

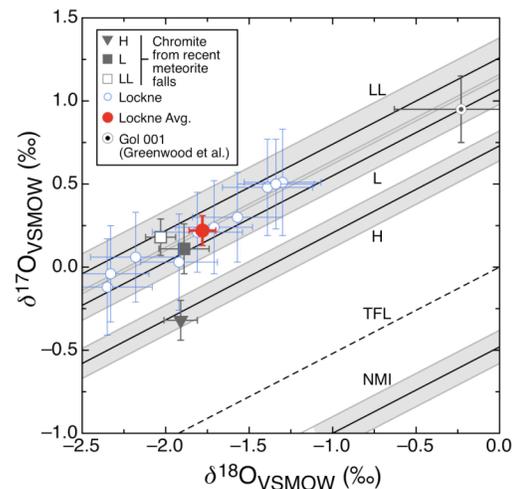
**DETERMINING THE IMPACTOR OF THE ORDOVICIAN LOCKNE CRATER: OXYGEN ISOTOPES IN CHROMITE VERSUS SEDIMENTARY PGE SIGNATURES** B. Schmitz<sup>1,3</sup>, P. R. Heck<sup>2</sup>, C. Alwmark<sup>1</sup>, N. T. Kita<sup>2</sup>, B. Peucker-Ehrenbrink<sup>3</sup>, T. Ushikubo<sup>2</sup>, and J. W. Valley<sup>2</sup>, <sup>1</sup>Department of Geology, Sölvegatan 12, Lund University, SE-22362 Lund, Sweden, birger.schmitz@geol.lu.se, <sup>2</sup>Department of Geology and Geophysics, University of Wisconsin, 1215 W. Dayton St., Madison, WI 53706, USA, <sup>3</sup>Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA.

**Introduction:** There are two recent opposing views on the type of impactor that created the well-preserved, ca. 10 km-in-diameter Lockne crater (458 Ma) in central Sweden [1, 2]. Abundant extraterrestrial chromite grains (ca. 75 per kg) with L-chondritic element composition in the Lockne crater resurge deposits (Loftarstone) indicates that the impact was related to the 470 Ma break-up of the L-chondrite parent body [1]. The other view, based on Ir/Cr and platinum group element (PGE) ratios of the same resurge deposits, as well as a reinterpretation of the compositional signature of the chromite grains studied by [1], suggests that the impactor was a non-magmatic iron meteorite (NMI) [2]. Here we present SIMS oxygen isotopic data for the extraterrestrial chromite from the Loftarstone in order to further constrain its origin. We also discuss the (un)reliability of PGE patterns in sediments for determining impactor types. We present PGE and Ir/Cr data for mid-Ordovician fossil meteorites with a confirmed L-chondritic origin, based on, e.g., oxygen isotopes and silicate inclusions in chromite, chromite element composition and chondrule sizes.

**Materials and methods:** Seven chromite grains with L-chondritic element composition according to [1] were selected from the Loftarstone for O isotope analysis. The grains were mounted on epoxy with a chromite standard UWCr-2 and polished. We performed 10 three-O-isotope analyses on the grains with the WiscSIMS Cameca IMS-1280 ion microprobe [3, 4]. We are able to achieve precisions of  $\leq 0.3\text{‰}$  for  $\delta^{18}\text{O}$  and  $\delta^{17}\text{O}$  and  $\leq 0.15\text{‰}$  for  $\Delta^{17}\text{O}$  ( $=\delta^{17}\text{O}-0.52 \times \delta^{18}\text{O}$ ) from single spot analysis. The uncertainties of the OH interference correction were insignificant ( $< 0.05\text{‰}$ ). This precision is enough to distinguish H from L and LL chondrites, see [3, 4]. Samples of fossil meteorites were analysed for PGEs at WHOI by isotope dilution with ICP-MS after NiS fire assay pre-concentration according to methods described in [5, 6].

**Oxygen isotopes:** The oxygen isotope results for the chromite grains from the Loftarstone are compared with oxygen isotope results for recently fallen H, L and LL meteorites in Fig. 1. It is clear that the Loftarstone grains show typical L or possibly LL composition. The grains also show the same oxygen isotopic composition as chromite grains from the fossil Österplana meteorites. Values of  $\Delta^{17}\text{O}$  from chromite grains from modern H, L and LL chondrites analyzed with identical conditions fall onto  $\Delta^{17}\text{O}$  group averages [7] and

demonstrate the reliability of our analytical method. The  $\Delta^{17}\text{O}$  data for the Loftarstone chromite show little variability ( $0.05\text{‰}$  1 SD;  $n=10$ ) and average at  $1.15 \pm 0.04\text{‰}$  (weighted average based on individual 2 SD errors). This is consistent with  $\Delta^{17}\text{O}$  of chromite from modern Ergheo L5 fall ( $1.09 \pm 0.07\text{‰}$ , weighted average as above), and with the  $\Delta^{17}\text{O}$  group average of modern L or LL chondrites ( $1.07 \pm 0.09\text{‰}$  1 SD;  $n=26$ ;  $1.26 \pm 0.12\text{‰}$  1 SD, respectively, [7]). Oxygen isotope ratios of the Loftarstone chromite grains lie on a mass-dependent fractionation line beyond the analytical uncertainty, while the weighted average is similar to that of Ergheo L5 (Fig. 1). No correlation of  $\delta^{18}\text{O}$ ,  $\delta^{17}\text{O}$ , or  $\Delta^{17}\text{O}$  with any measured element concentration was observed. The  $\Delta^{17}\text{O}$  value of the Loftarstone grains ( $1.15 \pm 0.04\text{‰}$ ) is clearly distinct from  $\Delta^{17}\text{O}$  of NMI meteorites ( $-0.48 \pm 0.10\text{‰}$ ; 1 SD;  $n=23$ ; [8]; Fig. 1).

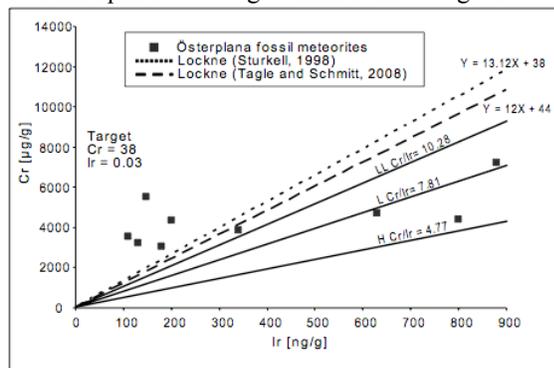


**Fig. 1:** Three-O-isotope diagram. Loftarstone chromite individual analyses (open circles) are shown with 2 SD error bars. The weighted Loftarstone average (solid circle) is shown with its weighted average error based on individual 2 SD errors. Gol 001 is a bulk analysis of ca. 100 chromite grains shown with 2 SD error bars from the fossil meteorite Österplana 029 (Gol 001) reported by [9]. Chromite data from recent ordinary chondrites (triangle and box symbols) are weighted averages of SIMS data from [3]. Mass-dependent fractionation lines are shown for terrestrial samples (TFL; dashed line), for average compositions of group H, L and LL ordinary chondrites [7] and NMI meteorites [8] (solid lines) and their standard deviations (shaded boxes).

**Chromium and PGEs:** The Ir/Cr ratios of Loftarstone bulk sediment samples were plotted by [2], and mixing lines assuming a two-component-mixing between target rock and impactor were compared to chondrite-target rock mixing lines. It was argued that

the Loftarstone mixing line deviates significantly from those with a chondritic impactor, supporting rather a NMI impactor. In Fig. 2 we have plotted the Ir and Cr contents of six mid-Ordovician fossil meteorites [10, 11] compared to the impactor-target rock mixing lines used by [2]. The figure shows that the more weathered outer parts of the fossil meteorites generally have significantly lower Ir/Cr ratios than the central parts with higher content of PGEs. This shows that Ir is generally more easily mobilized than Cr during diagenesis. The Ir/Cr ratios also vary substantially within and between the fossil meteorites. Different precursor meteorite groups would be implicated depending on the extent of diagenetic alteration of a particular sample.

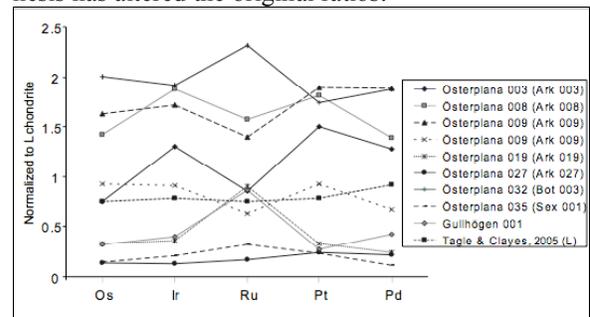
The Loftarstone is basically a mix of three components, impactor, crustal igneous rock and marine limestone, each with a different Ir/Cr ratio, see [10]. Taking also this in consideration may have significant effects on the slopes of mixing lines such as in Fig. 2.



**Fig. 2:** Ir and Cr content of nine samples from fossil L-chondritic meteorites Öst 001, 007, 009, 011, 030, and 036, compared with mixing lines by [2] for assumed two component mix between target rock and impactor for the Loftarstone based on two data sets. Included in the figure are also expected mixing lines with different chondritic impactors, following [2] and [12]. Slopes for the Loftarstone mixing lines were based on Ir contents <4.5 ppb, whereas fossil meteorites contain 100-880 ppb Ir.

We show in Fig. 3 that the PGE patterns of eight confirmed L-chondritic fossil meteorites with Ir contents in the range 61-939 ppb give highly variable PGE patterns, with no or only little resemblance to the patterns of recent unweathered L chondrites. It would not have been possible to establish the L-chondritic origin of the fossil meteorites from the PGE patterns, despite the fact that much of the original PGEs are preserved. As a central argument for a NMI impactor of the Lockne crater, [2] uses the Ru/Ir ratio measured in the Loftarstone. They show that recent L chondrites have ratios in the range between 1.42 and 1.62, and that the corresponding ratio in the Loftarstone lies at  $2.00 \pm 0.11$ , outside the L-chondritic range but in accord with a NMI impactor. The Ru/Ir ratios of the eight fossil L chondrites in Fig. 3 vary between 1.00 and 3.83, none of the ratios fall in the range for recent L

chondrites. Despite preserved high PGE content diagenesis has altered the original ratios.



**Fig. 3:** L-chondrite normalized PGE patterns for nine samples from fossil L-chondritic meteorites Öst 003, 008, 009, 019, 027, 032, 035 and Gul 001. Recent L-chondrite data from [12] and [13].

**Discussion:** Only for very few craters larger than 1.5 km has the impactor type been established, mainly because physical pieces of the impactors generally are missing (see [1, 2, 13]. The extremely abundant chromite grains with L-chondritic composition in the Loftarstone were interpreted by [1] as representing relict physical fragments of an impactor in relatively deep water. Using a grossly exaggerated scale when presenting the same chromite element data, [2] questioned the L-chondritic origin of the grains, but suggested no other likely origin of the grains. In [1] it is discussed that the chromite in the Loftarstone sometimes shows minor deviations from a typical L-chondritic composition, related to hydrothermal alteration of the grains after the impact, but on the whole the majority of the grains still reveal a clear L-chondritic origin, as now also confirmed by O-isotopic analyses. The NMI meteorites do not contain common chromites of the type found in the Loftarstone [14].

**Conclusions:** Oxygen isotopes confirm that the abundant extraterrestrial chromite grains in the Loftarstone are L (or LL) chondritic (see [1]). The isotopic results are clearly incompatible with NMI composition. Analyses of Cr and PGEs of fossil L-chondritic meteorites show that meteoritic elemental ratios in ancient sedimentary environments are altered to an extent that they can not be used for detailed assessment of precursor meteorite group. The claim by [2] that the Lockne crater was caused by an NMI impactor lacks substance entirely. The Lockne crater is likely related to the L-chondrite parent body breakup at 470 Ma.

**References:** [1] Alwmark C. and Schmitz B. (2007) *EPSL* 253, 291 [2] Tagle R. and Schmitt R.T. (2008) *LPS XXXIX*, Abs. #1418 [3] Heck P. R. et al. (2009) *LPS XL*, this vol. [4] Kita N. T. et al. (2009) *Chem. Geol.*, submitted [5] Hassler D. et al. (2000) *Chem. Geol.* 166, 1 [6] Peucker-Ehrenbrink B. et al. (2003) *G<sup>3</sup>* doi 10.1029/2002GC000414 [7] Clayton R. N. et al. (1991) *GCA* 55, 2317 [8] Clayton R. N. and Mayeda T. K. (1996) *GCA* 60, 1999 [9] Greenwood R. C. et al. (2007) *EPSL* 262, 204 [10] Schmitz B. et al. (1996) *EPSL* 145, 31 [11] Schmitz B. et al. (1997) *Science* 278, 88 [12] Wasson J. T. and Kallemeyn G.W. (1988) *PTRSL, Ser. A* 325, 535 [13] Tagle R. and Claeys P. (2005) *GCA* 69, 2877 [14] Bunch T.E. et al. (1970) *Contr. Mineral. Petrol.* 25, 297.