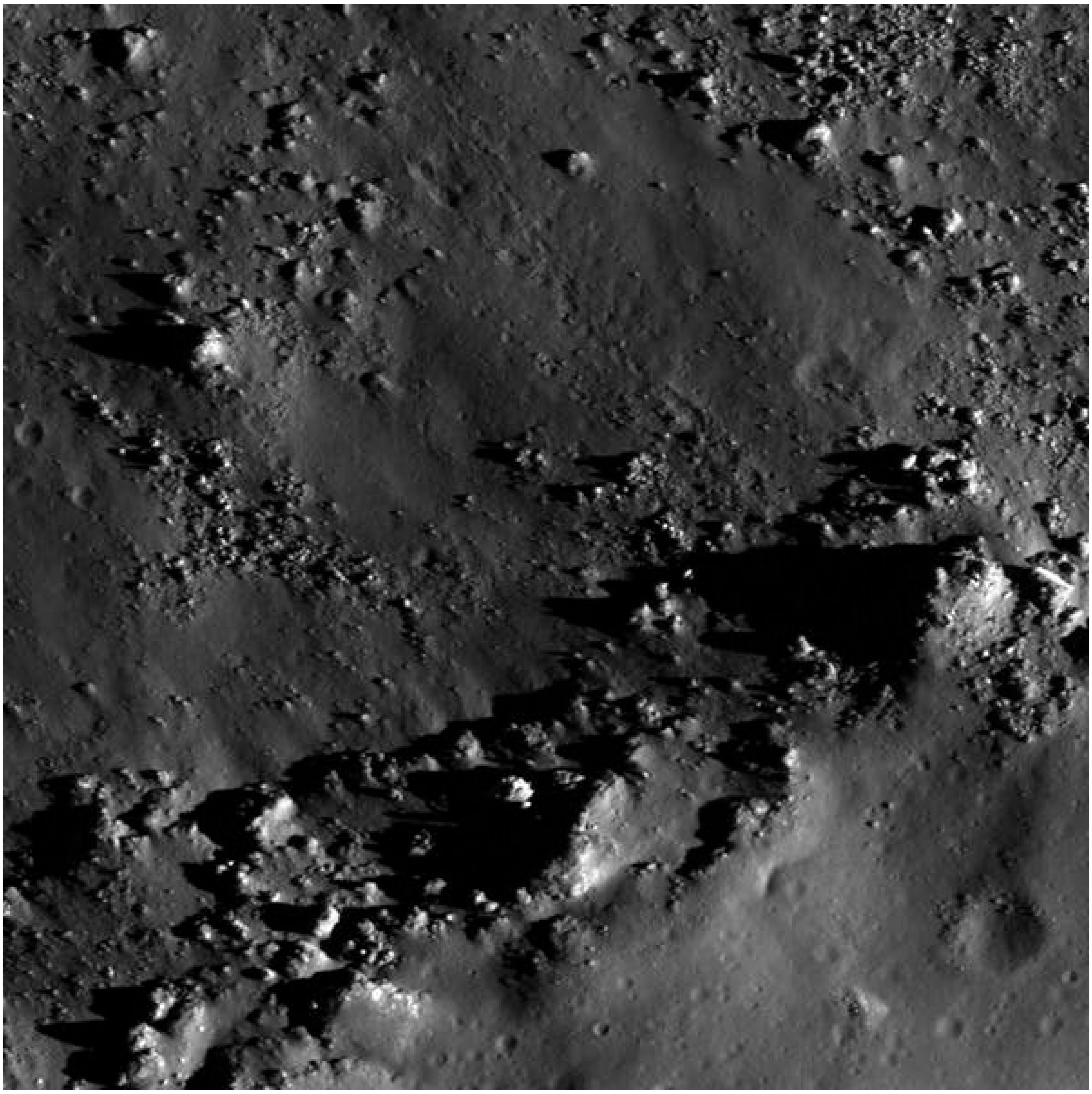
Planetary science

Impacts increased at the end of the Palaeozoic (January 2019)

Because it is so geologically active the Earth progressively erases signs of asteroid and comet impacts, by erosion, burial or even subduction in the case of the oceanic record. As a result, the number of known craters decreases with age. To judge the influence of violent extraterrestrial events in the past geologists therefore rely on secondary outcomes of such collisions, such as the occasional presence in the sedimentary record of shocked quartz grains, glassy spherules and geochemical anomalies of rare elements. The Moon, on the other hand, is so geologically sluggish that its surface preserves many of the large magnitude impacts during its history, except for those wiped out by later such events. For instance, a sizeable proportion of the lunar surface comprises its dark maria, which are flood basalts generated by gigantic impacts around 4 billion years ago. Older impacts can only be detected in its rugged, pale highland terrains, and they have been partially wiped out by later impact craters. The Moon's surface therefore preserves the most complete record of the flux and sizes of objects that have crossed its orbit shared with the Earth.

The Earth presents a target thirteen times bigger than the cross sectional area of the Moon so it must have received 13 times more impacts in their joint history. Being about 81 times as massive as the Moon its stronger gravitational pull will have attracted yet more and all of them would have taken place at higher speeds. The lunar samples returned by the Apollo Missions have yielded varying ages for impact-glass spherules so that crater counts combined with evidence for their relative ages have been calibrated to some extent to give an idea of the bombardment history for the Earth Moon System. Until recently this was supposed to have tailed off exponentially since the Late Heavy Bombardment between 4.0 to 3.8 billion years ago. But the dating of the lunar record using radiometric ages of the small number of returned samples is inevitably extremely fuzzy. A team of planetary scientists from Canada, the US and Britain has developed a new approach to dating individual crater using image data from NASA's Lunar Reconnaissance Orbiter (LRO) launched in 2009 (Mazrouei, S. *et al.* 2019. Earth and Moon impact flux increased at the end of the Paleozoic. *Science*, v.**363**, p. 253-257; DOI: 10.1126/science.aar4058).

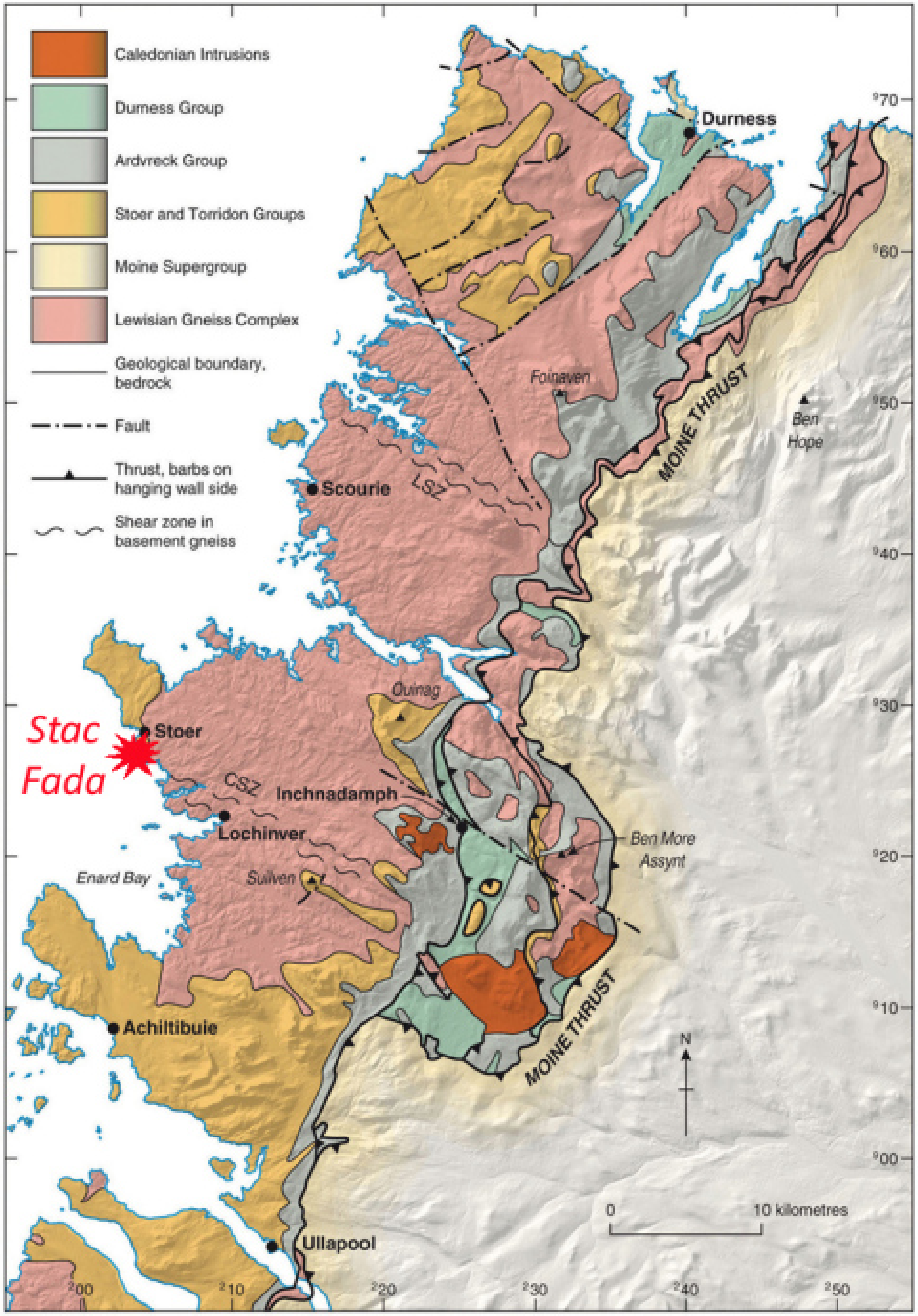
The method that they devised is, curiously, based on thermal imagery from the LRO's Diviner instrument which records the Moon's surface temperature. Comparison of day- and night-time temperatures produces a measure of surface materials' ability to retain heat known as thermal inertia. A material with high thermal inertia stays warmer for longer at night. When a crater forms it partly fills with rock fragments excavated by the impact. When fresh these are full of large blocks of rock that were too massive to be blasted away. But these blocks are exposed to bombardment by lesser projectiles for the lifetime of the crater, which steadily reduces them to smaller fragments and eventually dust. Blocks of solid rock retain significantly more solar heat than do gravelly to dust-sized materials: thermal inertia of the crater floor therefore decreases steadily with age.



Blocky surface of a relatively young lunar crater (Credit: NASA)

As well as day- and night thermal data provided by the Diviner instrument, from which thermal inertia values are calculated, the LRO deploys two cameras that capture black and white images of the surface in the visible range, with a resolution of about a metre. They enable the blockiness of crater floors to be estimated. Sara Mazrouei and colleagues measured blockiness and thermal inertia of the floors of 111 craters more than 10 km across, ages of nine of which had been modelled independently using counts of smaller craters that subsequently accumulated on their floors shown by even finer resolution images from the Japanese Kaguya orbiter. Their results are surprising. About 290 Ma ago the rate of large impacts on the Moon increased by a factor of 2.6. This might explain why the Neoproterozoic and Palaeozoic Eras are deficient in terrestrial craters. Another inference from the results is that the number of objects in Earth-crossing orbits suddenly increased at the end of the Carboniferous. Maybe that resulted from an episode of collisions and break-up of large bodies in the Asteroid Belt or, perhaps, some kind of gravitational perturbation by Jupiter. The age-distribution of large craters on Earth is no help because of their ephemeral nature. Moreover, apart from Chicxulub that is bang on the K-Pg boundary, there is little evidence of an increase in impact-driven mass extinctions in the Mesozoic and Cenozoic. Nor for that matter did igneous activity or sediment deposition undergo any sudden changes. There are sediments that seem to have formed as a result of tsunami devastation, but none greater in magnitude than could have been caused by major earthquakes. Or … maybe geologists should have another look at the stratigraphic record.

A major Precambrian impact in Scotland **(June 2019)**



Grossly simplified geological map of NW Scotland, showing the location of the Torridonian impactite (credit: British Geological Survey)

The northwest of Scotland has been a magnet to geologists for more than a century. It is easily accessed, has magnificent scenery and some of the world's most complex geology. The oldest and structurally most tortuous rocks in Europe – the Lewisian Gneiss Complex – which span crustal depths from its top to bottom, dominate much of the coast. These are unconformably overlain by a sequence of mainly terrestrial sediments of Meso- to Neoproterozoic age – the Torridonian Supergroup – laid down by river systems at the edge of the former continent of Laurentia. They form a series of relic hills resting on a rugged landscape carved into the much older Lewisian. In turn they are capped by a sequence of Cambrian to Lower Ordovician shallow-marine sediments. A more continuous range of hills no more than 20 km eastward of the coast hosts the famous Moine Thrust Belt in which the entire stratigraphy of the region was mangled between 450 and 430 million years ago when the elongated microcontinent of Avalonia collided with and accreted to Laurentia.

Exposures are the best in Britain and, because of the superb geology, probably every geologist who graduated in that country visited the area, along with many international geotourists. The more complex parts of this relatively small area have been mapped and repeatedly examined at scales larger than 1:10,000; its geology is probably the best described on Earth. Yet, it continues to throw up dramatic conclusions. However, the structurally and sedimentologically simple Torridonian was thought to have been done and dusted decades ago, with a few oddities that remained unresolved until recently.

One such mystery lies close to the base of the vast pile of reddish Torridonian sandstones, the Stac Fada Member of the Stoer Group. Beneath it is a common-or-garden basal breccia full of debris from the underlying Lewisian Complex, then red sandstones and siltstones deposited by a braided river system. The Stac Fada Member is a mere 10 m thick, but stretches more than 50 km along the regional NNE-SSW strike. It comprises greenish to pink sandstones with abundant green, glassy shards and clasts, previously thought to be volcanic in origin, together with what were initially regarded as volcanic spherules – the results of explosive reaction of magma when entering groundwater or shallow ponds. Until 2002, that was how ideas stood. More detailed sedimentological and geochemical examination found quartz grains with multiple lamellae evidencing intense shock, anomalously high platinum-group metal concentrations and chromium isotopes that were not of this world. Indeed, the clasts and the ensemble as a whole look very similar to the 'suevites' around the 15 Ma old Ries Impact crater in Germany. The bed is the product of mass ejection from an impact, a designation that has attracted great attention. In 2015 geophysicists suggested that the impact crater itself may coincide with an isolated gravity low about 50 km to the east. A team of 8 geoscientists from the Universities of Oxford and Exeter, UK, have recently reported their findings and ideas from work over the last decade. (Amor, K, *et al*. 2019. The Mesoproterozoic Stac Fada proximal ejecta blanket, NW Scotland: constraints on crater location from field observations, anisotropy of magnetic susceptibility, petrography and geochemistry. *Journal of the Geological Society*, online; DOI: 10.1144/jgs2018-093).

The age of the Stac Fada member is around 1200 Ma, determined by Ar-Ar dating of K-feldspar formed by sedimentary processes. Geochemistry of Lewisian gneiss clasts compared with in situ basement rocks, magnetic data from the matrix of the deposit, and evidence of compressional forces restricted to it suggest that the debris emanated from a site to the WNW of the midpoint of the member's outcrop. Rather than being a deposit from a distant source, carried in an ejecta curtain, the Stac Fada material is more akin to that transported by a volcanic pyroclastic flow. That is, a dense, incandescent debris cloud moving near to the surface under gravity from the crater as ejected material collapsed back to the surface. On less definite grounds, the authors suggest that a crater some 13 to 14 km across penetrating about 3 km into the crust may have been involved.

Together with evidence that I described in Impact debris in Britain (*Magmatism* February 2018) and Britain's own impact (*Planetary Science* November 2002) it seems that Britain has directly witnessed three impact events. But none of them left a tangible crater.

Last day of the dinosaurs **(September 2009)**

As they say, 'everyone knows' that the dinosaurs were snuffed out, except, of course, for those that had evolved to become birds and somehow survived. When it happened is known quite precisely – at the end of the Cretaceous (66.043 ± 0.011 Ma) – and there were two possible causal mechanisms: emissions from the Deccan Trap flood basalts and/or the Chicxulub impact crater. But what was the Cretaceous-Palaeogene (K-Pg) boundary event actually like? Many have speculated, but now there is evidence.

In 2016 a deep-sea drilling rig extracted rock core to a depth of 1.35 km beneath the sea floor off Mexico's Yucatan Peninsula, slightly off the centre of the circular Chicxulub structure (see K-T (K-Pg) boundary impact probed, November 2016). This venture was organised and administered jointly by the International Ocean Discovery Program (IODP) and the International Continental Scientific Drilling Program (ICDP) as Mission Specific Platform Expedition no. 364. Results from the analysis of the cored rock sequence have been generating pulses of excitement among palaeontologists, petrologists and planetary scientist on a regular basis. The science has been relatively slow to emerge in peer-reviewed print. Appetites have been whetted and the first substantial paper is about the bottom 130 metres of the core (Gulick, S.P.S. and 29 others 2019. The first day of the Cenozoic. *Proceedings of the National Academy of Sciences*. 9 September 2019; DOI: 10.1073/pnas.1909479116). It might seem as though the publication schedule has been stage managed to begin with, literally, the 'bang' itself.

The deepest 20 m thick layer is mainly silicate glass. It was formed in the seconds after the 12 km-wide impactor arrived to smash through the water and sea-floor sediments of the early Caribbean Sea, at speed of around 20 Km s^{-1}. It vaporised water and rock as well as shoving aside the surrounding sea and blasting debris skyward and outward. In an instant a new hole in the crust was filled with molten rock. The overlying rock is a veritable apple-crumble of shattered debris mixed with and held together by glass, and probably formed as water flowed into the crater to result in explosive reaction with the molten crystalline crust beneath. The fragments lessen in size up the core, probably reflecting ejected material mixed in the displaced seawater. Impact specialists have estimated that this impactite layer formed in little more than ten minutes after collision. The glass-laden breccia is abruptly capped by bedded sediments, considered to have been delivered by the backwash of a huge, initial tsunami. In them are soils and masses of charcoal, from the surrounding land areas, scorched and burnt by the projectile's entry flash, inundated by the tsunami and then dragged out to sea as it receded. These are the products of the hours following the impact as successive tsunamis swashed to and fro across the proto-Caribbean Basin; hence 'The first day of the Cenozoic', of Gulick *et al*.'s title.

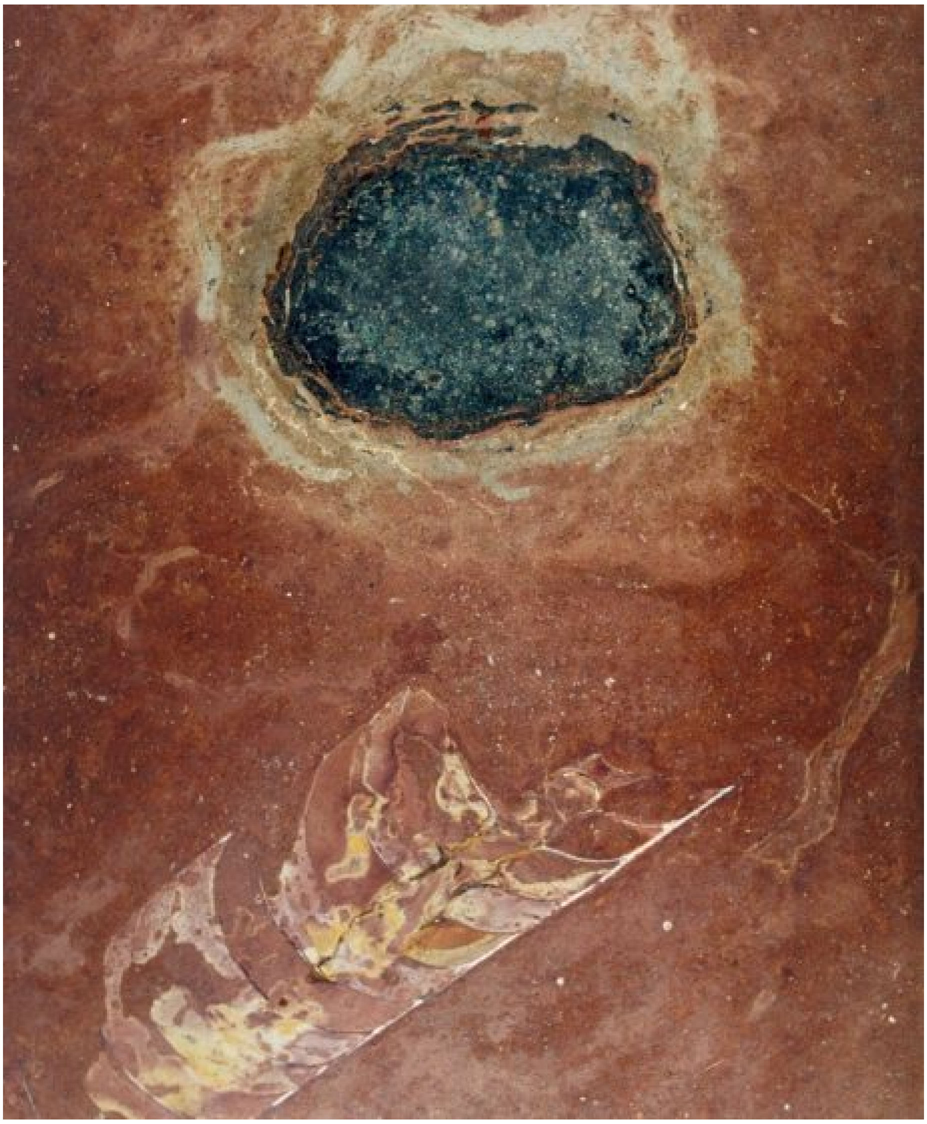
Artist's impression of the Chicxulub impact (Credit: Barcroft Productions for the BBC)

Other cores drilled beyond the scope of the Chicxulub crater during offshore oil exploration show a sequence of limestones with thick beds of gypsum ($CaSO_4.2H_2O$). Yet the crater debris itself contains no trace of this mineral. Around 325 Gt of sulfur, almost certainly in the form of SO_2, entered the atmosphere on that first day, adding to the dust. Ending up in the stratosphere as aerosols it would have diffused solar radiation away from the surface, resulting in an estimated 25°C global cooling that lasted 25 years. The sulfur oxides in the lower atmosphere ended up in acid rain that eventually acidified the upper ocean to devastate shallow-marine life.

See also: Amos, J. 2019. The day the dinosaurs' world fell apart. (BBC News 10 September 2019); Rocks at asteroid impact site record first day of dinosaur extinction(Phys.org*)*; Wei-Haas, M. 2019. Last day of the dinosaurs' reign captured in stunning detail. *National Geographic*, 9 September 2019.

Ordovician ice age: an extraterrestrial trigger **(September 2019)**

The Ordovician Period is notable for three global events; an explosion in biological diversity; an ice age, and a mass extinction. The first, colloquially known as the Great Ordovician Biodiversification Event, occurred in the Middle Ordovician around 470 Ma ago (see The Great Ordovician Diversification, September 2008) when the number of recorded fossil families tripled. In the case of brachiopods, this seems to have happened in no more than a few hundred thousand years. The glacial episode spanned the period from 460 to 440 Ma and left tillites in South America, Arabia and, most extensively, in Africa. Palaeogeographic reconstructions centre a Gondwanan ice cap in the Western Sahara, close to the Ordovician South Pole. It was not a Snowball Earth event, but covered a far larger area than did the maximum extent the Pleistocene ice sheets in the Northern Hemisphere. It is the only case of severe global cooling bracketing one or the 'Big Five' mass extinctions of the Phanerozoic Eon. In fact two mass extinctions during the Late Ordovician rudely interrupted the evolutionary promise of the earlier threefold diversification, by each snuffing-out almost 30% of known genera.



L-chondrite meteorite in iron-stained Ordovician limestone together with a nautiloid (credit: Birger Schmitz)

A lesser-known feature of the Ordovician Period is a curious superabundance of extraterrestrial debris, including high helium-3, chromium and iridium concentrations, preserved in sedimentary rocks, particularly those exposed around the Baltic Sea (Schmitz, B. and 19 others 2019. An extraterrestrial trigger for the mid-Ordovician ice age: Dust from the breakup of the L-chondrite parent body. *Science Advances*, v. **5,**eaax4184; DOI: 10.1126/sciadv.aax4184). Yet there is not a sign of any major impact of that general age, and the meteoritic anomaly occupies a 5 m thick sequence at the best studied site in Sweden, representing about 2 Ma of deposition, rather than the few centimetres at near-instantaneous impact horizons such as the K-Pg boundary. Intact meteorites are almost exclusively L-chondrites dated at around 466 Ma. Schmitz and colleagues reckon that the debris represents the smashing of a 150 km-wide asteroid in orbit between Mars and Jupiter. Interestingly, L-chondrites are more abundant today and in post-Ordovician sediments than they were in pre-Ordovician records, amounting to about a third of all finds.

This suggests that the debris is still settling out in the Inner Solar System hundreds of million years later. Not long after the asteroid was smashed a dense debris cloud would have entered the Inner Solar System, much of it in the form of dust.

The nub of Schmitz *et al'*s hypothesis is that considerably less solar radiation fell on Earth after the event, resulting in a sort of protracted 'nuclear winter' that drove the Earth into much colder conditions. Meteoritic iron falling the ocean would also have caused massive phytoplankton blooms that sequestered CO_2 from the Ordovician atmosphere to reduce the greenhouse effect. Yet the cooling seems not to have immediately decimated the 'booming' faunas of the Middle Ordovician. Perhaps the disruption cleared out some ecological niches, for new species to occupy, which may explain sudden boosts in diversity among groups such as brachiopods. Two sharp jumps in brachiopod species numbers are preceded and accompanied by 'spikes' in the number of extraterrestrial chromite grains in one Middle Ordovician sequence. One possibility, suggested in an earlier paper (Schmitz, B. and 8 others 2008. Asteroid breakup linked to the Great Ordovician Biodiversification Event. *Nature Geoscience*, v. **1**, p. 49-53; DOI: 10.1038/ngeo.2007.37) is that the undoubted disturbance may have killed off species of one group, maybe trilobites, so that the resources used by them became available to more sturdy groups, whose speciation filled the newly available niches. Such a scenario would make sense, as mobile predators/scavengers (e.g. trilobites) may have been less able to survive disruption, thereby favouring the rise of less metabolically energetic filter feeders (e.g. brachiopods).

See also: Sokol, J. 2019. Dust from asteroid breakup veiled and cooled Earth. *Science*, v. **365**, pp. 1230: DOI: 10.1126/science.365.6459.1230, How the first metazoan mass extinction happened (Earth-logs, May 2014)

Extraterrestrial sugar **(November 2019)**

The coding schemes for Earth's life and evolution (DNA and RNA), its major building blocks and basic metabolic processes have various sugars at their hearts. How they arose boils down to two possibilities: either they were produced right here by the most basic, prebiotic processes or they were supplied from interplanetary or interstellar space. All kinds of simple carbon-based compounds turn up in spectral analysis of regions of star formation, or giant molecular clouds: CN, CO, C_2H, H_2CO up to 10 or more atoms that make up recognisable compounds such as benzonitrile (C_6H_5CN). Even a simple amino acid (glycene – CH_2NH_2COOH) shows up in a few nearby giant molecular clouds. Brought together in close proximity, instead of dispersed through huge volumes of near-vacuum, a riot of abiotic organic chemical reactions could take place. Indeed, complex products of such reactions are abundant in carbonaceous meteorites whose parent asteroids formed within the solar system early in its formation. Some contain a range of amino acids though not, so far, the five bases on which genetics depends: in DNA adenine, cytosine, guanine and thymine (replaced by uracil in RNA). Yet, surprisingly, even simple sugars have remained elusive in both molecular clouds and meteorites.

Artist's impression of the asteroid belt from which most meteorites are thought to originate (Credit: NASA/JPL)

A recent paper has broken through that particular barrier (Furukawa, Y. *et al.* 2019. Extraterrestrial ribose and other sugars in primitive meteorites. *Proceedings of the National Academy of Sciences*. Online; DOI: 10.1073/pnas.1907169116). Yoshihiro Furukawa and colleagues analysed three carbonaceous chondrites and discovered traces of 4 types of sugars. It seems that sugar compounds have remained elusive because those now detected are at concentrations thousands of times lower than those of amino acids. Contamination by terrestrial sugars that may have entered the meteorites when they slammed into soil is ruled out by their carbon isotope ratios, which are very different from those in living organisms. One of the sugars is ribose, a building block of RNA (DNA needs deoxyribose). Though a small discovery, it has great significance as regards the possibility that the components needed for living processes formed in the early Solar System. Moon formation by giant impact shortly after accretion of the proto-Earth would almost certainly have destroyed such organic precursors. So, if the Earth's surface was chemically 'seeded' in this way it is more likely to have occurred at a later time, perhaps during the Late Heavy Bombardment 4.1 to 3.8 billion years ago (see: Did mantle chemistry change after the late heavy bombardment? In *Earth-logs* September 2009)

Should you worry about being killed by a meteorite? **(December 2019)**

In 1994 Clark Chapman of the Planetary Science Institute in Arizona and David Morrison of NASA's Ames Research Center in California published a paper that examined the statistical hazard of death by unnatural causes in the United States (Chapman, C. & Morrison, D. 1994. Impacts on the Earth by asteroids and comets: assessing the hazard. *Nature*, v. **367**, p. 33–40; DOI:10.1038/367033a0). Specifically, they tried to place the risk of an individual being killed by a large asteroid (~2 km across) hitting the Earth in the context of more familiar unwelcome causes. Based on the then available data about near-Earth objects – those whose orbits around the Sun cross that of the Earth – they assessed the chances as ranging between 1 in 3,000 and 1 in 250,000; a chance of 1 in 20,000 being the most likely. The results from their complex calculations turned out to be pretty scary, though not as bad as dying in a car wreck, being murdered, burnt to death or accidentally shot. Asteroid-risk is about the same as electrocution, at the higher-risk end, but significantly higher than many other causes with which the American public are, unfortunately, familiar: air crash; flood; tornado and snake bite. The lowest asteroid-risk (1 in 250 thousand) is greater than death from fireworks, botulism or trichloroethylene in drinking water; the last being 1 in 10 million.

Chapman and Morrison cautioned against mass panic on a greater scale than Orson Welles's 1938 CBS radio production of H.G. Wells's *War of the Worlds* allegedly resulted in. Asteroid and comet impacts are events likely to kill between 5,000 and several hundred million people each time they happen but they occur infrequently. Catastrophes at the low end, such as the 1908 Tunguska air burst over an uninhabited area in Siberia, are likely to happen once in a thousand years. At the high end, mass extinction impacts may occur once every hundred million years. As might be said by an Australian, 'No worries, mate'! But you never know…

Michelle Knapp's Chevrolet Malibu the morning after being struck by a stony-iron meteorite. Having bought the old car for US$ 300, Michelle sold it as a curiosity item for US$ 25,000 meteorite fetching US$ 50,000 (credit: John Bortle)

How about ordinary meteorites that come in their thousands, especially when the Earth's orbit takes it through the former paths taken by disintegrating comets? When I was a kid rumours spread that a motor cyclist had a narrow escape on the flatlands around Kingston-upon-Hull in East Yorkshire, when a meteorite landed in his sidecar: probably apocryphal. But Michelle Knapp of Peeskill, New York, USA had a job for the body shop when a 12 kg extraterrestrial object hit her Chevrolet Malibu, while it was parked in the driveway. In 1954, Ann Hodges of Sylacauga, Alabama was less fortunate during an afternoon nap on her sofa, when a 4 kg chondritic meteorite crashed through her house roof, hit a radiogram and bounced to smash into her upper thigh, badly bruising her. For an object that probably entered the atmosphere at about 15 km s^{-1}, that was indeed a piece of good luck resulting from air's viscous drag, the roof impact and energy lost to her radiogram. The offending projectile became a doorstop in the Hodge residence, before the family kindly donated it to the Alabama Museum of Natural History. Another fragment of the same meteorite, found in a field a few kilometres away, fetched US$ 728 per gram at Christie's auction house in 2017. Perhaps the most unlucky man of the 21st century was an Indian bus driver who was killed by debris ejected when a meteorite struck the dirt track on which he was driving in Tamil Nadu in 2016 – three passengers were also injured. But that is disputed, some claiming that the cause was an explosive device.