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A fossil winonaite-like meteorite in Ordovician limestone: A piece of the impactor that broke up the L-chondrite parent body?

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ABSTRACT

About a quarter of all meteorites falling on Earth today originate from the breakup of the L-chondrite parent body ~470 Ma ago, the largest documented breakup in the asteroid belt in the past ~3 Ga. A window into the flux of meteorites to Earth shortly after this event comes from the recovery of about 100 fossil L chondrites (1–21 cm in diameter) in a quarry of mid-Ordovician limestone in southern Sweden. Here we report on the first non-L-chondritic meteorite from the quarry, an 8 cm large winonaite-related meteorite of a type not known among present-day meteorite falls and finds. The noble gas data for relict spinels recovered from the meteorite show that it may be a remnant of the body that hit and broke up the L-chondrite parent body, creating one of the major asteroid families in the asteroid belt. After two decades of systematic recovery of fossil meteorites and relict extraterrestrial spinel grains from marine limestone, it appears that the meteorite flux to Earth in the mid-Ordovician was very different from that of today.

1. Introduction and background

Of the meteorites falling on Earth today about 85% are ordinary chondrites, divided based on iron and metal content into the H, L and LL groups. Among these the H and L groups make up 45% each, with the remainder being LL chondrites (Bevan et al., 1998). Since the 1960s it has been known that most of the L chondrites show shock features and K–Ar gas retention ages of ~470 Ma, reflecting that the parent body of these meteorites broke up in a major collisional event at this time (Anders, 1964; Keil et al., 1995; Bogard, 2011; Swindle et al., 2014). Backtracking the orbits of individual members of asteroid families shows that either the ~6000 member Flora or ~1000 member Gefion families may be the residual remains in the asteroid belt (Nesvorný et al., 2002, 2009; Kyte et al., 2011). The breakup has also left prominent traces in Earth's geological record. In 1993, following two chance finds of fossil meteorites in mid-Ordovician marine limestone in Sweden, a systematic search for such meteorites was initiated in the Thorsberg quarry in southern Sweden (Schmitz et al., 2001; Schmitz, 2013). In the quarry, mid-Ordovician limestone is sawed for production of floor plates, among other uses. The lithified sediments were deposited far from land and formed slowly, 2–4 mm Ka^{-1}. It is in the industrial process that the meteorites are recovered, and until today 101 meteorites, 1–21 cm in diameter, have been found, representing ~98% of all fossil meteorites known to science. The recovered meteorites fell over an area of ~20 000 m^2 of the sea floor during ~2 Ma. The limestone beds being sawed and yielding meteorites, however, represent <1 Ma of time. All meteorites except the one discussed in this paper are ordinary chondrites, and they are all (or almost all) L chondrites (Schmitz, 2013). Comparisons with the recent flux of meteorites indicate a flux at least one to two orders of magnitudes higher in the mid-Ordovician (Schmitz et al., 2001). This is also supported by the distribution in strata worldwide of sediment-dispersed, relict

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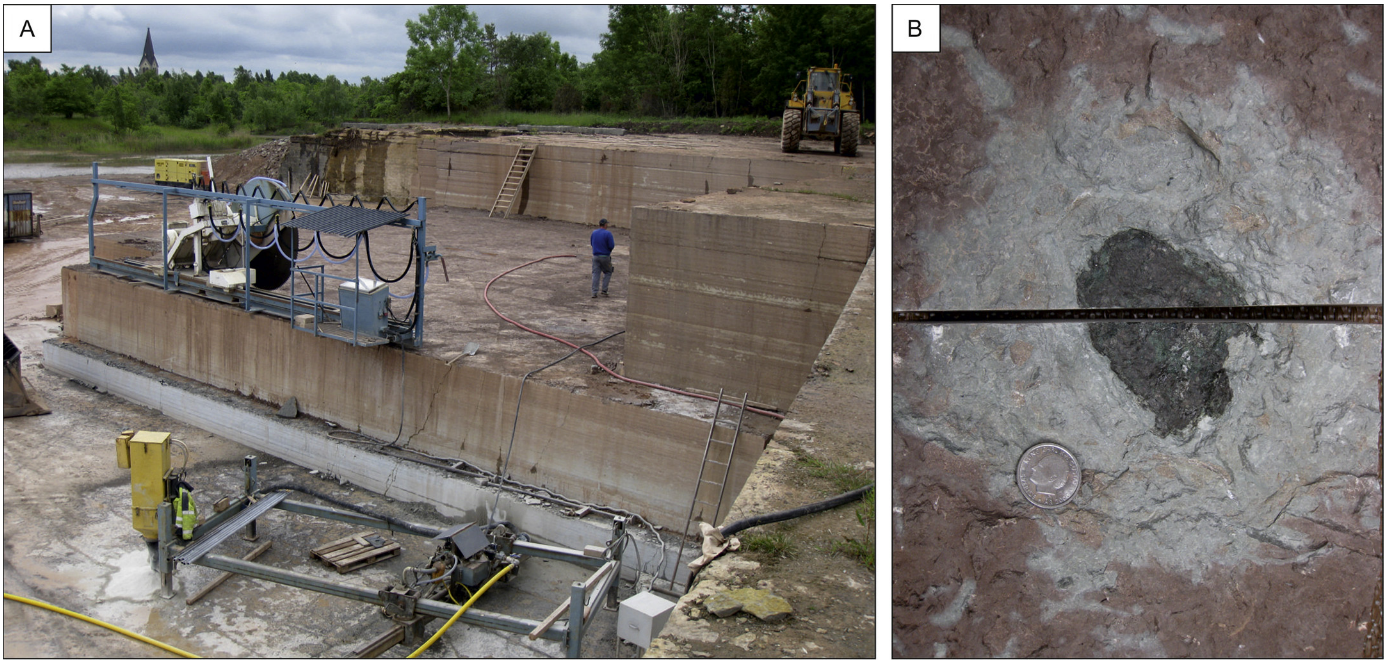

Fig. 1. The Thorsberg quarry and the Mysterious Object. (A) Thorsberg quarry on June 15, 2013. See Fig. 2 for names of different beds. The Österplana church is seen in the back. (B) The Mysterious Object from the Glaskarten 3 bed. The meteorite is 8 × 6.5 × 2 cm in size. It was found in the youngest quarried bed of the Thorsberg quarry, at the top of the section.

L-chondritic chromite grains (63–250 μm in diameter), representing the ancient flux of micrometeorites (Schmitz et al., 2003; Schmitz and Häggström, 2006; Heck et al., 2008, 2010; Cronholm and Schmitz, 2010; Meier et al., 2010, 2014; Lindskog et al., 2012; Schmitz, 2013).

In the collection of fossil meteorites there has until now been no second type of meteorite that could represent the impactor that hit the L-chondrite parent body. Neither do we know of any other type among recently fallen meteorites with gas retention ages of 470 Ma, similar to the L chondrites (Bogard, 2011). Establishing the character of the impactor could give insights about whether the breakup, and possibly also coeval environmental perturbations on Earth, are related to a large-scale astronomical event affecting the entire solar system (Schmitz, 2013). For example, if the impactor was a comet this could reflect a general perturbation of the orbits of Oort cloud comets and an increase in the comet flux to the inner solar system (Perryman, 2009). One would also expect that in the systematic recovery of fossil meteorites, sooner or later a meteorite representing the non-L-chondritic background flux would be found. On June 26, 2011 the quarry workers were removing limestone beds of low industrial quality from the upper part of their quarry. In the quarry's uppermost bed, Glaskarten 3, the quarry workers identified an 8 × 6.5 × 2 cm prominent gray clay inclusion as a fossil meteorite (Figs. 1–2). All fossil meteorites are almost completely replaced mainly by calcite and clay minerals, and spinel minerals are the only common relict components (Schmitz et al., 2001). Based on spinel analyses, it was soon obvious that this meteorite, with the working name Mysterious Object (MO), is of a completely different kind than the ordinary chondrite meteorites so far found. Here we discuss the possible origin of the MO based on analyses of elements and O and Ne isotopes in its spinels as well as concentrations and isotopes of Os in MO whole-rock. Based on the results, that hint at a winonaite-like origin, we also studied, for comparison, the spinel fraction of recently fallen meteorites that could be analogues to the MO.

2. Materials and methods

For detailed information on materials and methods, see Supplementary Online Material, only a summary is given here. The elemental compositions of chrome spinel grains from the MO and three recent winonaites, Winona, NWA 725 and NWA 4024, were determined with a scanning electron microscope (SEM) equipped with a calibrated energy dispersive spectrometer (EDS). The analyses were performed on polished surfaces, and a cobalt standard was used to control instrumental drift. Eight chrome spinel grains from the MO and a similar number from one of the L chondrites from the same quarry were prepared for oxygen-three isotopic analysis using multicollector secondary ion mass spectrometry (SIMS). Five MO grains and six L chondrites grains proved suitable for analysis. A primary Cs^+ ion beam with a spot size of ∼10 μm was used to sputter O-ions from the grains. The three oxygen isotopes were collected in multicollection mode using Faraday cups for ^{16}O and ^{18}O and an electron multiplier for ^{17}O. The data were standardized using Burma spinel. This is not ideal, because there is evidence of a matrix effect related to iron content in spinels (Heck et al., 2010). However, the L-chondrite spinels plot very close to the average O-isotope composition for bulk L chondrites, giving us confidence that our standardization is reasonable. In addition, matrix effects are mass-dependent and will move the compositions along a slope ∼0.52 line on an oxygen three-isotope plot. We are primarily interested in $\Delta^{17}O$ (defined as $\delta^{17}O - 0.52 \times \delta^{18}O$), the distance that an object plots away from the terrestrial mass-fractionation line, so conclusions are not sensitive to mass-dependent variations (see Supplementary Online Material for details). Helium and Ne isotopes were measured in each of seven chrome spinel grains from the MO with an ultra-high sensitivity noble gas mass spectrometer. Two small (12 and 43 mg) aliquots of the bulk MO meteorite were analyzed for Os and Os isotopes by inductively coupled plasma mass spectrometry (ICPMS) using different methods in two different laboratories.