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Determining the impactor of the Ordovician Lockne crater: Oxygen and neon isotopes in chromite versus sedimentary PGE signatures

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ABSTRACT

Abundant chromite grains with L-chondritic composition in the resurge deposits of the Lockne impact crater (458 Myr old; dia. ~10 km) in Sweden have been inferred to represent relict fragments of an impactor from the break-up of the L-chondrite parent body at 470 Ma. This view has been challenged based on Ir/Cr and platinum group element (PGE) patterns of the same resurge deposits, and a reinterpretation of the origin of the chromite grains. An impactor of the non-magmatic iron meteorite type was proposed instead. Here we show that single-grain oxygen and noble-gas isotope analyses of the chromite grains from the resurge deposits further support an origin from an L-chondritic asteroid. We also present PGE analyses and Ir/Cr ratios for fossil L-chondritic meteorites found in mid-Ordovician marine limestone in Sweden. The L-chondritic origin has been confirmed by several independent methods, including major element and oxygen isotopic analyses of chromite. Although the meteorites show the same order-of-magnitude PGE and Cr concentrations as recent L chondrites, the elements have been redistributed to the extent that it is problematic to establish the original meteorite type from these proxies. Different PGE data processing approaches can lead to highly variable results, as also shown here for the Lockne resurge deposits. We conclude that the Lockne crater was formed by an L-chondritic impactor, and that considerable care must be taken when inferring projectile type from PGEs in sedimentary ejecta deposits.

1. Introduction

Abundant fossil, L-chondritic meteorites in marine limestone from a mid-Ordovician (470 Ma) quarry in Sweden, and a two order-of-magnitude increase in L-chondritic micrometeorites in sedimentary strata of the same age worldwide, provide strong evidence for a breakup of the L-chondrite parent body in the asteroid belt at that time (Cronholm and Schmitz, 2010; Heck et al., 2010; Schmitz et al., 1996, 2001, 2008). Already in the 1960s the young K-Ar gas retention ages of many recently fallen L chondrites were inferred to reflect a major parent-body breakup event at around 500 Ma (Anders, 1964). Recently, refined ^{40}Ar/^{39}Ar measurements of L chondrites indicate an age of 470 ± 6 Ma for the event, which is the same age as for the sediments rich in L-chondritic material (Korochantseva et al., 2007). Although there is robust evidence for a dramatic increase in the flux of micrometeorites and meteorites to Earth for a few million years after the breakup event, model predictions of a coeval increase in the flux of larger L-chondritic asteroids to Earth are more difficult to test (Zappalà et al., 1998). Prominent changes around 470 Ma in Earth's fauna, such as the onset of the Great Ordovician Biodiversification Event (Schmitz et al., 2008), as well as an order-of-magnitude overrepresentation of mid-Ordovician impact craters among Earth's well-dated craters (Schmitz et al., 2001) give some support for an asteroid shower. More robust evidence, however, must come from studies of impact ejecta layers in the geological record, and from identifying the type of impacting projectiles. The problem is that large projectiles tend to become completely vaporized upon impact, leaving behind only a chemical fingerprint that may be fractionated by various processes and thus difficult to interpret. In rare cases pieces of the impactor are preserved, like in the Eltanin or Morokweng impact events (Kyte, 2002; Maier et al., 2006), allowing safe identification of projectile type. For one mid-Ordovician impact crater, the well-preserved, ca. 10 km diameter Lockne crater (458 Ma) in central Sweden, Alwmark and Schmitz (2007) reported an extreme enrichment of extraterrestrial chromite grains in the resurge deposits, the so called Loftarstone. More than 75 extraterrestrial chromite grains per kg of Loftarstone were found, which is three to four orders of

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magnitude more grains than in normal marine limestone. The chromite grains have an L-chondritic element composition and hence were interpreted as relict fragments of an impactor related to the 470 Ma L-chondrite breakup event. Tagle et al. (2008) challenged this view based on Ir/Cr and platinum group element (PGE) ratios of the Loftarstone, as well as a reinterpretation of the compositional signature of the chromite grains. They suggested that the impactor was a non-magmatic iron meteorite (NMI). This is a viable suggestion considering that PGE signatures of sedimentary ejecta have been shown to be usable under some conditions to identify projectile types (e.g., Evans et al., 1993).

In order to further constrain the origin of the Lockne crater we present here single-grain oxygen and noble gas isotopic data for the purported L-chondritic chromite grains from the Loftarstone. High precision oxygen isotopic analyses of fossil extraterrestrial chromite have proven to be a reliable method to identify precursor meteorite types (Greenwood et al., 2007; Heck et al., 2010). Neon isotopes can discern if an extraterrestrial chromite grain originates from a micrometeorite (solar-wind implanted Ne), meteorite (cosmic-ray Ne) or the interior of an extraterrestrial body with a size greater than the penetration depth (>ca. 2 m) of galactic cosmic rays (Heck et al., 2008; Meier et al., 2010). We also present PGE and Ir/Cr data for mid-Ordovician fossil meteorites for which the L-chondritic origin has been confirmed based on independent proxies, e.g. oxygen isotopes, element composition and silicate inclusions in chromite, and petrography including chondrule appearances. In light of these data we discuss the utility of PGE patterns in sediments for determining impactor types.

2. Materials and methods

The chromite grains (ca. 63–100 μm in diameter) studied here originate from the two Loftarstone samples FF2 and FF4 collected at the edge of the inner Lockne crater (see fig. 1 in Sturkell, 1998, for sample locations). The samples contain 2.5 and 2.0 ppb Ir, respectively (Sturkell, 1998). Alwmark and Schmitz (2007) recovered abundant extraterrestrial chromite grains from sample FF2, however, because of shortage of this material 50 g of sample FF2 and 300 g of sample FF4 were used for the present study. The procedure of recovering grains was the same as in Alwmark and Schmitz (2007) except that the HCl- and HF-leached residue fractions were not heated to remove coal, because this could have an effect on the noble gases.

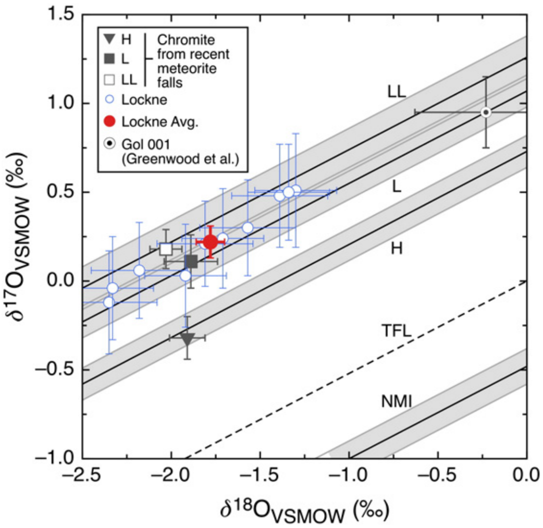

Fig. 1. Oxygen-three-isotope diagram. Loftarstone chromite individual analyses (open circles) are shown with 2 SD error bars. The weighted Loftarstone average (solid circle) is shown with its weighted average error based on individual 2 SD errors. Gol 001 is a bulk analysis of ca. 100 chromite grains shown with 2 SD error bars from the fossil meteorite Österplana 029 (Gol 001) reported by Greenwood et al. (2007). Chromite data from recent ordinary chondrites (triangle and box symbols) are weighted averages of SIMS data from Heck et al. (2010). Mass-dependent fractionation lines are shown for terrestrial samples (TFL; dashed line), for average compositions of group H, L and LL bulk ordinary chondrites (Clayton et al., 1991) and NMI meteorites (Clayton and Mayeda, 1996) (solid lines) and their standard deviations (shaded boxes).

Seven chromite grains with L-chondritic element composition according to Alwmark and Schmitz (2007) were selected from the Loftarstone for O isotope analysis, using a CAMECA IMS-1280 ion microprobe at the WiscSIMS Laboratory, University of Wisconsin–Madison (Kita et al., 2009). The grains were mounted in the center of 25 mm epoxy plugs with chromite standards UWCr-2 and UWCr-3 and polished to a flat low-relief surface (Heck et al., 2010). We performed oxygen-three-isotope analyses on the grains using the same instrument setup and analytical conditions as in the approach optimized for chromite analyses by Heck et al. (2010). The primary ion beam at 5 nA intensity was focused to a 15 μm spot. In total 10 analyses, bracketed by standard analyses, were obtained on the chromite grains. We are able to achieve precisions of ≤0.3‰ (2 SD) for $\delta^{18}O$ and $\delta^{17}O$ and ~0.2‰ for $\Delta^{17}O = (\delta^{17}O - 0.52 \times \delta^{18}O)$ from single spot analysis. The contribution of OH^- interference to $^{17}O^-$ was typically less than 0.1‰ and the uncertainties of the correction on $^{17}O/^{16}O$ ratios were insignificant (<0.05‰). This precision is sufficient to distinguish H versus L or LL chondrites. Values of $\Delta^{17}O$ from chromite grains from recently fallen H, L and LL chondrites, analyzed during the same session and reported by Heck et al. (2010), fell onto $\Delta^{17}O$ group averages obtained from bulk meteorite fluorination analysis (Clayton et al., 1991), and demonstrate the reliability of our analytical method (Fig. 1). The seven polished grains were also analyzed for major and minor elements with a CAMECA SX-51 electron probe microanalyzer (EPMA) at UW–Madison. For further details on the SIMS and EPMA procedures, see Heck et al. (2010).

In addition six L-chondritic chromite grains from the Loftarstone, each grain weighing between 1 and 4 μg, were analyzed for cosmogenic ^3He and ^{21}Ne at ETH-Zürich. As the amount of cosmogenic noble gases was expected to be very small, due to the small size of the grains, an ultra-high-sensitivity mass spectrometer and a low-blank extraction line were used for the measurements. The mass spectrometer concentrates gases into the ion source by a molecular drag pump (compressor), which gives a ca. two orders of magnitude higher sensitivity than the same instrument without a compressor ion source (Baur, 1999). Detection limits were $\sim 4 \times 10^{-16}$ cm^3 STP for ^{21}Ne and $\sim 2 \times 10^{-16}$ cm^3 for ^3He, and are defined as the 2σ scatters of the blank. For further details on the instrument, analytical procedures and calculations, see Heck et al. (2004, 2008) and Meier et al. (2010).

The selection of the 13 chromite grains discussed above was based on semi-quantitative element analyses of unpolished, whole grains, using an energy-dispersive spectrometer (Inca X-sight from Oxford Instruments) with a Si detector, mounted on a Hitachi S-3400 scanning electron microscope at Lund University. Cobalt was used for standard, see Alwmark and Schmitz (2009a) for further details. The analyses are mostly of sufficient quality to determine if a grain has an ordinary chondritic composition. Grains were discarded if there was any doubt of a chondritic origin.

Whole-rock samples (ca. 40–70 mg) of fossil L chondrites from mid-Ordovician marine limestone in Sweden (Schmitz et al., 2001) were analyzed for PGEs at Woods Hole Oceanographic Institution by isotope dilution with ICP-MS after NiS fire assay preconcentration according to methods described in Hassler et al. (2000) and Peucker-Ehrenbrink et al. (2003). The following meteorites were analyzed: Österplana 003, 008, 009, 019, 027, 032, 035 and Gullhögen 001 (Connolly et al., 2007). Concentrations were calculated using one (Ir), two (Ru, Pd, Pt), or three (Os) isotope ratios, and concentrations based on multiple ratios typically agree to better than 10% (Ru) and 5% (Pd, Pt). External reproducibility of PGE data was investigated by multiple analyses of standard reference materials (SRM) with certified PGE concentrations