THE IMPACT CRATERING RECORD FOR CLUES ON THE RATE OF COLLISIONS AND PROVENANCE.

S. Goderis[1], J. Belza[1] and Ph. Claeys[1], [1]Earth System Science, Dept. of Geology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium (Steven.Goderis@vub.ac.be).

Introduction: During crater formation on a planetary body a small amount of meteoritic material (vapor and/or melt) is incorporated into the impacted lithologies. This extraterrestrial contamination induces a measurable geochemical signal in these molten and/or shocked rocks that differs from the crustal signature. This signal can first confirm the impact origin of the structure and in ideal cases determine the precise nature of the projectile or in other words, the type of impacted meteorite. Precise characterization of the projectile can eventually link the impacted fragment to an asteroid family and help determine its provenance. At least three major geochemical methods are capable of detecting very small amounts of extraterrestrial material present in impact-related lithologies that, in most cases, do not exceed 1 wt% of bulk meteoritic material. Next to atypical isotope ratios (e.g., ^{187}Os/^{188}Os, ^{53}Cr/^{52}Cr, and ^{54}Cr/^{52}Cr), elevated concentrations of specific siderophile elements (e.g., Cr, Co, Ni, and the platinum group elements [PGE: Ru, Rh, Pd, Os, Ir, Pt]) and associated inter-element ratios (e.g., Rh/Ir, Pt/Pd, etc.) can be applied to study the extraterrestrial contributions incorporated into terrestrial rocks. As PGE concentrations in chondrites are generally two to four orders of magnitude higher than common crustal or mantle abundances, these are ideally suited for the detection and characterization of minute amounts of PGE-enriched meteoritic material admixed in impactites. However, this approach does not work for PGE-poor meteorites, including specific types of differentiated achondrites. Comprehensive comparative reviews have recently been published, evaluating their advantages and limitations [1, 2].

Terrestrial impactor population: To understand the origin of projectiles falling on Earth, we have started to characterize the projectiles responsible for the formation of large craters (>1 km) over the last 3 billion years. So far, the record is rather incomplete. Of the terrestrial craters larger than 1 km, most of the projectiles have only been characterized down to the level of chondrites or iron meteorites without further details [3]. This is insufficient to link them to asteroid families or disruption events, or to identify possible changes in the frequency or type of impacted meteorites through time. Seven of the Phanerozoic structures (>1 km) for which the projectiles have been characterized down to the level of specific class types are ordinary chondrites (OC). Only one, the 200-km in diameter Chicxulub crater stands out as a carbonaceous chondrite. Recent work on other impact structures such as 6 km Sääksjärvi, 23 km Rochechouart, 5 km Gardnos, and 19 km Dellen reveals another recurrent type of projectile: non-magmatic iron (NMI) meteorites [4-6]. Based on the existing record, the OC and NMI seem to be the two most common types of impactors falling on Earth since the beginning of the Phanerozoic. They are both composed of olivine, pyroxene and some metal in different proportions [7]. The sources of these bodies could both be represented by a fraction of the S-type asteroids. This class of asteroids has widely varying spectra and is well represented among the NEO and in the Inner Main Belt population between 1.9 and 2.8 AU, a zone that is affected by some of the strongest resonances [8]. Further back in time, we can speculate on the possibility of a somewhat different distribution in projectile types. While for several yet to be correlated late Archean (2.63-2.49 Ga) spherule layers in the Hamersley Basin (Australia) and Griqualand West Basin (South Africa) ordinary chondritic projectiles have been proposed [9], for three early Archean spherule beds in Barberton, South Africa, a carbonaceous chondritic impactor is confirmed using Cr isotope ratios [10].

Lunar impactor population: A number of authors have tried to determine the composition of the projectile components in the lunar samples collected during the Apollo missions in the 1970s (see [11] for a summary). Recently, the impactor components in the Apollo 17 aphanitic melt breccias and in the lunar meteorite NWA482 show the closest affinities to chondritic meteorites [11]. However, the impactor components in Apollo 17 poikilitic melt breccias and impact melt clasts from Apollo 14 breccia 14321 clearly differ from those in bulk chondrites in ^{187}Os/^{188}Os, Ru/Ir, Pt/Ir, and Os/Ir ratios. The authors explain these characteristics as the result of differentiated iron-rich impactor bodies. This explanation is not fully satisfactory, clearly further studies are needed to refine our understanding of the origin of the lunar impactors.

Rate of collision and provenance: Discussing collisions on the Earth-Moon system, several other crucial questions surface. It is currently difficult to judge if the rate of impact remained constant since the Late Heavy Bombardment, or if it varied, with possible higher collision rates during specific periods, as apparently indicated by recent data. The constancy of the source of these projectile is another key question, has the projectile provenance changed through geological time? Several possible clusters of impact events can be recognized. For example an asteroid shower is considered most likely to explain the elevated interplanetary dust particles flux and high concentration of impact craters present some ~35 million years ago in the late Eocene [12-14]. Another example occurred some 470 million years ago [15]. It is characterized by abundant (micro)meteorites (L-chondrites) preserved in Ordovician limestone layers of southern Sweden. Although the record is poor, several craters seem to concentrate in this same time window. In the Phanerozoic and late Archean, impact debris also seems to cluster in two time windows of 2.65 to 2.5 billion years ago and 3.47 to 3.24 billion years ago [16]. Finally, the most dramatic collisional event is certainly the Late Heavy Bombardment, between 4 and 3.8 billion years ago that devastated the Earth-Moon system and most likely the whole inner solar system [17]. It is linked to a major shift in the orbits of the giant gas planets [18]. The other elevated terrestrial impact rates probably derived from collisions of various magnitudes taking place in the asteroid belt. The Ordovician event is linked to a major disruption of the L chondrite parent body [19]. Also for the Chicxulub impact in Yucatán, 65 million years ago, that sealed the fate of the dinosaurs and triggered the late major mass extinction on Earth, the disruption of a parent body in the main asteroid belt has been proposed [20]. So can we compare peaks in the impact record considering their differences in magnitude, and how? What does the compositional difference of the impactors imply, especially when contradicting the domination of asteroid populations by C-type asteroids?

Conclusion: Although our present knowledge on projectile population distribution and on the existence of periods with abnormal bombardment rates (e.g., the Late Heavy Bombardment, Early Ordovician, late Eocene) is incomplete, terrestrial and lunar projectile identification studies have unraveled a few simple trends that need to be confirmed and interpreted. Systematic application of one or more of the methodologies described above in all available impact material samples might give further hints about the nature of and the processes that take place in the asteroid belt.

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