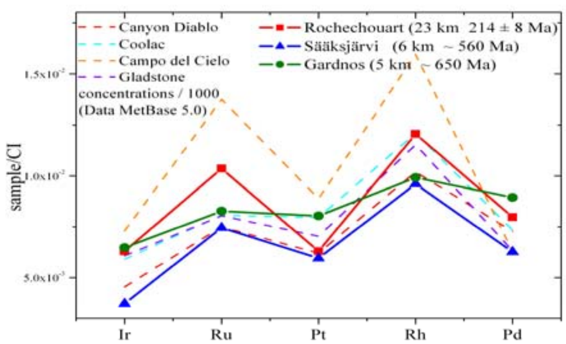

Fig. 3. *The similarity in the element patterns of platinum group elements in the impact melt of Rochechouart, Sääksjärvi and Gardnos (mutiplied by 5), support the interpretation of non-magmatic-meteorites as projectiles for these craters (for more details see [27]). Canyon Diablo are meteorite fragments of the Arizona crater projectile.*

Space weathering, as assumed for OC, is suggested to produce a reduction of Fe^{2+} into metallic iron on the surfaces exposed to cosmic ray, resulting in a shift of the spectra toward an apparent higher abundance of iron. The main mineral phases forming NMI meteorites are olivine, pyroxene, metal [20], which are the same minerals suggested for S-type asteroids and found in OC.

Discussion: S-type asteroids could represent a mixed population of OC and NMIs as the mineralogical components match the suggested composition of S-type asteroids, based the interpretation of the reflected spectra. Improvements in the differentiation criteria could help to estimate the relative proportion of these two diffferent asteroids among S-type asteroids. The abundance of OC as projectiles is not necessarily evidence for the abundance of OC-asteroids. OC originate in the inner part of the main asteroid belt between 1.9 and 2.8 AU [23; 24; 25]. 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, which are responsible for the transfer of asteroidal material into the inner solar system [28]. This area is also shared by differentiated asteroids (e.g., [26]). Hence, the relative position of OC parent bodies, and maybe NMI meteorites, within the asteroid belt strongly biases 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.

Conclusions: The terrestrial impactor population is mainly composed of inner belt objects as suggested by astronomical modelling of the production of NEOs [2]. The two main type of projectiles (OCs and NMIs) have a composition similar to the one expected for the abundant S-type asteroids. Not only "space weathering" of OC but also the fact that the NMI asteroids could contain relatively high proportion of iron can explain the strong variation in the spectra of S-type asteroids. Therefore, based on composition and abundance of projectiles in terrestrial craters, it could be suggested that a certain proportion of the S-type asteroids are parent bodies of NMIs meteorites.

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Ref. [1] Ivezic et al. (2001) *Astron. J.* 122, 2749-2784; [2] Morbidelli et al. (2002) In *Asteroids III* 409-421. The University of Arizona Press; [3] Binzel (2004) *Icarus* 170, 259–294.; [4] Grady 2000 Camb. Uni. Press; [5] Meibom and Clark (1999) *MAPS* 34, 7-24; [6] Pieters and McFadden (1994) *Ann. Rev. Earth and Planet. Sci.* 22, 457-497; [7] Chapman and Salisbury (1973) *Icarus* 19, 507-522; [8] Chapman (1996) *Meteoritics* 31, 699-725; [9] Nesvorný et al. (2005) *Icarus* 173, 132-152; [10] Kyte (1998) *Nature* 396, 237-239; [11] Shukolyukov & Lugmair (2000) *Science* 282, 927-929; [12] McDonald (2001) *GCA* 65, 299-309; [13] Tagle & Claeys (2005) *GCA* 69, 2877-2889; [14] Tagle et al. (2006) *37th LPSC* abst. # 1278; [15] Tagle et al. (2006) *37th LPSC* abst. # 1277; [16] Norman et al. (2002) *EPSL* 202, 217-228; [17] Tagle and Berlin (Submitted) *MAPS*; [18] Wasson & Kallemeyn (2002) GCA 66, 2445-2473; [19] Benedix et al. (2000) *MAPS* 35, 1127-1141; [20] Mittelfehldt et al. (1998) In *Planetary Materials* p. 4-195. Mineral. Soc. Am. [21] Tagle and Hecht (2006) *MAPS* 41, 1721-1735; [22] Goderis et al. (2006) *GSA* 38 abst. # 119-8; [23] Gradie and Tedesco (1982) *Science* 216, 1405-1407; [24] Gaffey et al. (1993) *MAPS* 28, 161-187; [25] Farinella et al. (1993) *Icarus* 101, 174-187; [26] Wood (2005) in *C&PD*, 953-971 [27] Tagle et al. (2003) *34th LPSC* abst. # 1835. [28] Morbidelli et al. (2002) In *Asteroids III* pp. 409-421. The University of Arizona Press.