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Geochimica et Cosmochimica Acta 183 (2016) 198–233

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Chemostratigraphy of the Sudbury impact basin fill: Volatile metal loss and post-impact evolution of a submarine impact basin

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Received 20 November 2015; accepted in revised form 3 April 2016; available online 8 April 2016

Abstract

The 1.85 Ga Sudbury structure provides a unique opportunity to study the sequence of events that occurred within a hydrothermally active subaqueous impact crater during the late stages of an impact and in its aftermath. Here we provide the first comprehensive chemostratigraphic study for the lower crater fill, represented by the ca. 1.4 km thick Onaping Formation. Carefully hand-picked ash-sized matrix of 81 samples was analysed for major elements, full trace elements and C isotopes.

In most general terms, the composition of the clast-free matrix resembles that of the underlying melt sheet. However, many elements show interesting chemostratigraphies. The high field strength element evolution clearly indicates that the crater rim remained intact during the deposition of the entire Onaping Formation, collapsing only at the transition to the overlying Onwatin Formation. An interesting feature is that several volatile metals (e.g., Pb, Sb) are depleted by >90% in the lower Onaping Formation, suggesting that the impact resulted in a net loss of at least some volatile species, supporting the idea of "impact erosion," whereby volatile elements were vaporised and lost to space during impact. Reduced C contents in the lower Onaping Formation are low (<0.1 wt%) but increase to 0.5–1 wt% up stratigraphy, where $\delta^{13}C$ becomes constant at −31‰, indicating a biogenic origin. Elevated Y/Ho and U/Th require that the ash interacted with saline water, most likely seawater. Redox-sensitive trace metal chemostratigraphies (e.g., V and Mo) suggest that the basin was anoxic and possibly euxinic and became inhabited by plankton, whose rain-down led to a reservoir effect in certain elements (e.g., Mo). This lasted until the crater rim was breached, the influx of fresh seawater promoting renewed productivity.

If the Sudbury basin is used as an analogue for the Hadean and Eoarchaean Earth, our findings suggest that hydrothermal systems, capable of producing volcanogenic massive sulphides, could develop within the rims of large to giant impact structures. These hydrothermal systems did not require mid-ocean ridges and implicitly, the operation of plate tectonics. Regardless of hydrothermal input, enclosed submarine impact basins also provided diverse isolated environments (potential future oases) for the establishment of life.

Keywords: Submarine impact; Hydrothermal environment; Sudbury; Volatile loss; Origin of life

1. INTRODUCTION

The role of large to giant meteorite impacts on terrestrial geology is an area of long-standing interest (e.g., Maher and Stevenson, 1988; Elkins-Tanton et al., 2004). One significant question concerns the flux of meteoritic material

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http://dx.doi.org/10.1016/j.gca.2016.04.007
0016-7037/

brought to the Earth during the late phases of planetary accretion, particularly with respect to the platinum group elements (PGEs), which display highly distinctive chondritic signatures (e.g., Petrus et al., 2015a), and water, which is thought to have originated in part from extraterrestrial sources during all stages of planetary accretion (e.g., Morbidelli et al., 2000). Kimura et al. (1974) discovered a discrepancy between the absolute and relative abundances of siderophile elements in the Earth's mantle compared to experimental data regarding their sequestration into the metallic core. These authors proposed that a "late veneer" of meteoritic material was added to the upper mantle inventory of siderophile elements. This delivery could have occurred during the cataclysmic Late Heavy Bombardment between 4.0 and 3.8 Ga (Maier et al., 2009), in a relatively lower temperature and lower energy regime than earlier planetary accretion. It is therefore possible that these giant impactors also delivered volatile species, including water and carbon, both essential for the construction and evolution of our planet's hydrosphere and biosphere (e.g., Kleine, 2011).

A second area of interest concerning meteorite impacts is the evolution of life. Popular ideas for the origin of life centre around the chemical evolution and synthesis of organic molecules in subaqueous environments such as warm lakes or lagoons, or in particular in hydrothermal springs near mid ocean ridge systems (Lazcano et al., 1983; Baross and Hoffman, 1985). The discovery of "Lost City"-type hydrothermal systems, found several kilometres away from mid ocean ridges with ultramafic chemical compositions has promoted comparisons with the putative primordial ocean floor (e.g., Kelley et al., 2005). However, these systems too implicitly assume operation of plate spreading. The high hydrostatic pressure of subaqueous environments is favourable to the spontaneous synthesis of organic molecules, and excludes harmful solar or cosmic radiation (e.g., Daniel et al., 2006 and references therein). It has long been known that carbonaceous chondrites of the CI and CM group, and more recently comets (Goesmann et al., 2015), contain a variety of organic compounds (e.g., Cloëz, 1864) including glycine, β-alanine and γ-amino-n-butyric acid (Ehrenfreund et al., 2001). The influx of meteoritic material to the Earth during the late stages of planetary accretion possibly delivered both sufficient amounts of these essential building blocks and the energy necessary for the synthesis of complex organic molecules (e.g., Chyba et al., 1990). However, it has also been speculated that the energy delivered by giant impacts was sufficient to heat the atmosphere to a point that would sterilise the planet. For example, impactors 250 km in diameter could deliver enough energy to sterilise the entire planet including the deep oceans (Maher and Stevenson, 1988; Sleep et al., 1989). Recent investigations indicate that impact induced boiling and evaporation of the early oceans may have continued until at least as late as 3.25 Ga (Lowe and Byerly, 2015). It seems probable that the energy delivered from large (>65 km diameter) or giant (>250 km diameter) meteorite impacts would have eradicated life from at least the surface of the Earth repeatedly, only to be re-established in another location by the remnant extremophiles that survived the previous event (Maher and Stevenson, 1988; Abramov and Kring, 2004). Stüeken et al. (2013) discussed the difficulty of combining all the necessary factors for the synthesis of organic molecules into one single environment on the Hadean surface. In this context, the role of impact basins have remained underexplored, largely because of the paucity of such structures on the modern Earth surface.

In the existing literature, research has largely focused on the study of impact ejecta layers, deposited outside the impact structure. For example, most of the knowledge regarding the consequences of the Chicxulub impact event come from the study of time-equivalent sediments rather than from data of the buried structure itself (e.g., Alvarez et al., 1980) with only a few studying drill core data of the impact fill (e.g., Keller et al., 2004). Recently, Petrus et al. (2015a) presented the first detailed account of the distribution of meteoritic signatures within the crater fill of the ca. 1.85 Ga Sudbury structure. The current paper builds on the study of Petrus et al. (2015a) by providing the first comprehensive chemostratigraphic study for a large impact basin fill, for use as an analogue for the effects of Hadean impact events on the development of early life.

2. GEOLOGICAL SETTING AND RELEVANT PREVIOUS WORK

The roughly 60 km × 30 km Sudbury impact structure, Ontario, Canada, is a topic of long-standing controversy. Originally it was believed to be of igneous origin (e.g., Muir, 1984), due to the presence of the differentiated igneous body known as the Sudbury Igneous Complex (SIC), the evidence for the presence of hydrothermal activity (e.g., Ames et al., 1998, 2006), and many volcanic features in the immediate crater fill (e.g., Ames et al., 2002). However, more recent studies have led to the consensus (e.g., Grieve, 1994) that the structure is the remnant of an originally much larger circular multi-ring impact basin with a diameter of between 150 and 260 km (Pope et al., 2004). Structural comparison with the lunar crater classifications of Baker and Head (2013) suggests that the Sudbury structure may have originally resembled a protobasin or even a peak-ring basin depending on the unknown original size. Regardless of this classification, in this manuscript, the term 'crater' is used to refer to the geological structure generated by the meteorite impacts of any size, whereas the term 'basin' is used in a sedimentological sense, referring to the body of water hosted by the crater, creating an isolated depositional environment.

The impact occurred on the terrane boundary between the southernmost Superior Province and the Southern Province, dominated by granites, gneisses, metasediments and metavolcanics. The occurrence of carbonaceous clasts within the basin fill (Bunch et al., 1999) and the discovery of impact-generated surge deposits in the Gunflint Formation cherts (Addison et al., 2005, 2010) have supported the consensus that the target was subaqueous, possibly in the shallow foreland basin of the Penokean orogenic belt (e.g., Shanks and Schwerdtner, 1991). The remnant of the crater has been deformed into an ellipsoid-shaped syncline