way into the deeper parts of the mantle. However, if they do manage to reach the deep mantle, the models predict that they will be able to mature there and be mixed and melted to form ocean-island magmas in the fashion suggested by Chauvel and co-authors (Fig. 1).

The Nd–Hf modelling exercise conducted by Chauvel and co-authors is elegant in its simplicity, but several geochemical aspects remain to be tested. Marine sediments vary enormously in their elemental and isotopic composition from place to place[9]. Chauvel and co-authors chose only a single sedimentary composition. Whether this composition is indeed representative of the global average will have to await a survey of the Nd and Hf isotopic compositions of marine sediments subducting at oceanic trenches worldwide. In the modelling by Chauvel and co-authors, time is considered a prime determinant for generating isotopic heterogeneities in the mantle[2]. However, it could very well be that local compositional variations are more important. In addition, other studies have invoked chemical processes internal to the mantle and not external sources such as sediments or oceanic crust, to explain mantle heterogeneity[10,11].

Thus, the debate regarding the external versus internal source of mantle heterogeneity and the ultimate fate of subducting slabs continues. It is likely to be resolved by a better quantification of fluxes into the mantle at subduction zones, improved models that consider composition as well as convection, better resolution of seismic images of the mantle, and consideration of the full suite of geochemical tracers relevant to the problem of recycling within the deep Earth.

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PALAEONTOLOGY

Meteoritic spur to life?

From about 470 million years ago, the Middle Ordovician period witnessed a rapid increase in biodiversity. This explosion in numbers of species is almost perfectly contemporaneous with an increased frequency of meteorite impacts.

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The development of life on Earth has been punctuated by dramatic extinction events and by periods of enhanced biodiversification. The Ordovician period (from about 489 to 443 million years ago) witnessed one of the 'Big Five' mass extinctions in Earth history and also one of the most important intervals of biodiversification, with the emergence of relatives of many of today's marine organisms such as clams and snails. This major increase in biodiversity is sometimes termed as the 'Great Ordovician Biodiversification Event'[1–2], and differs from other periods of biodiversification in that it was not directly related to the recovery of life after an extinction event. Ever since the diversity of Ordovician fauna at a generic level has been evaluated in detail[3], various attempts have been made to identify what drove this biodiversification[1,4]. However, a fully satisfactory explanation had not been offered. On page 49 of this issue, Schmitz and co-authors[5] discuss a fascinating new hypothesis, which relates the increase in biodiversity to an increased bombardment of meteorites around 470 million years ago.

Not only did new phyla — major biological categories that contain several classes of animals — emerge during the Ordovician period, but it was also a time of dramatic increase in the number of species of marine organisms that dwell at different depths in the sea (Fig. 1). In investigating the reasons for these changes, biological aspects, in addition to the more commonly evoked external factors, cannot be ignored. Any comprehensive solution for the Ordovician diversification must give a reason for the enhanced and sustained genetic mutations necessary for the dramatic increase in the number of species. These biological processes can be deeply affected by external factors including extraterrestrial events such as gamma-ray bursts and asteroid or meteorite impacts, as well as by regional or global parameters such as physical and chemical changes in the Earth's environments. A recent review[4] of these factors suggests that they all seem to have influenced the Great Ordovician Biodiversity Event to some extent (Fig. 1).

Schmitz and co-authors argue that an extraterrestrial event — the disintegration of a body in the asteroid belt — played an important role in the Great Ordovician Biodiversification Event by causing sustained impacts of fragments from kilometre-sized asteroids to micrometeorites[6] on the Earth's surface. This bombardment is estimated to have lasted for 10–30 million years after the initial break-up of the parent body[7] and the resultant meteorite fragments can be found in the layers of rocks that were deposited at the time.

Schmitz and co-authors sampled and analysed meteoritic fragments that occur in rocks from the Baltic and Scandinavian regions, as well as from China. They also conducted a detailed analysis of fossil brachiopods — ancient clam-like organisms — from the Baltic and Scandinavian region. Their data suggest that the very first impacts during the Middle Ordovician period in Baltoscandia are perfectly contemporaneous with the onset of the second and faster pulse of the diversification of brachiopods documented in this region (see Figs 2–3 in ref. 5). This is unlikely to be a mere coincidence and strongly hints at a causal relationship between the extraterrestrial asteroid flux and the acceleration of brachiopod diversification. Environmental perturbations generated by recurrent impacts of the larger bodies on the seafloor probably created a number of new ecological niches and suppressed others. These successive changes meant that those organisms best suited to adapt were most likely to thrive.

The story is not perfect, however. The first significant increase in the number of brachiopod species (see Figs 2–3 in ref. 5) is documented early in the Middle Ordovician period. However, meteorite remains that are of this age have not been found from the rocks that Schmitz and co-authors have looked at, suggesting that the biodiversification process started slightly before the first significant bombardment of meteorite showers on the Baltic and Scandinavian region and China. This is important to bear in mind when evaluating their argument for perfect synchroneity between the biodiversification and an enhanced frequency of meteorite impacts.

Before this hypothesis can be definitively adopted as the main trigger of the Great Ordovician Biodiversity Event, more evidence needs to be gathered. The same detailed work, which has presently been conducted on brachiopods, should be conducted on several other significant fossil groups represented in the Baltic and Scandinavian regions in order to determine whether their biodiversification patterns are identical and contemporaneous with those for the brachiopods. Similarly, meteorites of the same type and age as those found in the Baltic and Scandinavian region and China need to be documented at other locations too. Further research has already been initiated in South China, but for a global event as significant as the Great Ordovician Biodiversification Event, meteorites should be found randomly distributed throughout rocks of that age.

Furthermore, the possibility of finding impacts of the same type and age on the Moon and even on the neighbouring rocky planets should be explored — it is quite possible that the ellipsoids of those planets were suitable for capturing remains of the disintegrated parent body of the meteorites.

Other periods of increased rates of biodiversification, especially during the Late Ordovician period, have been documented at the global scale for various marine invertebrate groups (Fig. 1). The hypothesis of Schmitz and co-authors would be strengthened if these later periods of diversity changes were also supported by coincident meteorite remains.

Finally, as mentioned earlier, the main episode of meteoritic bombardment most probably lasted for a few tens of million years after the disruption of the parent body. Therefore, if one accepts the extraterrestrial explanation, biodiversification should have increased continuously during most of the Ordovician period. This is not documented for all the fossil groups — for example, diversity dropped during the beginning of the Late Ordovician period as reported in previous global compilations[1]. Hence, factors other than the meteorite impacts may have been at play.

At any rate, if additional work supports the provocative and interesting hypothesis suggested by Schmitz and co-authors, it will no longer be appropriate to regard projectiles from space solely as 'killers'. It is quite likely that when such objects were of moderate size and when their flux was sufficiently sustained, they favoured the emergence of new species through recurrent modifications of shallow marine environments.

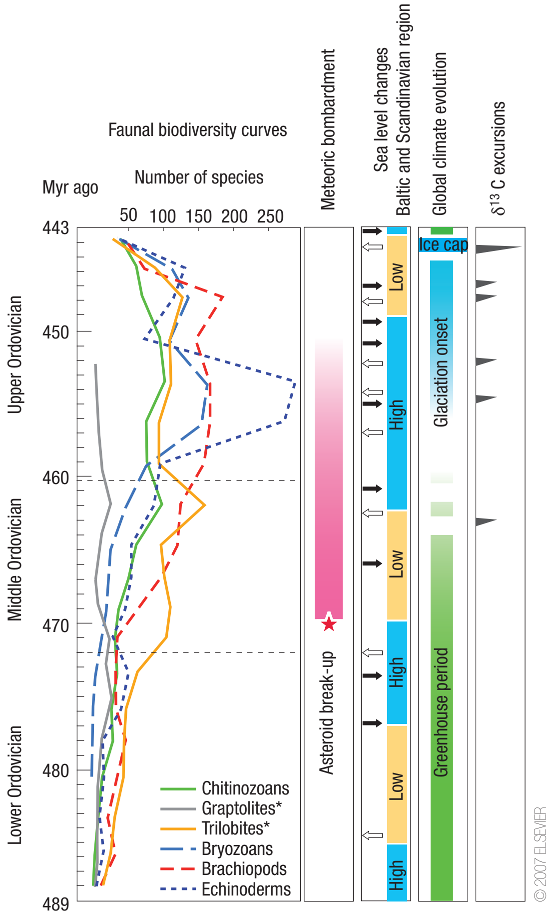

Figure 1 Meteorites and biodiversity. Timing of the asteroid disruption and of the subsequent meteorite showers on Earth (pink bar; ref. 5) compared with the global diversification trends at the species level for selected groups of Ordovician organisms (left-hand panel. Faunal data compiled from ref. 1. Asterisks indicate regional curves from the Baltic and Scandinavian region). Changes in sea level and global climate as well as unusual signals in carbon isotope compositions suggesting important changes to the Earth's carbon cycling system are shown for comparison (right-hand panels), as possible alternative causes for the Great Ordovician Biodiversification Event. The black and white arrows represent major inrcreases and decreases in sea level, respectively. Adapted from ref. 4.

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