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Chromium isotope evidence in ejecta deposits for the nature of Paleoproterozoic impactors

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ABSTRACT

Non-mass dependent chromium isotopic signatures have been successfully used to determine the presence and identification of extra-terrestrial materials in terrestrial impact rocks. Paleoproterozoic spherule layers from Greenland (Grænsesø) and Russia (Zaonega), as well as some distal ejecta deposits (Lake Superior region) from the Sudbury impact (1849 ± 0.3 Ma) event, have been analyzed for their Cr isotope compositions. Our results suggest that 1) these distal ejecta deposits are all of impact origin, 2) the Grænsesø and Zaonega spherule layers contain a distinct carbonaceous chondrite component, and are possibly related to the same impact event, which could be Vredefort (2023 ± 4 Ma) or another not yet identified large impact event from that of similar age, and 3) the Sudbury ejecta record a complex meteoritic signature, which is different from the Grænsesø and Zaonega spherule layers, and could indicate the impact of a heterogeneous chondritic body.

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1. Introduction

The Earth has been subjected to numerous large impacts since its accretion (i.e., the giant impact related to the origin of the Moon, the Late Heavy Bombardment), but little evidence of its bombardment history is preserved in modern geologic records (e.g., Koeberl, 2006a, 2006b). About 190 impact structures have so far been confirmed on the Earth's surface, but very few date to the Paleoproterozoic or older. In contrast to remote sensing and other geophysical methods, the confirmation of impact structures on Earth requires the detection of either shock metamorphic effects in minerals and rocks, and/or the presence of a meteoritic component in these rocks. Apart from studying meteorite impact craters directly, information can also be gained from the study of impact ejecta. These are layers of melted and shocked rock or mineral fragments, including millimeter- to centimeter-sized impact spherules and glasses (such as tektites) that form from melt and vapor condensate droplets, as well as accretionary lapilli (Glass and Simonson, 2012). In the absence of meteorite fragments, the presence of a meteoritic component within the target rocks can be verified by measuring abundances and inter-element ratios of siderophile elements (e.g., Cr, Co, Ni), and especially the Platinum Group Elements (PGE), which are orders of magnitudes more abundant in meteorites than in terrestrial crustal rocks (Koeberl et al., 2012). The Re–Os isotopic method is also traditionally used for the detection of iron meteorite and chondritic material because they have a different $^{187}Os/^{188}Os$ ratio from the Earth's crust (Koeberl, 2014). However, all these methods are not sufficient to distinguish between chondrite types. The Cr isotope method allows a better identification of the type of meteoritic material involved because well-resolved Cr isotopic differences do exist between meteorites (Shukolyukov and Lugmair, 1998; Trinquier et al., 2007; Moynier et al., 2009). The Cr isotopic composition of each chondrite group is distinct; and while the $^{54}Cr/^{52}Cr$ ratio of some achondrites overlaps with that of chondrites (e.g., eucrites and ordinary chondrites, (Fig. 1) (Trinquier et al., 2007), it is possible to distinguish them from one another by coupling $^{53}Cr/^{52}Cr$ and $^{54}Cr/^{52}Cr$ ratios (Fig. 2). This approach has been successfully used for the identification of the impactors involved in the formation of the Morokweng, Bosumtwi, Clearwater, Lappajärvi, and Rochechouart (Koeberl et al., 2007) impact structures, as well as for ancient ejecta layers (e.g., Trinquier et al., 2006; Quitté et al., 2007; Kyte et al., 2003, 2011).

Evidence for the bombardment of the Earth (i.e., impact structures and ejecta) between 1.6 Ga and 2.5 Ga is rare. Only three distal impact ejecta layers, namely the Grænsesø (South Green-

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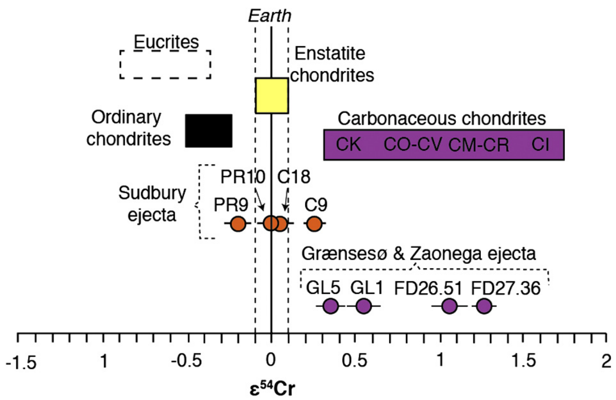

Fig. 1. ε^{54}Cr values measured in Sudbury ejecta (Pine River and Coleraine drill cores), and Zaonega and Grænsesø spherule deposits (see legend of Table 1 and text for details) compared to eucrites, enstatite, ordinary, and carbonaceous chondrites (Meteorite data compilation from Göpel et al., 2015).

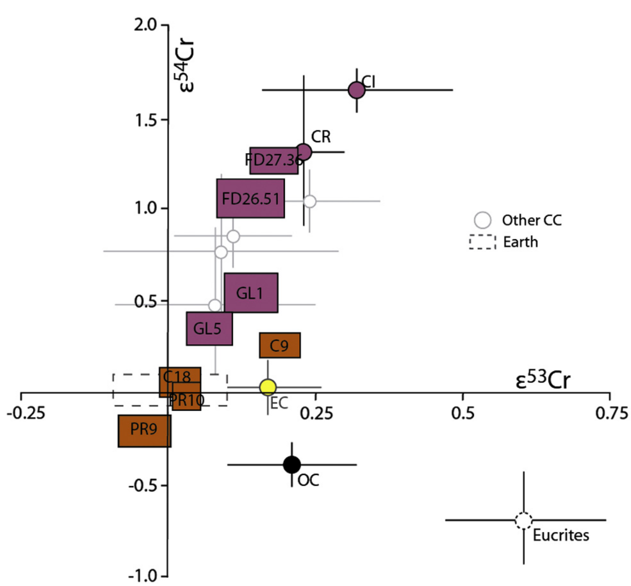

Fig. 2. ε^{53}Cr versus ε^{54}Cr plot. Comparison of Pine River, Coleraine, Zaonega and Grænsesø ejecta samples (rectangles) compared to the average compositions (adapted from Foriel et al., 2013) of chondrites (circles), eucrite (dotted circle) and the Earth (dashed rectangles).

land) and Zaonega (Karelia, North West Russia) spherule layers, and the Sudbury layer in the lake Superior region ejecta (North America) have been recognized. The ages of these deposits range from 1830 ± 3 Ma to 2130 ± 65 Ma, and brackets the ages of the two largest and oldest terrestrial impact structures presently found at the surface of the Earth, Vredefort (2023 ± 4 Ma; Kamo et al., 1996) and Sudbury (1849 ± 0.3 Ma; Krogh et al., 1984) (Turtle et al., 2005). However, there is no geochemical evidence that links the ejecta in Greenland and Russia to one of these events, or other large undiscovered or totally eroded impact event(s). Here, we investigate the Cr isotopic composition of samples from these ejecta layers in order to identify the nature of the impactors, as well as to discuss the possible relationships between these layers, and their link with the Sudbury and Vredefort impact structures. Specifically, we analyzed orphan spherule layers from Greenland and Russia, and confirmed distal ejecta deposits (Lake Superior region, Canada) from the Sudbury impact event (Chadwick et al., 2001; Koeberl et al., 2002; Huber et al., 2014a, 2014b; Petrus et al., 2015). Our results provide new evidence for an impact origin of these ejecta deposits, and therefore, the sources of bombardment of the Earth at around 2 Ga.

2. Samples and methods

2.1. Paleoproterozoic ejecta layers

Layers interpreted as ejecta from the Sudbury event have been recognized at more than 15 sites in the Lake Superior area (e.g., Addison et al., 2005; Cannon et al., 2010). Many arguments support the idea that they are all products of a single impact: 1) Their similarities in geological characteristics; 2) the regional persistence of the layers at a constant stratigraphic level atop the main local iron formations (Fig. S1); 3) their major and trace element chemical composition closer to that of the "Onaping" melts in Sudbury structure than to any local rocks in the Lake Superior region (Cannon et al., 2010); 4) the regional variations in thickness and petrographic content of the layers consistent with their distances from the current crater location (Cannon et al., 2010); 5) the well-known age of the Sudbury impact close to the estimated depositional age of the layers; and 6) the fact that no other contemporaneous impact structure has yet been found, neither other ejecta layer at any of the sites where the Sudbury ejecta layer was already observed.

The detection of a meteoritic component in rocks from Sudbury is supported by the geochemical studies of both the crater's rocks and ejecta layers (e.g., Pufahl et al., 2007; Cannon et al., 2010). More geochemical evidence for the composition of the Sudbury impactor recently came from the signature of PGE advocating a meteoritic, and more specifically a chondritic origin (Huber et al., 2014b; Petrus et al., 2015).

The Grænsesø spherule layer is the least studied layer among the three described here. It is located in the Ketilidian orogeny (South Greenland) and composed of spherules within a dolomite layer that constitutes the upper part of the Paleoproterozoic metasedimentary Vallen group. Spherules represent more than 15% of the total volume of the layer, at least locally the rest being carbonates, chert clasts, and epiclastic sand grains (Chadwick et al., 2001). Despite the absence of evidence for shock features, Chadwick et al. (2001) re-interpreted their origin based on a detailed textural analysis of individual spherules, and presented evidence for an impact origin rather than resulting from a volcanic or biological activity. The spherules are generally larger (∼1 mm) than possible spherulitic fossils (∼0.3 mm), and their shapes are more circular than volcanic spherules that tend to be on average more elongated (Heiken and Wohletz, 1985). Provided that the impact origin is confirmed, this layer must have been associated with a large impact event because of the high abundance of spherules and estimated thickness of the layer (Chadwick et al., 2001). Based on the ages of the intrusions that crosscut the basement and the ejecta layer, the age of the layer is loosely constrained between 1848 ± 3 Ma and 2130 ± 65 Ma (Chadwick et al., 2001; Garde et al., 2002). This time interval is concordant with the ages of both the Vredefort and Sudbury impact structures but too broad to infer a direct link with one of them. Moreover, there is no geochemical evidence yet for the presence of a meteoritic component in this layer. The only bulk rock composition published so far (Chadwick et al., 2001) shows very slight PGE enrichments compared to the average composition of the continental crust, and PGE patterns different from those of Sudbury ejecta (Fig. 3).

Recently, a similar spherule layer was discovered in the Paleoproterozoic Zaonega formation in Karelia (North West Russia), which represents supplementary physical evidence for a ∼2 Ga impact event. The spherules are enriched and distributed into multiple layers in the drill cores, suggesting that the ejecta were disturbed during and/or after its initial deposition (Huber et al., 2014a). This spherule layer shows structural similarities with the Grænsesø spherule deposits. Like the Grænsesø layer, this layer is hosted in dolostones, whose depositional age is constrained be-

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