

Asteroid breakup linked to the Great Ordovician Biodiversification Event

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The rise and diversification of shelled invertebrate life in the early Phanerozoic eon occurred in two major stages. During the first stage (termed as the Cambrian explosion), a large number of new phyla appeared over a short time interval ~540 Myr ago. Biodiversity at the family, genus and species level, however, remained low until the second stage marked by the Great Ordovician Biodiversification Event in the Middle Ordovician period^{1–3}. Although this event represents the most intense phase of species radiation during the Palaeozoic era and led to irreversible changes in the biological make-up of Earth's seafloors, the causes of this event remain elusive. Here, we show that the onset of the major phase of biodiversification ~470 Myr ago coincides with the disruption in the asteroid belt of the L-chondrite parent body—the largest documented asteroid breakup event during the past few billion years^{4,5}. The precise coincidence between these two events is established by bed-by-bed records of extraterrestrial chromite, osmium isotopes and invertebrate fossils in Middle Ordovician strata in Baltoscandia and China. We argue that frequent impacts on Earth of kilometre-sized asteroids—supported by abundant Middle Ordovician fossil meteorites and impact craters⁶—accelerated the biodiversification process.

Evidence for an early Palaeozoic major asteroid breakup was already established in the 1960s when recent ordinary chondrites of the L type were shown to commonly have K–Ar gas retention or shock ages of about 450–500 Myr (refs 4,5). About 20% of the meteorites reaching Earth today are shocked L chondrites from this event. The finds of more than 50 fossil L-chondritic meteorites (1–20 cm in diameter) in Middle Ordovician limestone in southern Sweden show that the meteorite flux was enhanced by one to two orders of magnitude for at least a few million years after the disruption event^{6,7}. The L-chondritic origin of the fossil meteorites is demonstrated by element and oxygen isotope analyses of relict chromite grains as well as by petrographic studies of chondrule textures^{6–8}. Chromite is the only common mineral in chondrites that survives extensive weathering on the wet Earth surface. In the limestone beds containing common meteorites, abundant chromite grains from decomposed meteorites and micrometeorites are also found^{9–11}. Cosmic-ray-induced ²¹Ne in chromite from the fossil

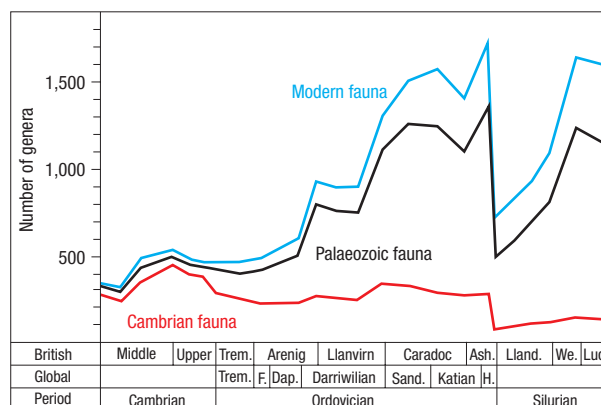


Figure 1 Global biodiversity change at family level through the early Palaeozoic era.

Although this diagram from Sepkoski (1995; ref. 15) gives a good representation of the overall biodiversity trend, the resolution is too crude for correlation with field data. Trem. = Tremadocian (Global) and Tremadoc (British), Ash. = Ashgill, Lland. = Llandovery, We. = Wenlock, Lud. = Ludlow, F. = Floian, Dap. = Dapingian, Sand. = Sandbian, H. = Hirnantian.

meteorites increases upwards in the strata, supporting a common origin from an asteroid breakup event¹². High-precision ⁴⁰Ar–³⁹Ar dating of recent L chondrites has constrained the timing of their parent-body disruption to 470 ± 6 Myr ago, which is identical within uncertainties to the age of 467.3 ± 1.6 Myr ago for the beds with fossil meteorites according to the latest geologic timescale¹³.

During the Great Ordovician Biodiversification Event (GOBE), in the Middle to Late Ordovician, biodiversity at the family level increased from a Phanerozoic all-time-low in the Cambrian and Early Ordovician to levels approximately three times higher in the Late Ordovician^{1–3,14,15} (Fig. 1). The new biodiversity levels of marine life were matched by an increase in biocomplexity, and were sustained until the end of the Palaeozoic except for short-term declines in connection with extinction events in

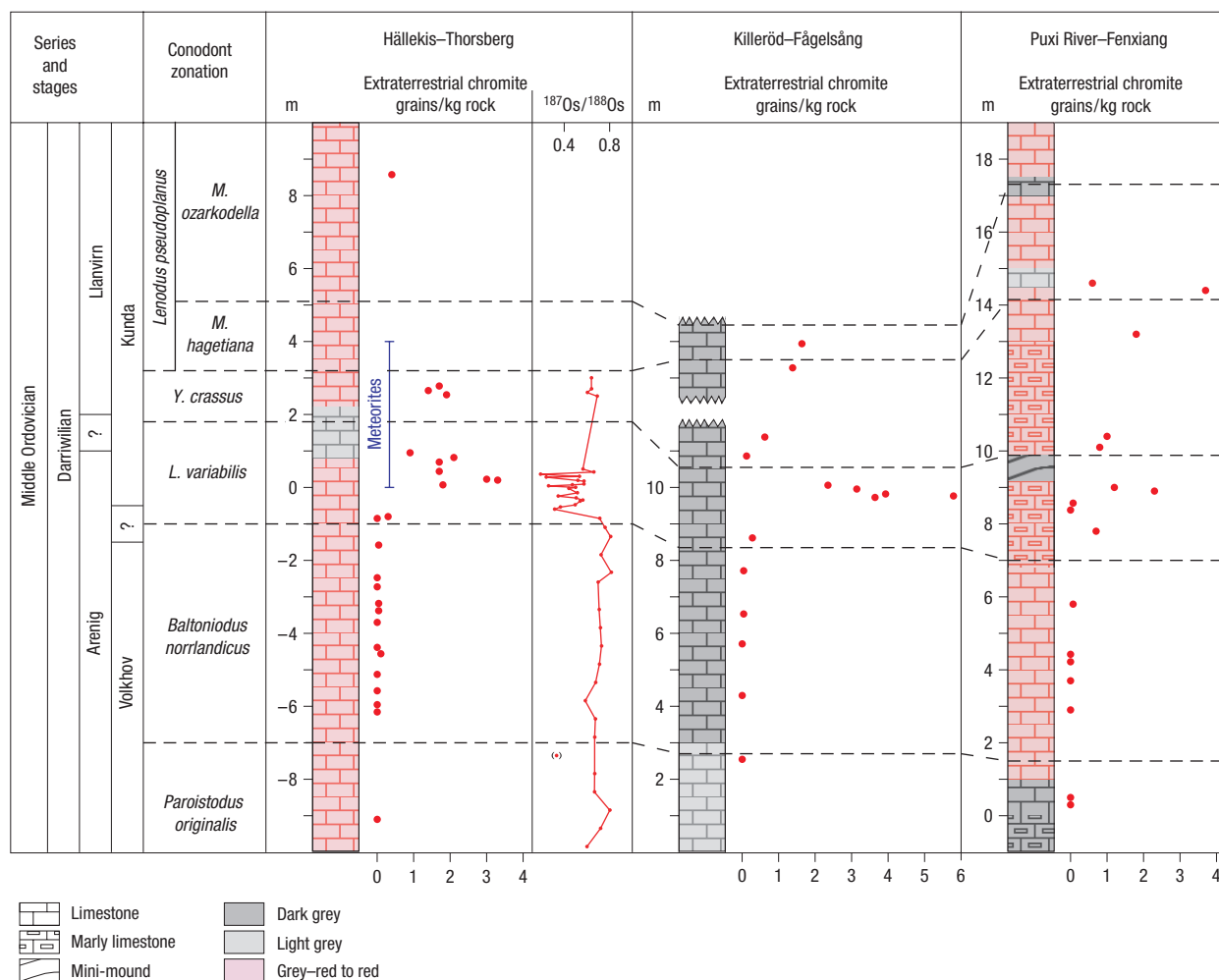


Figure 2 Distribution of extraterrestrial (chondritic) chromite and osmium isotopes through Middle Ordovician sections in Sweden and China. Results are shown for sections at Kinnekulle (Hällekis and Thorsberg quarries) and southern Scania (Killeröd and Fågelsång sections), 350 km apart in southern Sweden, and the Puxi River and Fenxiang sections, 4 km apart in south-central China. The distribution of Os isotopes across the Hällekis section is also shown. The stratigraphic interval yielding abundant fossil meteorites in the Thorsberg quarry is indicated⁶. The conodont biostratigraphy shown has been produced specifically for this study, using consistent taxonomic concepts for the different sections. *M. ozarkodella* = *Microzarkodina ozarkodella*.

the latest Ordovician and Late Devonian periods. The GOBE generated few new higher taxa, for example phyla, but witnessed a staggering increase in biodiversity at, for example, species level among a wide variety of groups of skeletal invertebrates^{2,3,15}. Diagrams of changes in global or regional biodiversity during the GOBE give only a crude representation of the timing and pace of the faunal change^{15,16}. The global signal represents a combination of many regional diversity changes across a range of fossil groups^{2,3}. The most focused global compilation through the early Palaeozoic, shown in Fig. 1, demonstrates a sharp rise in biodiversity at about the Arenig–Llanvirn boundary (about 466 Myr ago). This signal is evident across a number of groups, such as the brachiopods, cephalopods and echinoderms, but less clear in some members of the Cambrian fauna (trilobites) and the modern fauna (gastropods)¹⁵. It also corresponds to the second-cycle diversity peak in conodonts recognized by Sweet¹⁷. The causes of the GOBE, and its relation to both intrinsic (biological) and extrinsic (environmental) factors are not known². Many authors have suggested a link to increasing levels of atmospheric oxygen, favouring the radiation of aerobic metazoan life together with an expansion of the phyto and zooplankton^{18,19}.

Although biodiversity diagrams such as in Fig. 1 show the broad outline of change, at a higher resolution they suffer from the effects of poor correlation and poor preservation of faunas, focus on a particular horizon or group of fossils and data binning. To relate biological change to physical events, detailed high-resolution multiparameter records across complete and fossil-rich sections are required. Here, we have constrained the precise stratigraphic level for the L-chondrite disruption event by searches for sediment-dispersed extraterrestrial (chondritic) chromite grains and Os isotopic studies in Middle Ordovician sections with condensed limestone (Fig. 2). These results are matched by the most detailed bed-by-bed studies of the distribution of brachiopod species across Middle Ordovician strata in Baltoscandia (Fig. 3) conducted until now.

The sections studied for extraterrestrial chromite grains occur at Kinnekulle and in southern Scania, 350 km apart in southern Sweden, and at Puxi River (Puquie) and Fenxiang, 4 km apart in south-central China near Yichang, Hubei province. The extraterrestrial chromite grains (> 63 µm) have been retrieved from about 10–30-kg-sized limestone samples that were dissolved in HCl and HF acid¹⁰. The extraterrestrial chromite can be readily

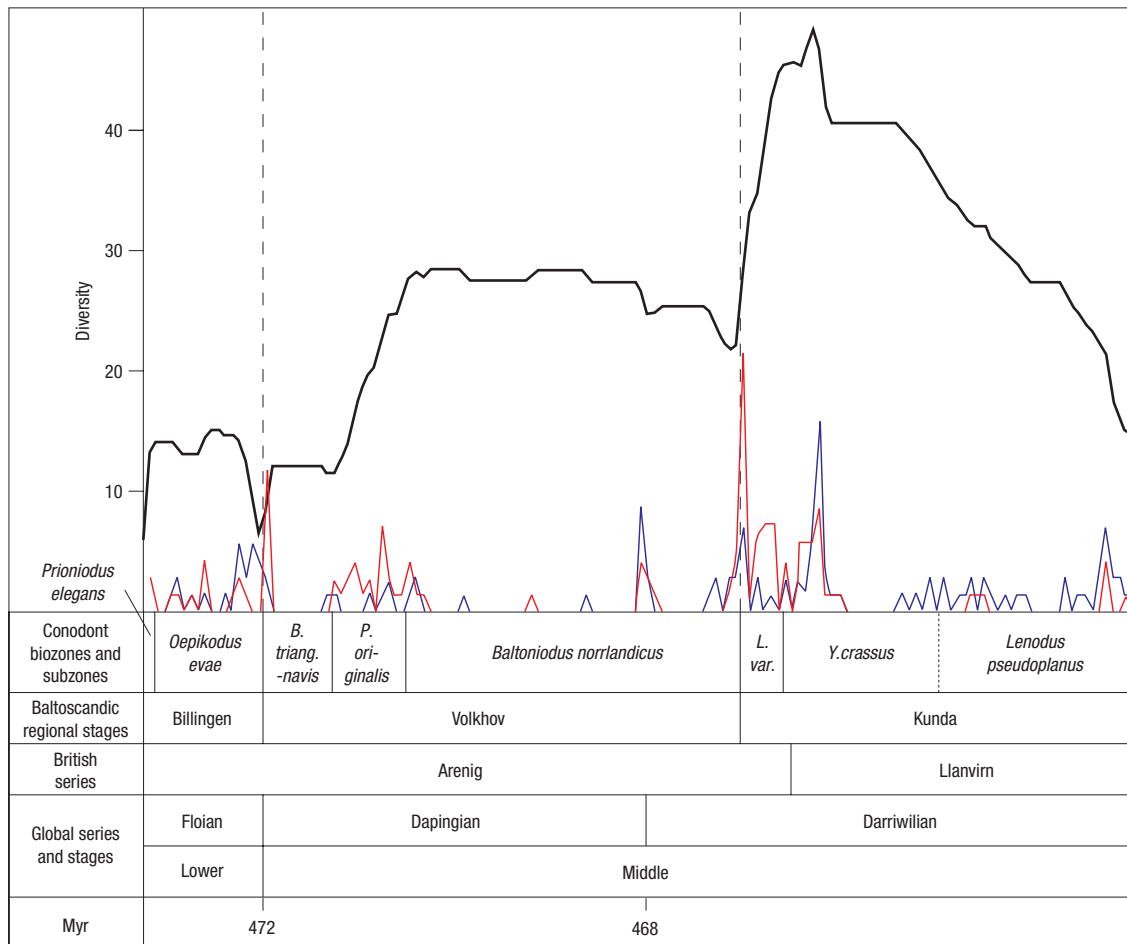


Figure 3 Total diversity of brachiopod species (number of species) through part of the Lower and Middle Ordovician in Baltoscandia. The results are based on bed-by-bed collections at eight localities²². Note the dramatic increase in biodiversity (black line) and high extinction (blue line) and origination (red line) levels following the regional Volkhov–Kunda boundary, that is, the same level where extraterrestrial chromite appears and Os isotopes change in Fig. 2. *B. triang.-navis* = *Baltoniodus triangulatus-navis*. The dashed lines show the boundaries between the regional states.

distinguished from terrestrial chromite by its distinct element composition^{6,10}. The results of the extraterrestrial chromite searches are shown in Fig. 2 and in the Supplementary Information. In the section studied in greatest detail, at Kinnekulle, in 379 kg of limestone from 14 levels across 9 m of strata below the *Lenodus variabilis* zone, only 5 extraterrestrial chromite grains were found¹⁰ (Fig. 2). The values then increased dramatically to typically 1–3 extraterrestrial chromite grains per kilogram of rock in the *L. variabilis*, *Yangtzeplacognathus crassus* and *Microzarkodina hagetiana* zones. In this interval, a total of 332 extraterrestrial chromite grains were found in 174 kg of rock. In southern Scania and in China, the distribution trends of extraterrestrial chromite grains are very similar to that at Kinnekulle. In southern Scania, some beds in the *L. variabilis* zone contain up to 6 extraterrestrial chromite grains per kilogram of rock, whereas only 2 grains were found in 125 kg in the beds spanning 7 m below¹¹. In the Chinese sections, 89 kg of limestone below the *L. variabilis* zone yielded only 1 extraterrestrial chromite grain compared with 117 extraterrestrial chromite grains in 89 kg in the overlying beds (Fig. 2).

The first appearance of common extraterrestrial chromite grains in the lower *L. variabilis* zone in the three sections is a strong indication of the precise timing of the disruption of the L-chondrite

parent body. The data also represent strong support for an increase by two orders of magnitude in the flux of micrometeorites and meteorites to Earth following the disruption event, as previously suggested on the basis of studies of the Swedish sections alone^{9–11}. There is no indication that changes in sedimentation rates, on average a few millimetres per thousand years, can explain the observed major trend in extraterrestrial chromite concentrations, although individual beds may have formed at different rates. That the disruption event occurred in the lower *L. variabilis* zone is consistent with cosmic-ray-induced ²¹Ne ages of chromite grains from the fossil meteorites¹². In 5–10-Myr-old younger condensed limestone in the Gärde quarry, central Sweden, we found 9 extraterrestrial chromite grains in 23 kg of rock. This indicates that the extraterrestrial chromite flux is still enhanced compared with that before the asteroid breakup. The low pre-breakup concentrations of extraterrestrial chromite grains are similar to concentrations measured in similarly condensed sediments from much younger periods. For example, in 210 kg of pelagic limestone (average sedimentation rate about 2.5 mm kyr⁻¹) from the famous Late Cretaceous–Paleocene Gubbio section in Italy we found only 6 extraterrestrial chromite grains²⁰.

Our analyses of ¹⁸⁷Os/¹⁸⁸Os ratios in whole-rock limestone samples through the Kinnekulle section show a relatively stable

trend with ratios around 0.6–0.8 through the lower 11 m of section, but from the same bed where the extraterrestrial chromite grains become common and further up, ratios mainly lie in the range 0.3–0.5 (Fig. 2; Supplementary Information). The simplest explanation for this prominent change is an increasing influence of an extraterrestrial component ($^{187}\text{Os}/^{188}\text{Os} \sim 0.12$) at the expense of a detrital/hydrogenous Os component ($^{187}\text{Os}/^{188}\text{Os} \sim 0.8$) (ref. 21), well in line with conclusions based on extraterrestrial chromite trends.

Some of the best sections for studies of Ordovician invertebrate diversification occur in Baltoscandia²². We have established the Middle Ordovician biodiversity trends for brachiopods on the basis of bed-by-bed sampling of more than 30,000 fossils from 8 sections in Baltoscandia (Fig. 3). The phylum Brachiopoda dominated the benthos of the Palaeozoic evolutionary fauna both in abundance and diversity and formed a pivotal part of the suspension-feeding food chains of the era. The phylum was widely dispersed across shallow to deep-water environments around all of the palaeocontinents. We show here that there are two intervals in the succession when the Baltoscandian brachiopod fauna suffered dramatic changes—one within the lower part of the regional Volkhov stage and one at the base of the Kunda stage (Fig. 3). The largest change occurs during exactly the same interval when the L-chondritic extraterrestrial flux peaks at the base of the Kunda stage, and when brachiopods more typical of the Palaeozoic evolutionary fauna, that is, orthides and strophomenides, diversified.

Modelling studies suggest an enhanced flux of extraterrestrial matter, including large asteroids, during 10–30 million years after major asteroid disruption events²³. The L-chondrite parent-body breakup at 470 Myr ago is thought to have created the Flora family of asteroids²⁴. These asteroids were particularly prone to enter Earth-crossing orbits because of their position relative to an important orbital resonance^{23,24}. Apparently, the Middle Ordovician interval with enhanced extraterrestrial flux is broadly coincident with the main phase of the GOBE^{1–3,15}. At least in Baltoscandia, the onset of the two events seems to coincide precisely (Figs 2, 3). Albeit speculative, the best explanation for the coincidence is that frequent impacts on Earth of large asteroids, fragments of the L-chondrite parent body, generated changes in the biota. Impact-related environmental perturbations may have accelerated a process driven also by intrinsic biological mechanisms. Although much contemporary research has focused on the negative effects of large impacts, such as in the Cretaceous–Tertiary boundary case²⁵, more minor and persistent impacts could generate diversity by creating a range of new niches across a mosaic of more heterogeneous environments. Such diversity increases are predicted by the well-established intermediate disturbance hypothesis, initially applied to diversity changes in coral reefs and tropical rainforests²⁶. Frequent impacts may also have destabilized ecological communities, allowing invasive species to take over and displace incumbent communities. The ecological and taxonomic amplitudes of the Middle Ordovician biodiversification may be decoupled and there are important feedback loops in the process. This phase of the diversification is marked by a brachiopod takeover from trilobites in benthic communities, and the establishment of recumbent life modes and size increases in many brachiopod clades. However, in contrast to the carnivores and detritus feeders of the modern fauna, the Palaeozoic fauna was then dominated by a suspension-feeding benthos with low metabolic rates better equipped to deal with and benefit from major environmental disruptions.

There are about 170 known impact craters on Earth and their record shows that impacts may have been more common by a factor of 5–10 during the Middle Ordovician compared with

other periods of the Phanerozoic^{6,13}. Four of seventeen known impact craters in Baltoscandia (Granby, Lockne, Kärddla and Tvären craters) are of Middle to early Late Ordovician age. For only very few of Earth's craters has it been possible to determine the impactor type, but for at least the 458-Myr-old Lockne crater in central Sweden, chromite in resurge deposits has implicated an L-chondritic impactor²⁷.

The strata in China and Baltoscandia that we show are rich in fossil meteorites and/or extraterrestrial chromite grains have long been known to include horizons with unusual lithologies. Over several hundred thousand square kilometres in southern Sweden, the succession of homogeneous red orthoceratite limestone is interrupted by a 1-m-thick anomalous grey, clay-rich interval with a peculiar fauna. During deposition of this bed, centimetre-sized cystoids seem to have literally covered the sea floor of a major part of the Baltic Basin. In west Russia, peculiar ooid horizons characterize the interval, and in China, unusual mini-mounds interrupt the normal succession of nodular marl and limestone²⁸ (Fig. 2). The possible relationship of these anomalous lithologies and structures to asteroid impacts or other astronomical perturbations, such as Solar System gravity disturbances, certainly warrants further studies. As shown here, at least on a regional scale, there is a close temporal coincidence between major biological change and the disruption of the L-chondrite parent body.

Recently, the impactor at the Cretaceous–Tertiary boundary has been tied by modelling to an asteroid disruption event at 160 Myr ago (ref. 29), but this event may not have led to a pronounced asteroid shower as focused in time as the one in the Middle Ordovician, and it has not left any obvious signal in the collision history of present-day meteorites.

METHODS

For chromite searches, samples of typically 10–30 kg of limestone were crushed and decalcified first in 6 M HCl and then in 18 M HF at room temperature. The acid-insoluble fraction, 63–355 μm , was searched for opaque minerals under the binocular microscope. Picked grains were mounted in epoxy resin and polished to a flat surface using a 1 μm diamond slurry. Element analyses were carried out with a scanning electron microscope–energy dispersive spectrometer^{9–11,27}. The extraterrestrial chromite grains are characterized first by high Cr_2O_3 contents of ~55–60 wt%, FeO concentrations in the range of ~25–30 wt%, low Al_2O_3 at ~5–8 wt% and MgO concentrations of ~1.5–4 wt%. The most discriminative feature, however, is narrow ranges of V_2O_5 , ~0.6–0.9 wt%, and TiO_2 , ~2.0–3.5 wt%, concentrations. For a grain to be classified as an extraterrestrial chromite grain, it has to have a composition within the defined ranges for all elements listed¹⁰.

For Os analyses, whole-rock limestone samples were ground in an agate mortar. Between 3–10 g of powdered sediment was weighed, mixed with an isotopically enriched spike containing ^{190}Os , dried at room temperature overnight and then mixed with borax, nickel and sulphur powder. After fusing the mixture for 90 min at 1,000 °C, the NiS bead was separated and dissolved in 6.2 M HCl and the residue filtered at 0.45 μm . Insoluble platinum-group-element-containing particles were dissolved in concentrated HNO_3 in a tightly closed Teflon vial at ~100 °C. After dissolution, the Teflon vial was chilled in ice water to minimize the escape of volatile OsO_4 . Osmium was then extracted from this vial with the sparging method directly into the torch of a single-collector inductively coupled plasma mass spectrometer (Finnigan Element). Typical Os blanks are <1 pg g^{-1} . Depending on the Os concentration, the precision in $^{187}\text{Os}/^{188}\text{Os}$ is between 0.5% and a few per cent. The details of the method and an evaluation of the accuracy and precision of the data have been published elsewhere³⁰.

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