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Rare meteorites common in the Ordovician period

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Most meteorites that fall today are H and L type ordinary chondrites, yet the main belt asteroids best positioned to deliver meteorites are LL chondrites[1,2]. This suggests that the current meteorite flux is dominated by fragments from recent asteroid breakup events[3,4] and therefore is not representative over longer (100-Myr) timescales. Here we present the first reconstruction of the composition of the background meteorite flux to Earth on such timescales. From limestone that formed about one million years before the breakup of the L-chondrite parent body 466 Myr ago, we have recovered relict minerals from coarse micrometeorites. By elemental and oxygen-isotopic analyses, we show that before 466 Myr ago, achondrites from different asteroidal sources had similar or higher abundances than ordinary chondrites. The primitive achondrites, such as lodranites and acapulcoites, together with related ungrouped achondrites, made up ~15–34% of the flux compared with only ~0.45% today. Another group of abundant achondrites may be linked to a 500-km cratering event on (4) Vesta that filled the inner main belt with basaltic fragments a billion years ago[5]. Our data show that the meteorite flux has varied over geological time as asteroid disruptions create new fragment populations that then slowly fade away from collisional and dynamical evolution. The current flux favours disruption events that are larger, younger and/or highly efficient at delivering material to Earth.

To investigate the past meteorite flux, we searched for relict chrome-spinel grains of coarse micrometeorites in condensed marine sediments in northwestern Russia, in a time window of ~10–100 kyr in the geological epoch of the Middle Ordovician period, which ranges from 470 to 458 Myr ago (Fig. 1; see Methods). Chrome spinels are the only minerals of meteorites and coarse micrometeorites that survived diagenesis in Ordovician limestone[6]. They retained their elemental and oxygen isotopic composition, enabling reliable classification based on single-grain microanalysis[7,8]. We also dissolved 32 meteorites of different types in HF or HCl acid to quantify their content of chrome-spinel grains. The sediment sample that we studied is about a million years older than the ~466-Myr-old sediments that contain the first collisional fragments from the L-chondrite parent body breakup (LCPB), the largest known asteroid disruption event in the past three billion years. The sampling level was chosen to exclude the extreme flux enhancement (more than two orders of magnitude[6,7]) of L-chondritic fragments after the LCPB that obscures the background flux for more than 1 Myr (refs [7–9]). The low, 50- to 100-kyr, cosmic-ray exposure ages of the oldest recovered fossil L chondrites[9] imply that any fragments from the LCPB that might have arrived on Earth before should have even shorter exposure ages. This indicates that a sample separation of one million years before the strata containing the first abundant L chondrites is large enough to assess the pre-LCPB flux. The interval sampled represents a time average of about 10 to 100 kyr and was selected with the aim of determining whether the composition of the meteorite flux to Earth was similar to or different from that of today. This is the first reconstruction of the background flux of the different meteorite types in a geological time perspective. Similar reconstructions are ongoing for other periods in the Earth's geological past[10].

The presence of surface-implanted solar-wind-derived helium and neon in sediment-dispersed extraterrestrial chrome spinels (SECs) that were recovered from similar sediments from several younger Ordovician beds from sites in Sweden, China and Russia is evidence that the SECs were parts of micrometeorites[11–13]. Because the abundance ratio of the two ordinary chondrite groups H and L chondrites in recently fallen coarse micrometeorites[14,15] is similar to this ratio in macroscopic meteorites, micrometeorites bearing coarse chromite grains can be used as a proxy for meteorites[7]. The same consistency between the composition of coarse micrometeorites and meteorites has been documented based on fossil material for the Ordovician period after the LCPB[8]. This relation is useful because of the much higher abundance of SECs compared with fossil meteorites[6], allowing analyses of a larger number of samples[7].

We recovered 46 chrome-spinel grains with diameters >63 µm, out of which 41 are extraterrestrial based on their oxygen isotopic and elemental composition (Table 1 and Supplementary Data 1; see Methods). We find a large diversity of micrometeorites that includes all three groups of ordinary chondrites and many types of achondrites in strikingly different proportions from today (Figs 2 and 3). Among the extraterrestrial grains, 23 originate from ordinary chondrites and 18 from achondrites. This corresponds to an ordinary chondrite/achondrite ratio of 1.3 compared with ~11 in today's flux (Table 1). The proportions of the three ordinary chondrite groups H, L and LL are markedly different from the recent flux, and from the flux immediately after the LCPB. Today, L and H chondrites fall in about equal proportions and together dominate the flux, but in the Ordovician prior to the LCPB the same can instead be said about the LL and L types (Table 1).

Considering the variation in abundances of large chrome-spinel grains in recent meteorites, there are significant uncertainties when translating SEC grain abundances into estimates of Middle Ordovician meteorite flux (see Supplementary Data 2). Some first-order minimum estimates for the achondritic versus ordinary chondritic flux can be made, however, if we assume that the chrome-spinel

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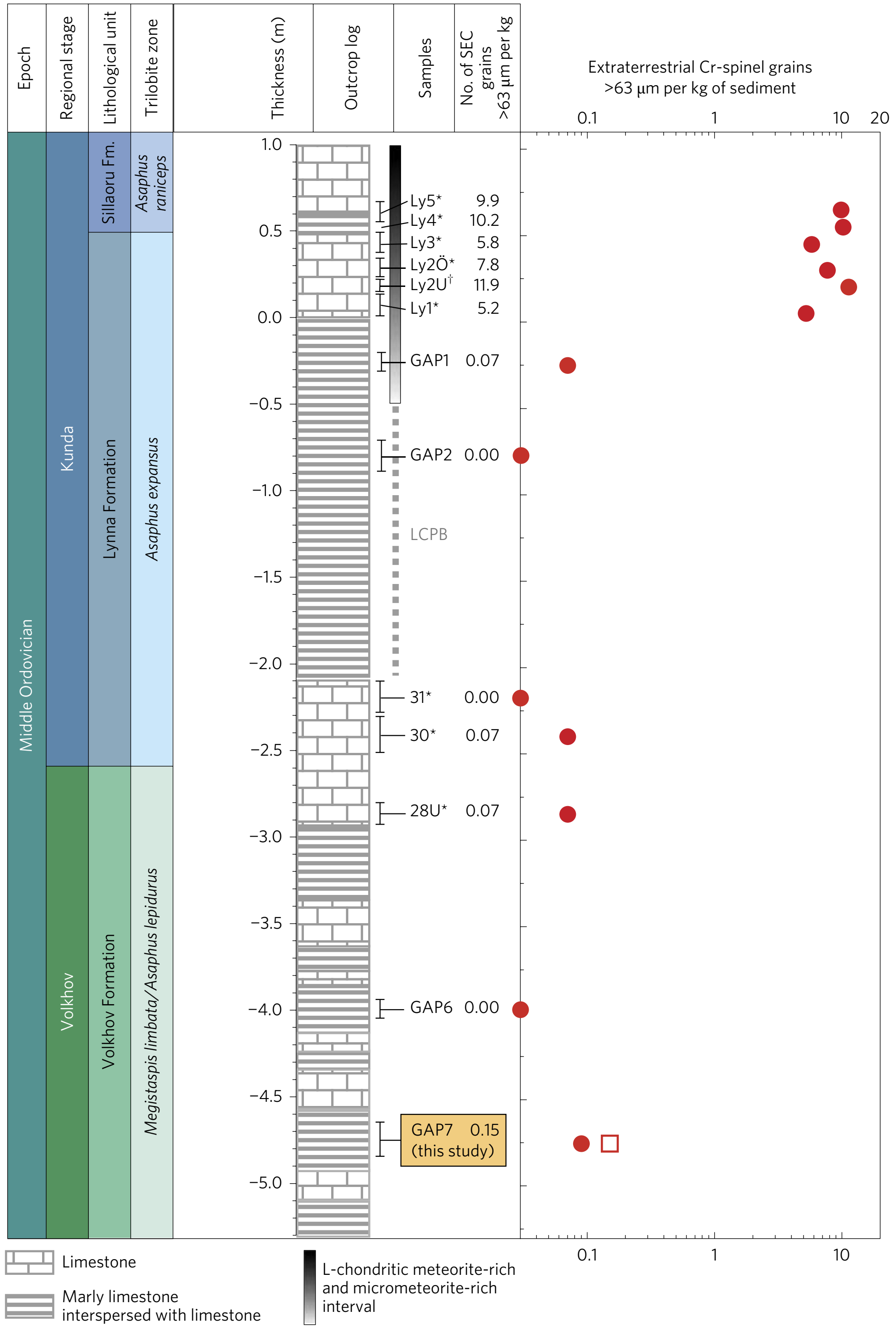

Figure 1 | Micrometeorite-bearing limestone beds at the Lynna River section in northwestern Russia that were deposited around 466 million years ago. The sample GAP7 was collected over an interval of highly condensed limestone, about 4 m below the level where the first SEC grains that clearly originate from the LCPB have been found. The abundance of all chrome-spinel grains with diameters >63 μm retrieved from the GAP7 sample is shown by the open square; the solid circles are grains from equilibrated ordinary chondritic micrometeorites. The GAP1, GAP2 and GAP6 samples searched for SEC grains were 14, 12 and 13 kg in size, respectively. Asterisks indicate the samples studied by Lindskog *et al.*[27] and a dagger symbol those studied by Heck *et al.*[7]. Fm., formation.

grain contents of the achondrites were generally lower than or equal to those of the ordinary chondritic (mostly types 5 and 6) micrometeorites that contributed chrome-spinel grains to the ancient sea floor. With this extremely conservative approach, the achondrites were almost or as common as the ordinary chondrites, and the primitive achondrites and related ungrouped achondrites made up between 15 and 34% of all achondrites and ordinary chondrites, compared with around 0.45% today (Table 1 and Supplementary Information). The true achondrite fraction, however, may have been significantly higher. Although we have only studied 13 achondrites, our data for the chrome-spinel content indicate generally lower numbers than for the ordinary chondrites. If these numbers

Table 1 | Classification of coarse micrometeorites in this study with their fractions of the total flux.

	Number of micrometeorites ~467 Myr ago (pre-LCPB; this work)	Fraction of micrometeorite flux ~467 Myr ago (pre-LCPB; this work)*	Fraction of micrometeorite and meteorite flux 466 Myr ago (post-LCPB)†	Fraction of meteorite flux today‡
Equilibrated ordinary chondrites	**23**	**≤56%**	**≥99%**	**90.6%**
H chondrites	5	12%	<1%	37.3%
L chondrites	9	22%	≥99%	43.0%
LL chondrites	9	22%	<1%	10.3%
Achondrites	**18**	**≥44%**	**<1%**	**7.1%**
Primitive and ungrouped achondrites including Bocaiuva-type	6–14	≥(15% to 34%)	<1%	0.45%
HED achondrites	4–12	≥(10% to 29%)	Not detected	6.6%

*The flux estimate is built on the very conservative assumption that achondritic meteorites on average are as rich in large chrome-spinel as the equilibrated ordinary chondrites. Our data for 32 meteorites indicate that achondrites generally contain fewer >63-µm chrome-spinel grains than equilibrated ordinary chondrites. †Data from refs [11,13,14,22]. ‡The data concern the fraction of the flux excluding the recent major meteorite groups poor in large chrome-spinel (see Supplementary Table 1 and Supplementary Data 2). Source: Meteoritic Bulletin database (www.lpi.usra.edu/meteor/). About 2.4% of today's flux consists of R chondrites, lunar and Martian meteorites that can be rich in chrome-spinel, but these are not listed because we did not find such types in the Middle Ordovician.

are accounted for in the palaeoflux estimates, achondrites dominated over ordinary chondrites.

The achondrite grains include one sample possibly from a rare Bocaiuva-type achondrite (category A; Figs 2 and 3). Based on the elemental and $\Delta^{17}O$ compositions of Bocaiuva[16,17] and our category A grain, we argue that the grain may represent a piece of the missing mantle fraction of the Bocaiuva parent body, or of the surface if the Bocaiuva iron was impact-generated. One of our chrome-spinel

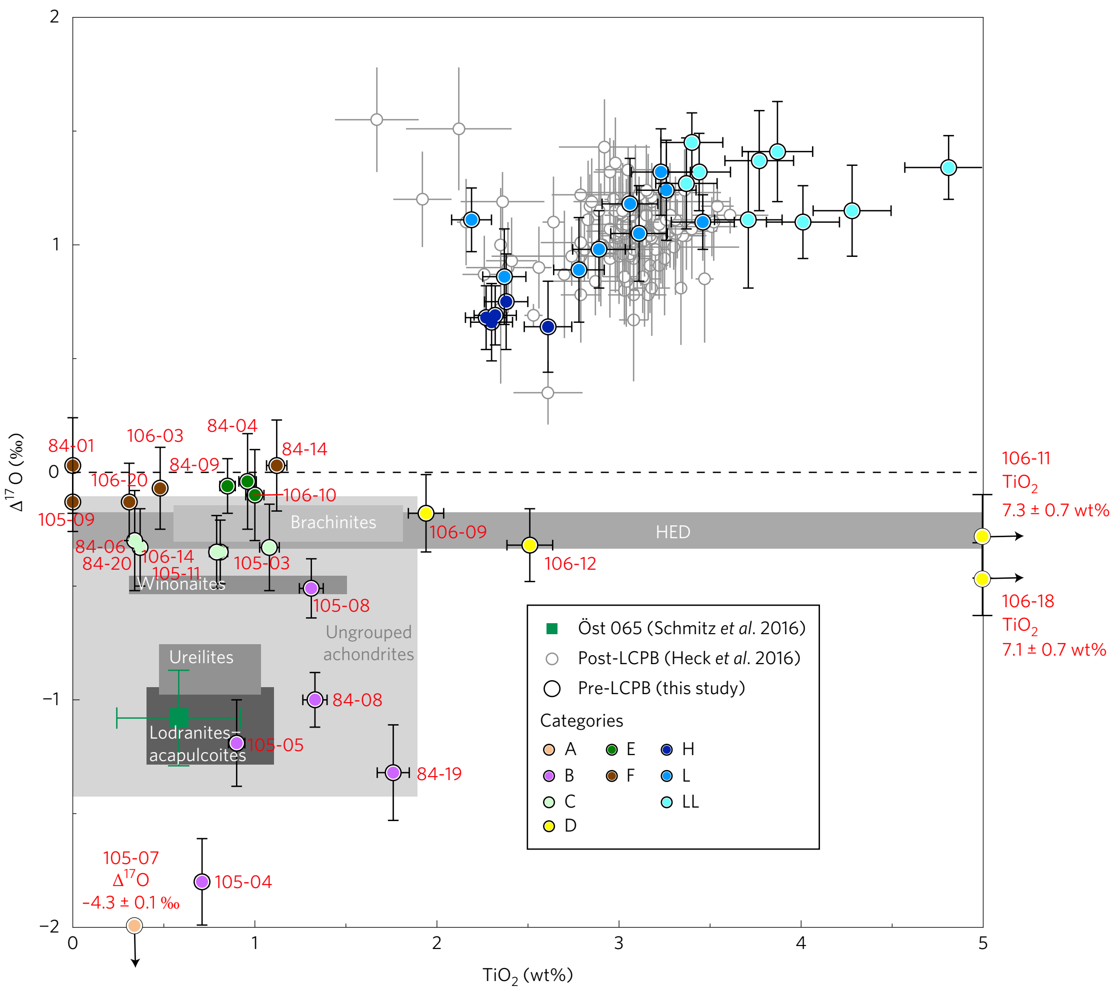

Figure 2 | Values of $\Delta^{17}O$ and TiO_2 of our data compared with compositions of different relevant meteorite groups. Reference data compilation is provided in Supplementary Data 3. Grains 105-07, 106-11 and 106-18 fall outside the range shown in this figure (see Supplementary Data 1). Österplana 065 (Öst) results are from Schmitz *et al.*[18]; post-LCPB results are from Heck *et al.*[7].

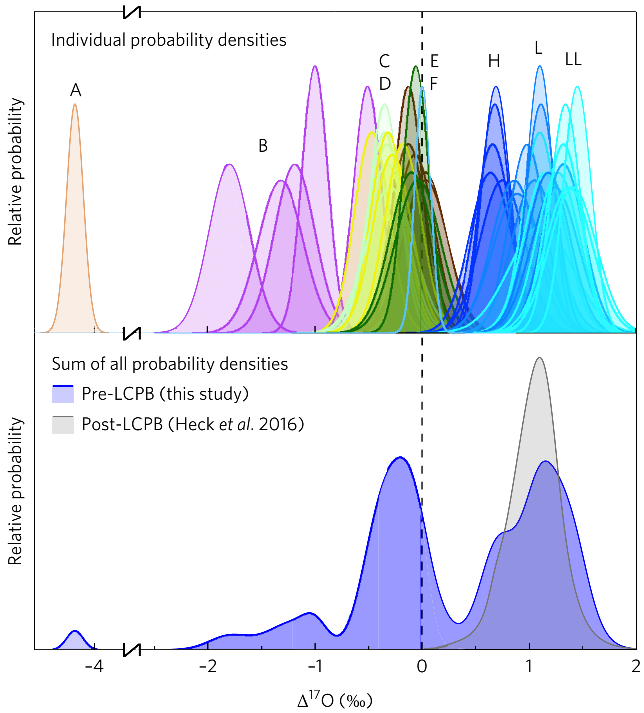

Figure 3 | Probability density functions (PDFs) of $\Delta^{17}O$ values showing the distribution of different micrometeorite categories. Top panel: PDFs from data of individual chrome-spinel grains analysed in this study labelled with the categories A–F as defined in the text (A, beige; B, purple; C, light green; D, yellow; E, dark green; F, brown), and the clearly resolved ordinary chondrite groups (H, L and LL). Bottom panel: Sums of all PDFs from data from this study compared with data from a previous study[7] of post-LCPB chrome-spinel grains. The post-LCPB flux was dominated by L-chondritic material from the asteroid breakup and obscures the background flux.

grains (#105-05) appears to come from the Österplana 065 type of ungrouped achondrite. In Middle Ordovician sediments that formed after the LCPB, a 8-cm fossil achondrite, Österplana 065, was recently found that has a Cr and O isotopic composition different from all known recent meteorite types[18]. This single find of a new type of achondrite among about 100 fossil L-chondritic meteorites indicates that the assemblage of micrometeoritic chrome spinel in our study may also harbour grains from meteorites not known today. For a random find of a single meteorite on Earth today, the likelihood is much greater that it would belong to a common group than a very rare group of meteorites. Based on this reasoning, it is likely that Österplana 065 belongs to a type of meteorite that was common in the flux in the Ordovician. The data in this study support that this was the case. For Österplana 065, we know that the chrome-spinel content was rather low, at 50 grains per gram. If we use this number in the palaeoflux estimates, this would mean that meteorites of the type represented by the single grain #105-05 would represent 20–30 times the mass to which one of the ordinary chondritic grains corresponds. The unexpected high fraction of ungrouped and related primitive achondritic material in sediments pre-dating the LCPB is evidence that some partially differentiated asteroids had disrupted and were capable of producing a relatively high flux of meteoroids at that time. The fact that the same fraction is smaller today probably indicates that their source families were small enough that meteoroid production by a collisional cascade could not keep up with newer families much closer to their peak flux.

As regards howardites, eucrites and diogenites (HED) achondrites, today the HED/ordinary chondrites ratio is about 0.1. With a range of 4–12 possible HED micrometeorites among our 41 extraterrestrial grains (of which 23 are ordinary chondritic), this represents a (grain-to-grain) HED/ordinary chondrites ratio in the range 0.2 to 0.5, which is significantly higher than today. Considering also that the HED meteorites on average contain fewer chrome-spinel grains in the >63-μm fraction than the equilibrated ordinary chondrites dominated by higher petrographic types (Supplementary Data 2), this gives additional support for HED meteorites being more abundant in the Middle Ordovician than today. This result is particularly interesting because the HEDs are believed to come from the Vesta family[19] that formed nearly 1 Gyr ago in the formation of the ~500-km Rheasilvia impact basin[5]. The collisional cascade for this family would have been just as capable, if not more so, of producing meteoroids ~467 Myr ago as today.

For our 23 samples with an unambiguously ordinary chondritic origin, the most significant difference from the recent flux composition is the high abundance of LL grains relative to H and L grains compared with post-LCPB and today (Table 1). Impact degassing ages of recent LL chondrite falls are sparse[20,21], and the only degassing age that could date the same event is that of the Morokweng meteorite (625 ± 163 Ma)[22]; others are mostly at or older than 1 Gyr, consistent with the dynamical age of the Flora asteroid family (950 +200/−170 Myr)[23], a likely source of the LL chondrites[2]. The H chondrites in the Earth's recent flux have impact degassing ages in the range of ~280–460 Myr, indicating one or a few younger events than the LCPB 466 Myr ago[21]. This could suggest that the primary source of today's H chondrites had not yet disrupted, whereas the LL source had disrupted and was closer to its peak meteoroid flux than it is now.

The smaller size fraction (<100 μm) of today's micrometeorites is dominated by carbonaceous chondritic material, reflecting the brittleness and fragmentation of such material on collision with Earth's atmosphere[24]. In the recent flux, the coarse micrometeorites that can contain 100-μm-sized unmelted spinel grans are dominated by ordinary chondritic material similar to the macrometeorite flux composition[24,25]. All previous studies on micrometeorites show that recent primitive achondrite-type micrometeorites are not a significant fraction of the present flux[26].

The large diversity in our sample of coarse micrometeorites, representing many different types and origins, confirms that the studied sediments did not sample one event such as an atmospheric breakup, a terrestrial impact or even a breakup of a single type of asteroid in space, but rather represent a time-averaged sample of the extraterrestrial flux to the Earth over ~10–100 kyr. We predict that the same diversity and abundances of coarse micrometeorites should be preserved in sediments of the same age globally.

Despite many uncertainties, using a conservative approach we have shown that the meteorite flux composition was fundamentally different ~467 Myr ago from today and varies on timescales of 10–100 Myr and longer. At that time, achondrites probably dominated over ordinary chondrites, and primitive achondrites and related ungrouped meteorites were at least one order and probably two orders of magnitude more abundant than today. This fits with the proposal that different asteroid families were dominating the meteorite flux at these times. Furthermore, it shows that only after the LCPB did L chondrites become the most significant type of coarse extraterrestrial matter that accreted to the Earth. These results confirm that the collisional cascade model of meteoroid delivery is reasonable and can help to tell us about the evolution of the asteroid belt. Studying different time windows will increase our knowledge of the variation of the flux of extraterrestrial material to the Earth in deep time and will provide new knowledge on the evolution of the asteroid belt from the Earth's sedimentary record[10].

Methods

For this study, we dissolved 270 kg of rock from the interval at and just below the '*Trypanites* bed' in the Lynna River section in the St Petersburg region of Russia. The Lynna River section studied here has been the focus over the past century of many studies of the palaeontological and sedimentological record (ref. [27] and references therein). The studied interval is located about 4.7 m below the base of the Ly1 bed[27] and is characterized by very high densities of burrows of a kind that typically develop on hard ground surfaces on the sea floor during extremely slow rates of sedimentation. The rocks were dissolved in HCl (6 M) and HF (11 M) at room temperature in the Lund University Astrogeobiology Laboratory, specially built for separation of extraterrestrial minerals from ancient sediments. After sieving at mesh sizes 32 and 63 μm, opaque chrome-spinel grains were identified by picking under the binocular microscope and by subsequent qualitative analysis by scanning electron microscopy/energy-dispersive spectroscopy (SEM/EDS)[6]. Only the >63-μm fraction has been used in the present study. We also dissolved small pieces (0.5 g to a few grams) of 32 recent and fossil meteorites in HF or HCl acid, to quantify variations in the content of chrome-spinel grains >63 μm in different meteorite types. We used grains >63 μm to be able to compare our results directly with previous studies of sediment-dispersed extraterrestrial chrome-spinel grains of the same size fraction and because terrestrial chrome spinels become more abundant at sizes below 63 μm. Furthermore, we have evidence to link the coarse micrometeorite populations that contain coarse chrome-spinel with the meteorite populations that also contain coarse chrome-spinel. We observe similar type abundances between the two populations today and in Middle Ordovician post-LCPB sediments[7,8].

Polished epoxy grain mounts with centrally mounted analytical standard[8] UWCr-3 were prepared. A Bruker white-light interferometric 3D microscope at Northwestern University was used to verify that grain-to-epoxy topography was kept below 3 μm (on average 2 μm) after polishing to minimize mass-dependent isotope fractionation effects during analysis by secondary ion mass spectrometry (SIMS)[28]. Major and minor element concentrations of polished grains on carbon-coated mounts were analysed quantitatively with SEM/EDS. Titanium and vanadium oxide concentrations are most resistant to weathering and are most useful, in conjunction with oxygen isotopes, to classify meteorites[6–8]. Isotopes of $^{16}O^-$, $^{17}O^-$ and $^{18}O^-$ were analysed with a Cameca IMS-1280 SIMS at the WiscSIMS Laboratory at the University of Wisconsin-Madison with conditions and procedures according to previous work[7,8]. This procedure includes analysis and correction for the hydride tailing interference on $^{17}O^-$ and bracketing with our analytical standard UWCr-3. The hydride correction was on average 0.17‰ with only three data points above 0.5‰ and all below 1.0‰ (see Supplementary Fig. 1 and Supplementary Data 4). As discussed previously[7], a correction below 1.0‰ still yields robust data, and no data needed to be rejected. A matrix correction was performed by calculating the Al-Mg-spinel fraction (see Supplementary Data 4) in a two-component mixture of Al-Mg-spinel and $FeCr_2O_4$ end members[8]. We determine parts per thousand deviations from VSMOW as $\delta^{18}O$, $\delta^{17}O$ and from the terrestrial mass-fraction line as $\Delta^{17}O$ ($=\delta^{17}O-0.52\times\delta^{18}O$), the latter being the main indicator for an extraterrestrial origin (Supplementary Figure 2). We analysed a total of 58 spots on 46 sediment-dispersed chromite and chrome-spinel grains (grain size ranging from 63 to about 200 μm). Based on post-SIMS SEM imaging of SIMS sputtering craters, no data points had to be rejected.

The ordinary chondritic grains can be divided into H, L and LL chondrite groups based on their TiO_2 and $\Delta^{17}O$ content as previously demonstrated[7,8] and as illustrated in Figs 2 and 3, and defined in Supplementary Data 1. There is some overlap in $\Delta^{17}O$ and TiO_2 compositions of L and LL chondrites. However, the distribution of $\Delta^{17}O$ and TiO_2 values clearly shows two different populations with different maxima that correspond to these two different groups of ordinary chondrites. The classification of the achondritic grains is more complex, partly because so few types of achondrites are known today for comparison. We have divided our achondritic grains into six categories (A to F) based on their elemental and oxygen isotopic composition (Supplementary Data 1 and Fig. 3).

Category A consists of one grain with an exceptionally low $\Delta^{17}O$ value of -4.3 ± 0.1‰. Carbonaceous chondrites of the CK group can have similar low $\Delta^{17}O$ values, but large chrome-spinel grains have not been observed in this group and are very rare in almost all other groups of carbonaceous chondrites, ruling out such an origin. There are some exceptionally rare pallasites (for example Eagle Station) and iron meteorites (Bocaiuva and NWA 176) that have such low $\Delta^{17}O$ values[17]. Neither pallasites nor iron meteorites contain enough large chrome-spinel grains to make a significant imprint on SEC-based studies like this. Silicate inclusions in Bocaiuva, however, contain chrome-spinel grains with remarkably similar elemental composition[16] to our category A grain (Supplementary Data 1).

The five grains in our category B have low $\Delta^{17}O$ values in the range −2 to −0.5‰. This indicates that the grains originate from primitive achondrites, such as lodranites, acapulcoites or related ungrouped achondrites. The recently recovered fossil achondrite Österplana 065 also falls into this category. This meteorite has a $\Delta^{17}O$ composition of -1.08 ± 0.21‰. One of our grains (#105–05) in category B has an oxygen-isotopic and elemental composition very similar to the chrome spinels of Österplana 065 (Fig. 2). Today, meteorites that would yield chrome spinels analogous to our group B grains are extremely rare.

Our category C contains five grains that have $\Delta^{17}O$ values in the range from −0.5‰ to clearly below the terrestrial fractionation line (TFL) within 2SD, and TiO_2 values <2wt%. Several recent primitive and ungrouped achondrites, for example the winonaites and brachinites, fall into the $\Delta^{17}O$ range that defines our category C. However, today two-thirds of the achondrites are ‘HED’ meteorites, thought to be excavated crustal material from the basaltic (4) Vesta asteroid or other V-type asteroids[19]. These HED meteorites can also have compositions that fall into the range defined as category C. Considering that we recovered as many as five primitive or related ungrouped achondrite grains (category B), it would be strange if there were not also a few such grains with slightly more positive $\Delta^{17}O$ values than the definition of category B. We therefore argue that some or several of the category C grains may also be from primitive or ungrouped achondrites, but a HED origin cannot be ruled out for some.

Our four grains of category D have $\Delta^{17}O$ values in a similar range to those of category C, but high to very high TiO_2 contents (ranging from ~2 wt% to higher than 7 wt%). Such high TiO_2 contents in chrome spinels are typical for HED meteorites and are not observed in primitive and ungrouped achondrites. We note that all the grains in categories C and D have high V_2O_3 contents (>0.5wt%) which is very rare among terrestrial chrome-spinel grains in Middle Ordovician sediments in Baltoscandia[27,29]. This confirms that the small negative offsets in $\Delta^{17}O$ relative to the TFL are real and not analytical or diagenetic artifacts.

The three grains of category E have $\Delta^{17}O$ values at the TFL but, although there is some uncertainty, we argue that their high V_2O_3 (1.2, 1.0, and 0.5 wt%, respectively) concentrations indicate an extraterrestrial origin.

Our category F contains five grains with $\Delta^{17}O$ values at the TFL and low (<0.5wt%) V_2O_3 concentrations. Probably all the grains in this group are terrestrial, but an extraterrestrial origin cannot be ruled out for some. Achondrites with a terrestrial oxygen isotopic composition could have formed in the terrestrial planet region with terrestrial oxygen isotopic compositions and could have been scattered into the main asteroid belt[30]. A recent example[31] of such an ungrouped achondrite is NWA 5363/5400/6077. The presence of solar-wind implanted or cosmic-ray produced spallogenic helium and neon would unequivocally determine an extraterrestrial origin for those grains.

The proportions of different types of pre-LCPB grains in the present study cannot be directly translated to flux proportions because the number of chrome-spinel grains in different meteorites varies by orders of magnitude (Supplementary Data 2). Our assemblage of grains is most likely to be representative mainly of the types of meteorites that are rich in large chrome-spinel grains. Therefore we can ignore potential contributions from meteorites that are very low in large chrome spinels, such as the carbonaceous and enstatite chondrites, iron meteorites, pallasites, angrites, aubrites and most ureilites. An ordinary chondrite of petrologic type 5 or 6 can typically contain around 1,000–1,500 chrome-spinel grains >63 μm per gram, whereas the equivalent number for ordinary chondrites of petrologic type 4 is only 50–150 grains per gram. In meteorites of higher petrologic types, chrome-spinel grains are generally also larger with higher degree of equilibration. In the recent flux of ordinary chondrites, types 5 and 6 also clearly dominate over type 4. Probably most of our ordinary chondritic SEC grains originate from the more equilibrated meteorites. Achondritic meteorites show also a wide range in chrome-spinel content, from being completely devoid of chrome spinel, like the winonaite Pontlyfni, up to about 1,000–1,300 grains per gram, examples being the ungrouped achondrite NWA 6077 or the brachinite NWA 3151. Howardites and diogenites contain around 600–900 grains per gram. Most primitive achondrites (that is, acapulcoites, lodranites and winonaites) have intermediate chrome-spinel contents, in the range of 200–800 grains per gram. We note that there are other types of meteorites that can be rich in large chrome-spinel grains, such as Martian meteorites, and Rumuruti chondrites, but none of our grains have elemental and oxygen isotopic compositions consistent with such origins. Similarly, there are some anomalous ureilites such as NWA 766 that contain common large chrome-spinel grains, but such grains differ in elemental composition from any of our samples (Supplementary Data 2). Middle Ordovician fossil L chondrites show chromite abundances very similar to recent L chondrites, attesting to the refractory nature of this meteorite component (Supplementary Data 2).

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
P.R.H. and B.S. conceived the study and wrote the paper with input from all authors. W.F.B. provided expertise on the collisional and dynamical evolution of the asteroid belt and meteoroid delivery models. B.S., F.T. and A.D. conducted the fieldwork. B.S., F.T. and A.C. extracted and prepared the samples for SEM/EDS and SIMS. A.C. performed the quantitative SEM/EDS analysis. P.R.H. and S.S.R. prepared the samples for SIMS and performed the SIMS and post-SIMS analyses. N.T.K. and C.D. set up SIMS analysis conditions and assisted with the analyses.

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Competing interests
The authors declare no competing financial interests.