

Planetary Science 2024

An astronomical background to flood basalt events and mass extinctions?

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Map of the Milky Way galaxy as it would appear from a viewpoint above the galactic centre. The Solar System is located in the Orion Spur (green dot) (Credit: Wikipedia)

Michael Rampino and Ken Caldeira of New York University and the Carnegie Institute have for at least three decades been at the forefront of studies into mass extinctions and their possible causes, including flood-basalt volcanism, extraterrestrial impacts and climate change. As early as 1993 the duo reported an ubiquitous 26-million year cycle in plate tectonic and volcanic activity. In Rampino's 2017 book *Cataclysms: A New Geology for the Twenty-First Century* the notion of a process similar to

Milutin Milankovich's prediction of Earth's orbital characteristics underpinning climate cyclicity figured in his thinking (see [Shock and Er ... wait a minute](#), Earth-logs, October 2017). Rampino postulated then that this longer-term geological cyclicity could be linked to gravitational changes during the Solar System's progress around the Milky Way galaxy. He was by no means the first to turn to galactic forces, [Johann Steiner having made a similar suggestion in 1966](#). The notion stems from the Solar System's wobbling path as it orbits the centre of the Milky Way galaxy about every 250 Ma, which may result in its passage through a vast layered variation in several physical properties aligned at right angles to galactic orbital motions. This grand astronomical theory is 'a story that will run and run'; and it has. It is possible that the galaxy has corralled dark matter in a disc within the galactic plane, which Rampino and Caldeira latched onto that notion a year after it appeared in [Physical Review Letters](#) in 2014.

As I commented in my brief [review of Rampino's book](#): "As for Rampino's galactic hypothesis, the statistics are decidedly dodgy, but chasing down more forensics is definitely on the cards." Indeed they have been chased in a recent review by the pair and their colleague Sedelia Rodriguez (Rampino, M.R., Caldeira, K. & Rodriguez, S. 2023. [Cycles of ~32.5 My and ~26.2 My in correlated episodes of continental flood basalts \(CFBs\), hyper-thermal climate pulses, anoxic oceans, and mass extinctions over the last 260 My: Connections between geological and astronomical cycles](#). *Earth-Science Reviews*, v. 246 ; DOI: 10.1016/j.earscirev.2023.104548; reprint available on request from [Rampino](#)). They base their amplified case on much more than radiometric dates of continental flood basalt (CFB) events matched against the stratigraphic record of biotic diversity. Among the proxies are published measurements of mercury and osmium isotope anomalies in oceanic sediments that are best explained by sudden increases in basaltic magma eruption; signs of deep ocean anoxia; new dating of marine and non-marine extinctions in the fossil record, and episodes of sudden extreme climatic heating.

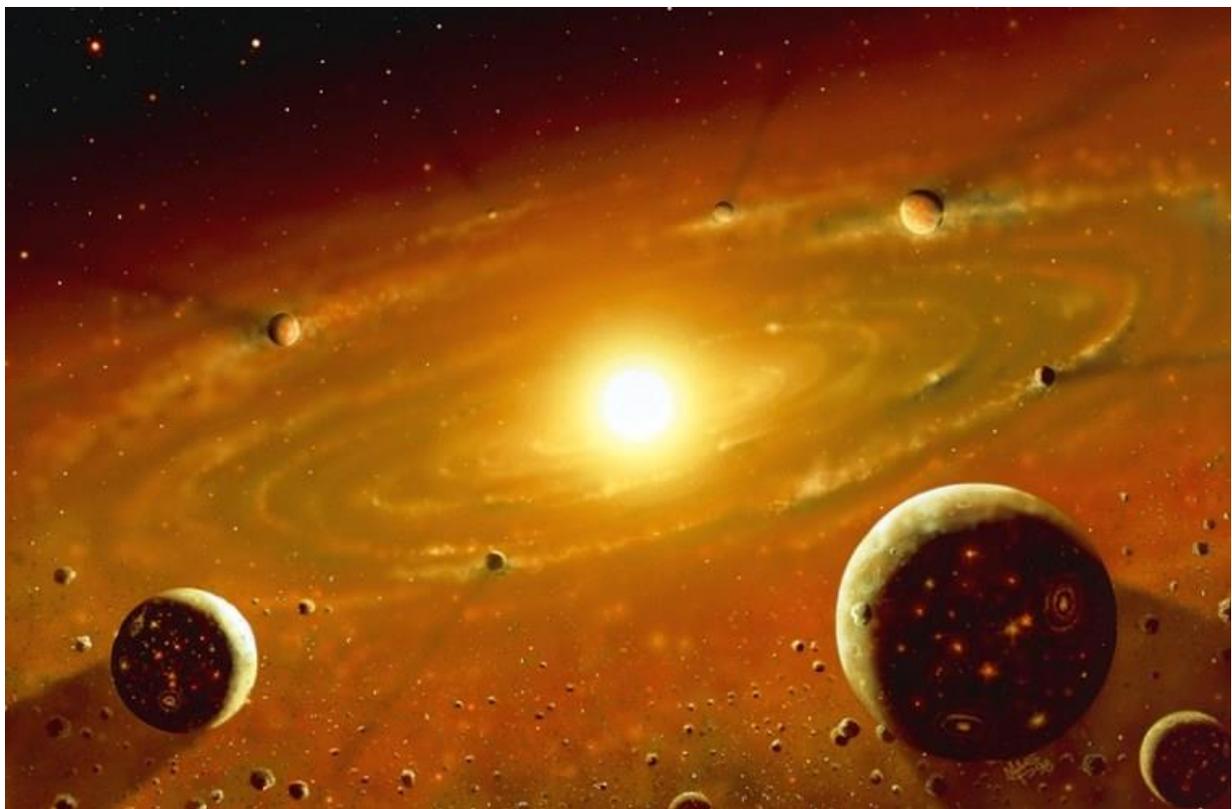
Statistical analysis of the ages of anoxic events and marine extinctions has yielded cycles of 32.5 and 26.2 Ma, those for CFBs having a 32.8 Ma periodicity. A note of caution, however: their data only cover the last 266 Ma – about one orbit of the solar system around the galactic centre. The authors attribute their interpretation of the cycles "to the Earth's tectonic-volcanic rhythms, but the similarities with known Milankovitch Earth orbital periods and their amplitude modulations, and with known Galactic cycles, suggest that, contrary to conventional wisdom, the geological events and cycles may be paced by astronomical factors".

Whether or not a detailed record of appropriate proxies can be extended back beyond the Late Permian, remains to be seen. The main fly-in-the-ointment is the tendency of CFB provinces to form high ground so that they are readily eroded away. Pre-Mesozoic signs of their former presence lie in basaltic dyke swarms that cut through older crystalline continental crust. The marine sedimentary record is somewhat better preserved. A search for distinctive anomalies in osmium isotopes and mercury concentrations, which are useful proxies for global productivity of basaltic magmas, will be costly. Moreover, dating will depend to a large degree on the traditional palaeontology of strata, which in Palaeozoic rocks is more difficult to calibrate precisely by absolute radiometric dating.

The chaotic early Solar System: when giant planets went berserk

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Readers of Earth-logs will be familiar with the way gravitational interactions between the planets that orbit the Sun control cyclical shifts in each other's rotational and orbital behaviours. The best known are the three [Milankovich cycles](#). The eccentricity of Earth's orbit (deviation from a circular path) changes according to the varying gravitational pulls exerted by Jupiter and Saturn as they orbit the Sun, and is dominated by 100 ka cyclicity. The tilt (obliquity) of Earth's rotational axis changes in 41 ka cycles. The direction in which the axis points relative to the Sun varies with its precession which has a period of about 25.7 ka. Together they control the amount of solar heating that our planet receives, best shown by the current variation in glacial-interglacial cycles. But the phenomena predicted by Milutin Milankovich show up in palaeoclimatic changes back to at least the late Precambrian. Climate changes resulting from the [gravitational effect of Mars](#) have recently been detected with a 2.4 Ma period. But that steady carousel of planetary motions hasn't always characterised the Solar System.



Cartoon showing planet formation in the early, unstable Solar System (Credit: Mark Garlick, Science Source)

Observations of other stars that reveal the presence of their own planetary systems show that some have giant planets in much closer orbits than those that circuit the Sun. Others occur at distances that extend as far as the orbital diameters as those in the Solar System: so perhaps giant planets can migrate. A possibility began to be discussed in the late 1990s that Jupiter, Saturn, Uranus and Neptune – and a fifth now-vanished giant planet – were at the outset in neat, evenly-spaced and

much closer orbits. But they were forced outwards later into more eccentric and generally askew orbits. In 2005, planetary astronomers gathered in Nice, France to ponder the possibilities. The outcome was the [‘Nice’ Model](#) that suggested that a gravitational instability had once emerged, which set the Solar System in chaotic motion. It may even have flung gigantic masses, such as postulated fifth giant planets, into interstellar space. This upheaval may have been due to a rapid change in the overall distribution of mass in the Solar System, possibly involving gas and dust that had not yet accreted into other planets or their planetesimal precursors. Chaotic antics of monstrous bodies and shifts in their combined gravitational fields can barely be imagined: it was nothing like the staid and ever present Milankovich Effect. Geologists have reconstructed one gargantuan event that reset the chemistry of the early Earth when it collided with another body about the size of Mars. That also flung off matter that became the Moon. Evidence from lunar and terrestrial zircon grains (see: [Moon-forming impact dated](#); March 2009) suggests the collision occurred before 4.46 billion years ago (when parts of both eventually crystallised from magma oceans), Solar System having begun to form at around 4.57 Ga. Could formation of the Moon record the early planetary chaos? Others have suggested instead that the great upheaval was the [Late Heavy Bombardment](#), between 4.1 and 3.8 Ga, which heavily cratered much of the lunar surface and those of moons orbiting the giant planets.

Another approach has been followed by Chrysa Avdellidou of the University of Leicester, UK and colleagues from France and the US (Avdellidoli, C. *et al.* 2024. [Dating the Solar System’s giant planet orbital instability using enstatite meteorites](#). *Science*, v. **384**, p. 348-352; DOI: 10.1126/science.adg8092) after discovery of a new family of asteroids: named after its largest member Athor. The composition of their surfaces, from telescopic spectra, closely matches that of EL enstatite chondrite meteorites. Dating these meteorites should show when their parent asteroids – presumably the Athors – formed. Using argon and xenon isotopes Mario Trieloff and colleagues from the University of Heidelberg, Germany in showed that the materials in EL enstatite chondrite meteorites were assembled a mere 2 Ma after the Solar System formed (Trieloff, M. *et al.* 2022. [Evolution of the parent body of enstatite \(EL\) chondrites](#). *Icarus*, v. 373, article 114762; DOI: 10.1016/j.icarus.2021.114762). Be that as it may, that the evidence came from small meteorites shows that the parent body, estimated as having had a 240 to 420 km diameter, was shattered at some later time. Moreover, at that very early date such bodies would have contained a ready heat source in the form of a short-lived isotope of aluminium (^{26}Al) which decays to stable ^{26}Mg , with a half-life of 0.717 Ma. ^{26}Al is thought to have been produced by a supernova that has been suggested to have triggered the formation of the Solar System. Excessive ^{26}Mg is found in many meteorites, evidence for metamorphism formed by such radiogenic heat. They also record the history of their cooling.

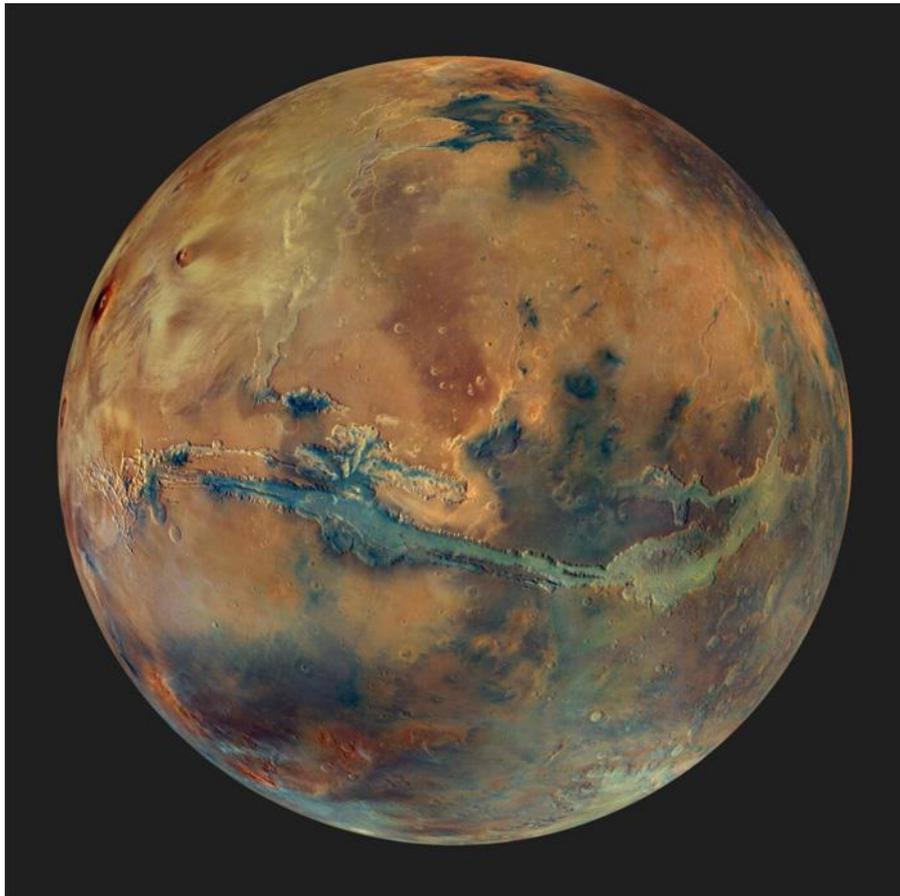
Avdellidoli *et al.* estimate that the 240 to 420 km Athor parental planetesimal had slowly cooled for at least 60 Ma after it formed. When it was shattered, the small fragments would have cooled instantaneously to the temperature of interplanetary space – a few degrees above absolute zero (-273.2 °C). From this they deduce the age of the chaotic restructuring of the early Solar System to be at least 60 Ma after its formation. Other authors use similar reasoning from other chondritic meteorite classes to suggest it may have happened even earlier at 11 Ma. But there are other views for a considerably later migration of the giant planets and the havoc that they wrought. The only widely agreed date, in what seems to be an outbreak of wrangling among astronomers, is for the Moon-forming collision: 110 Ma after formation of the Solar System. For me, at least, that’s good-

enough evidence for when system-wide chaos prevailed. The Late Heavy Bombardment between 4.1 and 3.8 Ga seems to require a different mechanism as it affected large bodies that still exist. It may have resulted from whatever formed the asteroid belt, for it was bodies within the range of sizes of the asteroids that did the damage, in both the Inner and Outer Solar System.

See also: [The instability at the beginning of the solar system](#). *MSUToday*, 27 April 2022: Voosen, P. 2024. [Giant planets ran amok soon after the Solar System's birth](#). *Science*, v. 384 news article eadp8889; DOI: 10.1126/science.adp8889

Ocean-floor sediments reveal the influence of Mars on long-term climate cycles

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One hemisphere of Mars captured by ESA's Mars Express. Credit: ESA / DLR / FU Berlin /

In 1976 three scientists from Columbia and Brown (USA) and Cambridge (UK) Universities published a paper that revolutionised the study of ancient climates (Hays J.D., Imbrie J. and Shackleton N.J. 1976. [Variations in the Earth's Orbit: Pacemaker of the Ice Ages](#). *Science*, v. 194, p. 1121-1132; DOI: 10.1126/science.194.4270.1121). Using variations in oxygen isotopes from foraminifera through two cores of sediments beneath the floor of the southern Indian Ocean they verified Milutin Milankovich's hypothesis of astronomical controls over Earth's climate. This centred on changes in

Earth's orbital parameters induced by gravitational effects from the motions of other planets: its orbit's eccentricity, and the tilt and precession of its rotational axis. Analysis of the frequency of isotopic variations in the resulting time series yielded Milankovich's predictions of ~100, 41 and 21 ka periodicities respectively. The time spanned by the cores was that of the last 500 ka of the Pleistocene and thus the last 5 glacial-interglacial cycles. Subsequently, the same astronomical climate forcing has been detected for various climate-induced changes in the earlier sedimentary record, including the glacial cycles of the [Carboniferous](#) and [Neoproterozoic](#), Jurassic climate changes due to [oceanic methane emissions](#) and many other types of cyclicity during the Phanerozoic.

As well as time series based on isotopic and other geochemical changes in marine cores, other variables such as thickness of turbidite beds or cyclical repetitions of short rock sequences such as the 'cyclothems' of Carboniferous age (repetitions of a limestone, sandstone, soil, coal sequence) have also been subject to frequency analysis. Sedimentary features that have not been tried are gaps or hiatuses in stratigraphic sequences where strata are missing from a deep-sea sequence. These signify erosion of sediment due to vigorous bottom currents in sequences otherwise dominated by continuous deposition under low-energy conditions. Three geoscientists from the University of Sydney, Australia and the Sorbonne University, France, have subjected records of gaps in Cenozoic sedimentation from 293 deep-sea drill cores to time-series analysis to discover what such 'big data' might reveal as regards climate fluctuations on the order of millions of years (Dutkiewicz, A., Boulila, S. & Müller, R.D. 2024. [Deep-sea hiatus record reveals orbital pacing by 2.4 Myr eccentricity grand cycles](#). *Nature Communications*, v. 15, article 1998; DOI: 10.1038/s41467-024-46171-5).

In theory gravitational interrelationships between all the orbiting planets should have an effect on the orbital parameters of each other, and thus the amount of received solar radiation and changes in global climate. As well as the Milankovich effect, longer astronomical 'grand cycles' may therefore have been reflected somehow in Earth's climatic history (Laskar, J. *et al.* 2004. [A long-term numerical solution for the insolation quantities of the Earth](#). *Astronomy & Astrophysics*, v. 428, p. 261-285; DOI: 10.1051/0004-6361:20041335). Based on Laskar *et al.*'s calculations Adriana Dutkiewicz and colleagues sought evidence for two predicted 'grand cycles' that result from orbital interactions between Earth and Mars. These are a 2.4 Ma period in the eccentricity of Earth's orbit and one of 1.2 Ma in the tilt of its axis.

The authors were able to detect cyclicity in the hiatus time series that is close to the 2.4 Ma Mars-induced waxing and waning of solar heating. Warming would increase mixing of ocean water through cyclones and hurricanes. That would then induce more energetic deep ocean currents and more erosion on the deep ocean floor: more gaps in sedimentation. Cooler conditions would 'calm' deep ocean currents so that deposition would outweigh evidence of erosion. The 1.2 Ma axial tilt cyclicity is not apparent in the data. Interestingly, the ~2.4 Ma cyclicity underwent a significant deviation at the Palaeocene-Eocene Boundary' (56Ma), seemingly predicted by Laskar *et al.*'s astronomical solutions as a chaotic orbital transition between 56 and 53 Ma. Dutkiewicz *et al.* also chart the relations between the sedimentary-hiatus time series and major tectonic, oceanographic, and climatic changes during the Cenozoic Era, and found that terrestrial processes did disrupt the Mars-related orbital eccentricity cycles.

The findings suggest that long-term astronomical climate forcing needs to be borne in mind for better understanding the future response of the ocean to global warming. Also, if Mars had such an influence so must have Venus, which is more massive and closer. That remains to be investigated, and also the effects of the giant planets. In the very distant past their behaviour may have resulted in unimaginable astronomical changes. According to the bizarrely named Nice Model a back and forth shuffling of the Giant Planets was probably responsible for the Late Heavy Bombardment 4.1 to 3.8 billion years (Ga) ago. Such errant behaviour may even have triggered the [flinging of some of the Sun's original planetary complement out of the solar system](#) and changed the outward order of the existing eight. Fortunately, the present planetary set-up seems to be stable ...

See also: Dutkiewicz, A., & Müller, R. D. 2022. [Deep-sea hiatuses track the vigor of Cenozoic ocean bottom currents](#). *Geology*, v. 50, p. 710–715; DOI: 10.1130/G49810.1; [Mars drives deep-ocean circulation in Earth's oceans, study suggests](#). *Sci News*, 13 March 2024.

Multiple Archaean gigantic impacts, perhaps beneficial to some early life

PUBLISHED ON [October 29, 2024](#)

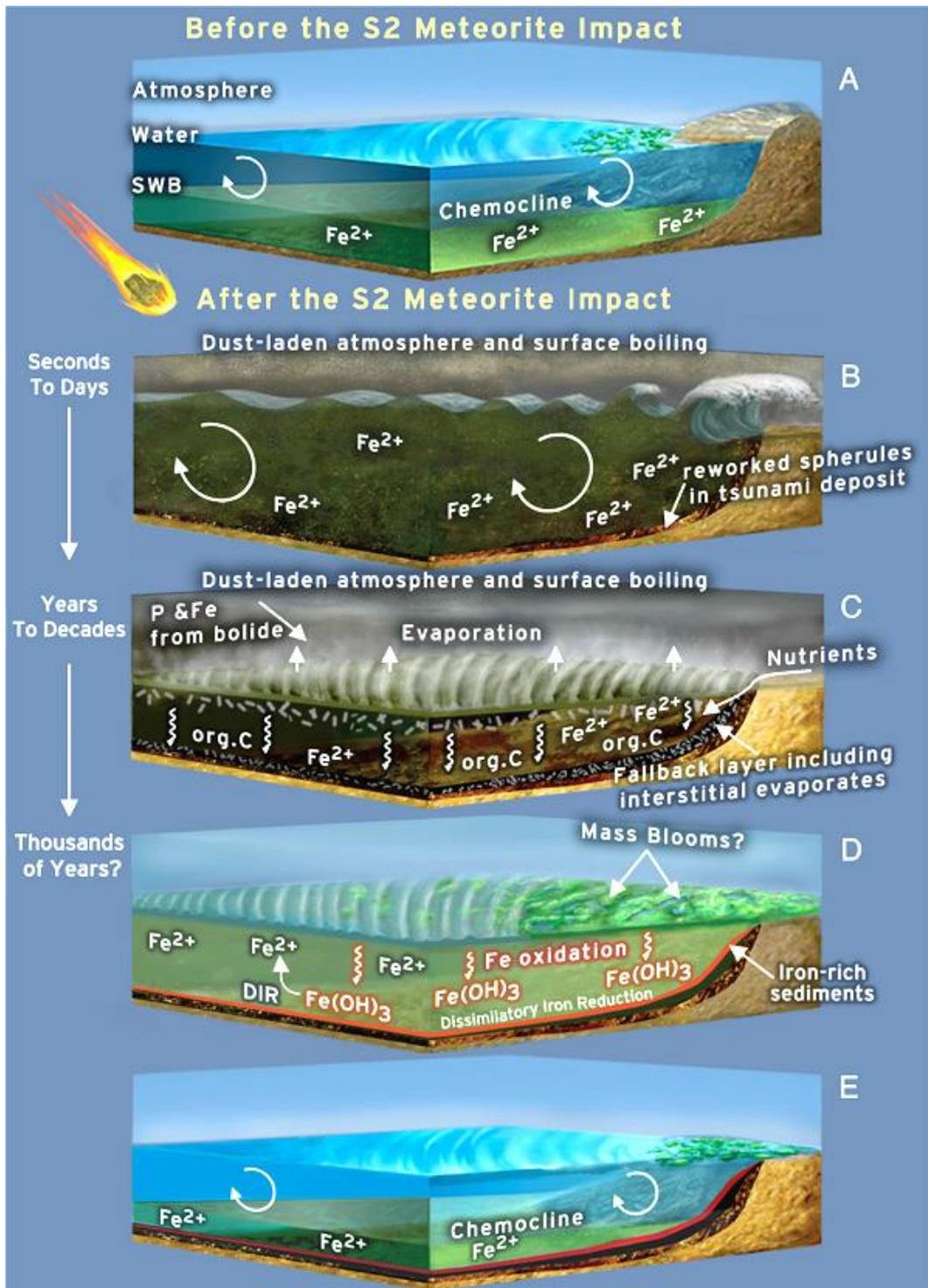


Impact debris layer in the Palaeoarchaeon Barberton greenstone belt of South Africa, which contains altered glass spherules and fragments of older carbonaceous cherts. (Credit: Credit: Drabon, N. et al., Appendix Fig S2B)

In March 1989 an asteroid half a kilometre across passed within 500 km of the Earth at a speed of 20 km s⁻¹. Making some assumptions about its density, the kinetic energy of this near miss would have been around 4×10^{19} J: a million times more than Earth's annual heat production and humanity's annual energy use; and about half the power of detonating every thermonuclear device ever assembled. Had that small asteroid struck the Earth all this energy would have been delivered in a

variety of forms to the Earth System in little more than a second – the time it would take to pass through the atmosphere. The founder of “astrogeology” and NASA’s principal geological advisor for the Apollo programme, the late [Eugene Shoemaker](#), likened the scenario to a ‘*small hill falling out of the sky*’. ([Read a summary of what would happen during such an asteroid strike](#)). But that would have been dwarfed by the 10 to 15 km impactor that resulted in the ~200 km wide Chicxulub crater and the K-Pg mass extinction 66 Ma ago. Evidence has been assembled for Earth having been struck during the Archaean around 3.6 billion years (Ga) ago by an asteroid 200 to 500 times larger: more like four Mount Everests ‘*falling out of the sky*’ (Drabon, N. *et al.* 2024. [Effect of a giant meteorite impact on Palaeoarchean surface environments and life](#). *Proceedings of the National Academy of Sciences*, v. 121, article e2408721121; DOI: [10.1073/pnas.2408721121](#))

In fact the Palaeoarchean Era (3600 to 3200 Ma) was a time of multiple large impacts. Yet their recognition stems not from tangible craters but strata that contain once glassy spherules, condensed from vaporised rock, interbedded with sediments of Palaeoarchean ‘greenstone belts’ in Australia and South Africa (see: [Evidence builds for major impacts in Early Archaean](#); August 2002, and [Impacts in the early Archaean](#); April 2014), some of which contain unearthly proportions of different chromium isotopes (see: [Chromium isotopes and Archaean impacts](#); March 2003). Compared with the global few millimetres of spherules at the K-Pg boundary, the Barberton greenstone belt contains eight such beds up to 1.3 m thick in its 3.6 to 3.3 Ga stratigraphy. The thickest of these beds (S2) formed by an impact at around 3.26 Ga by an asteroid estimated to have had a mass 50 to 200 times that of the K-Pg impactor.



Time line of possible events following a huge asteroid impact during the Palaeoarchaeon. (Credit: Drabon, N. et al. Fig 8)

Above the S2 bed are carbonaceous cherts that contain carbon-isotope evidence of a boom in single-celled organisms with a metabolism that depended on iron and phosphorus rather than sunlight. The authors suggest that the tsunami triggered by impact would have stirred up soluble iron-2 from the deep ocean and washed in phosphorus from the exposed land surface, perhaps some having been delivered by the asteroid itself. No doubt such a huge impact would have veiled the Palaeoarchaeon Earth with dust that reduced sunlight for years: inimical for photosynthesising

bacteria but unlikely to pose a threat to chemo-autotrophs. An unusual feature of the S2 spherule bed is that it is capped by a layer of altered crystals whose shapes suggest they were originally sodium bicarbonate and calcium carbonate. They may represent flash-evaporation of up to tens of metres of ocean water as a result of the impact. Carbonates are less soluble than salt and more likely to crystallise during rapid evaporation of the ocean surface than would NaCl.

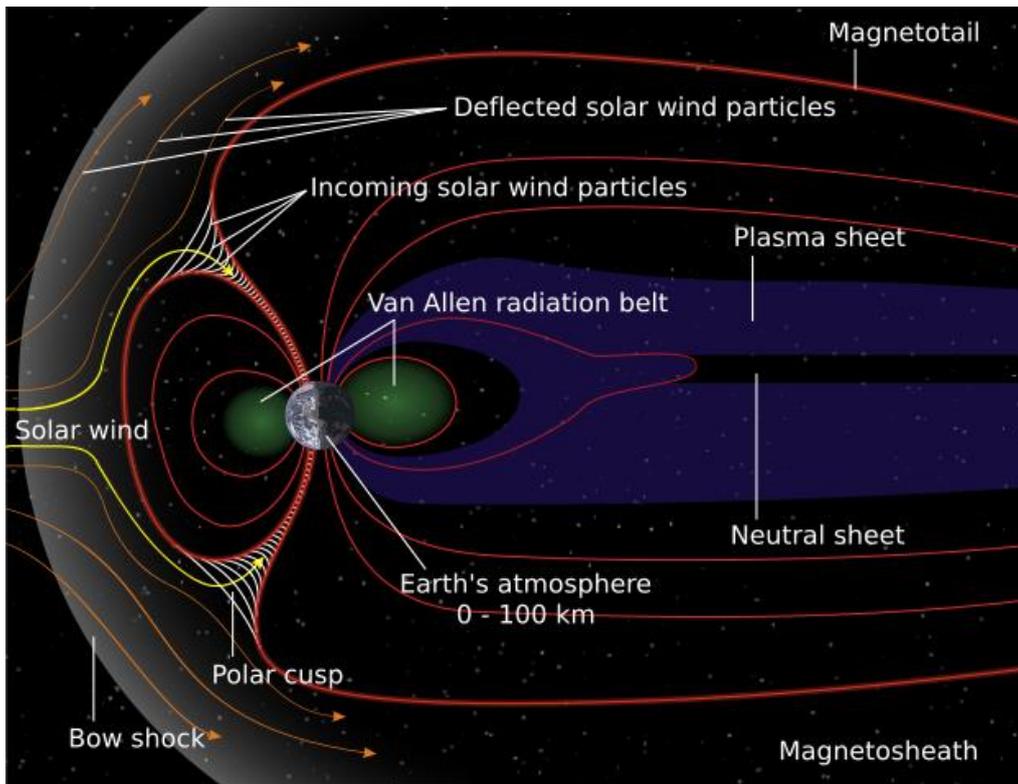
So it appears that early extraterrestrial bombardment in the early Archaean had the opposite effect to the Chicxulub impactor that devastated the highly evolved life of the late Mesozoic. Many repeats of such chaos during the Palaeoarchaeon could well have given a major boost to some forms of early, chemo-autotrophic life, while destroying or setting back evolutionary attempts at photo-autotrophy.

See also: King, A. 2024. [Meteorite 200 times larger than one that killed dinosaurs reset early life](#). *Chemistry World* 23 October 2024.

Evidence for Earth's magnetic field 3.7 billion years ago

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If ever there was one geological locality that 'kept giving' it would have to be the Isua supracrustal belt in West Greenland. Since 1971 it has been known to be the repository of the oldest known metasedimentary rocks, dated at around 3.7 Ga. Repeatedly, geochemists have sought evidence for life of that antiquity, but the Isua metasediments have yielded only ambiguous chemical signs. A more convincing hint emerged from iron-rich silica layers (jasper) in similarly aged metabasalts on [Nuvvuagittuk Island](#) in Quebec on the east side of Hudson Bay, Canada, which may be products of Eoarchaeon sea-floor hydrothermal vents. X-ray micro-tomography and electron microscopy of the jaspers revealed twisted filaments, tubes, knob-like and branching structures up to a centimetre long that contain minute grains of carbon, phosphates and metal sulfides, but the structures are made from hematite (Fe_2O_3) so an inorganic formation is just as likely as the earliest biology. Isua's most intriguing contribution to the search for the earliest life has been what look like stromatolites in a marble layer (see: [Signs of life in some of the oldest rocks](#); September 2016). Such structures formed in later times on shallow sea floors through the secretion of biofilms by photosynthesising blue-green bacteria.

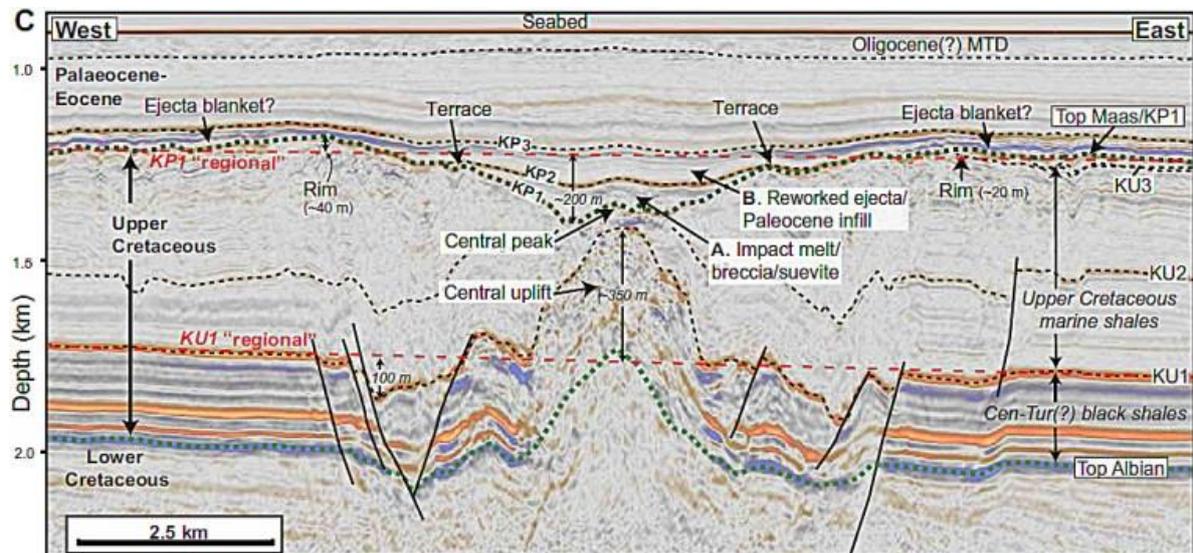


Structure of the Earth's magnetosphere that deflects charged particles which form the solar wind.
(Credit: Wikipedia Commons)

For life to form and survive depends on its complex molecules being protected from high-energy charged particles in the solar wind. In turn that depends on a strong geomagnetic field deflecting the solar wind as it does today, except for a small proportion that descend towards the poles and form aurora during solar mass ejections. In visits to Isua in 2018 and 2019, geophysicists from the Massachusetts Institute of Technology, USA and Oxford University, UK drilled over 300 rock cores from metasedimentary ironstones (Nichols, C.I.O. and 9 others 2024. [Possible Eoarchean records of the geomagnetic field preserved in the Isua Supracrustal Belt, southern West Greenland](#). *Journal of Geophysics Research (Solid Earth)*, v. **129**, article e2023JB027706; DOI: 10.1029/2023JB027706 Magnetisation preserved in the samples (remanent magnetism) suggest that it was formed by a geomagnetic field strength of at least 15 microtesla, similar to that which prevails today. The minerals magnetite (Fe_3O_4) and apatite (a complex phosphate) in the ironstones have been dated using U-Pb geochronometry and record a metamorphic event only slightly younger than the age of the Isua belt (3.69 and 3.63 Ga respectively). There is no sign of any younger heating above the temperatures that would reset the ironstones' magnetisation. The Isua remanent magnetisation is at least 200 Ma older than that found in igneous rocks from north-eastern South Africa dated at between 3.2 to 3.45 Ga. So even in the Eoarchean it seems likely that life, had it formed, would have avoided the hazard of exposure to the high energy solar wind. In all likelihood, however, in a shallow marine environment it would have had to protect itself somehow from intense ultraviolet radiation. That is now vastly reduced by stratospheric ozone (O_3) which could only form once the atmosphere had appreciable oxygen (O_2) content, i.e. after the Great Oxygenation Event beginning about 2.4 Ga ago. Undoubted stromatolites as old as 3.5 Ga suggest that early photosynthesising bacteria clearly had cracked the problem of UV protection somehow.

A companion crater for Chicxulub on the continental shelf of West Africa

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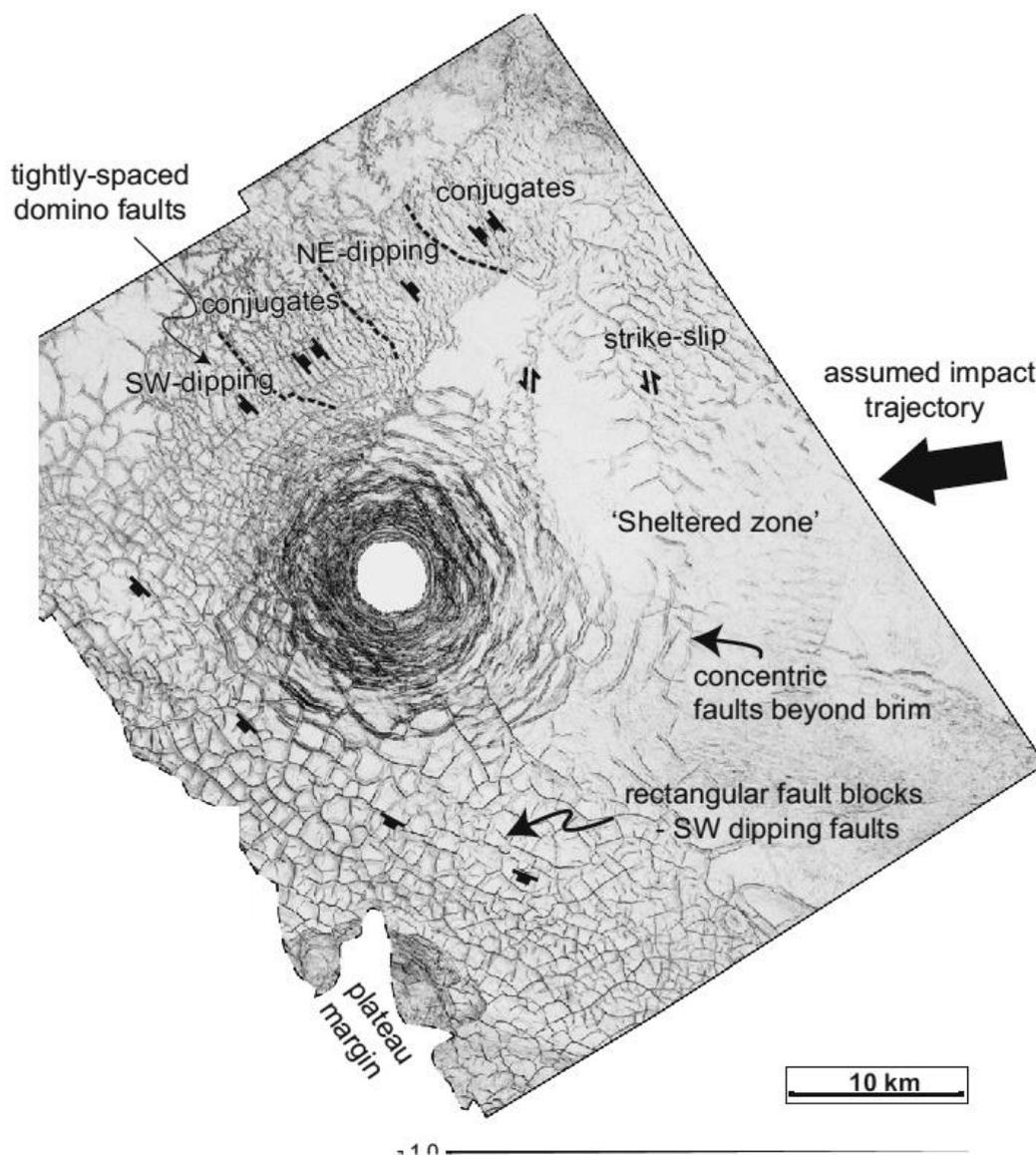


Interpreted 2D seismic section across the Nadir crater and central uplift beneath the Guinea Terrace. (Credit: Nicholson, et al. 2022. Fig 2c)

In 2022 four geoscientists from Heriot-Watt University in Edinburgh, Scotland and the Universities of Arizona and Texas (Austin), USA were geologically interpreting seismic-reflection data beneath the seafloor off Guinea and Guinea-Bissau, West Africa. Individual sedimentary strata that cover the upper continental crust show up as many reflectors. They are calibrated to rock cores from exploratory well that had revealed up to 8 km of sedimentary cover deposited continuously since the Upper Jurassic. The team's objective was to collect information on tectonic structures that had formed when South America separated from Africa during the Cretaceous. The geophysical data were from commercial reconnaissance surveys aimed at locating petroleum fields beneath part of the West African continental shelf known as the Guinea Terrace. One of the seismic sections revealed a ~9 km wide basin-like depression at the level of the Cretaceous-Palaeogene boundary, which is underlain by a prominent upward bulge in reflectors corresponding to the mid-Cretaceous, plus a large number of nearby faults (Nicholson, U., and 3 others 2022. [The Nadir Crater offshore West Africa: a candidate Cretaceous-Paleogene impact structure](#). *Science Advances*, v. 8, article eabn3096; DOI: 10.1126/sciadv.abn3096). Elsewhere on the Guinea Terrace the strata were featureless by comparison.

The Nadir crater showed many of the signs to be expected from an asteroid impact. That it drew attention stemmed partly from being of roughly the same age as the much larger 66 Ma Chicxulub impact off the Yucatan Peninsula of Mexico: the likely culprit for the K-Pg mass-extinction event. Perhaps both impactors stemmed from the break-up of a large, near-Earth asteroid because of gravitational forces resulting from a previous close encounter with either the Earth or another planet. The crater lies at the centre of a 23 km wide zone of faults that only affect Cretaceous and older strata; i.e. they formed just before the K-Pg event. The seismic data also show signs of

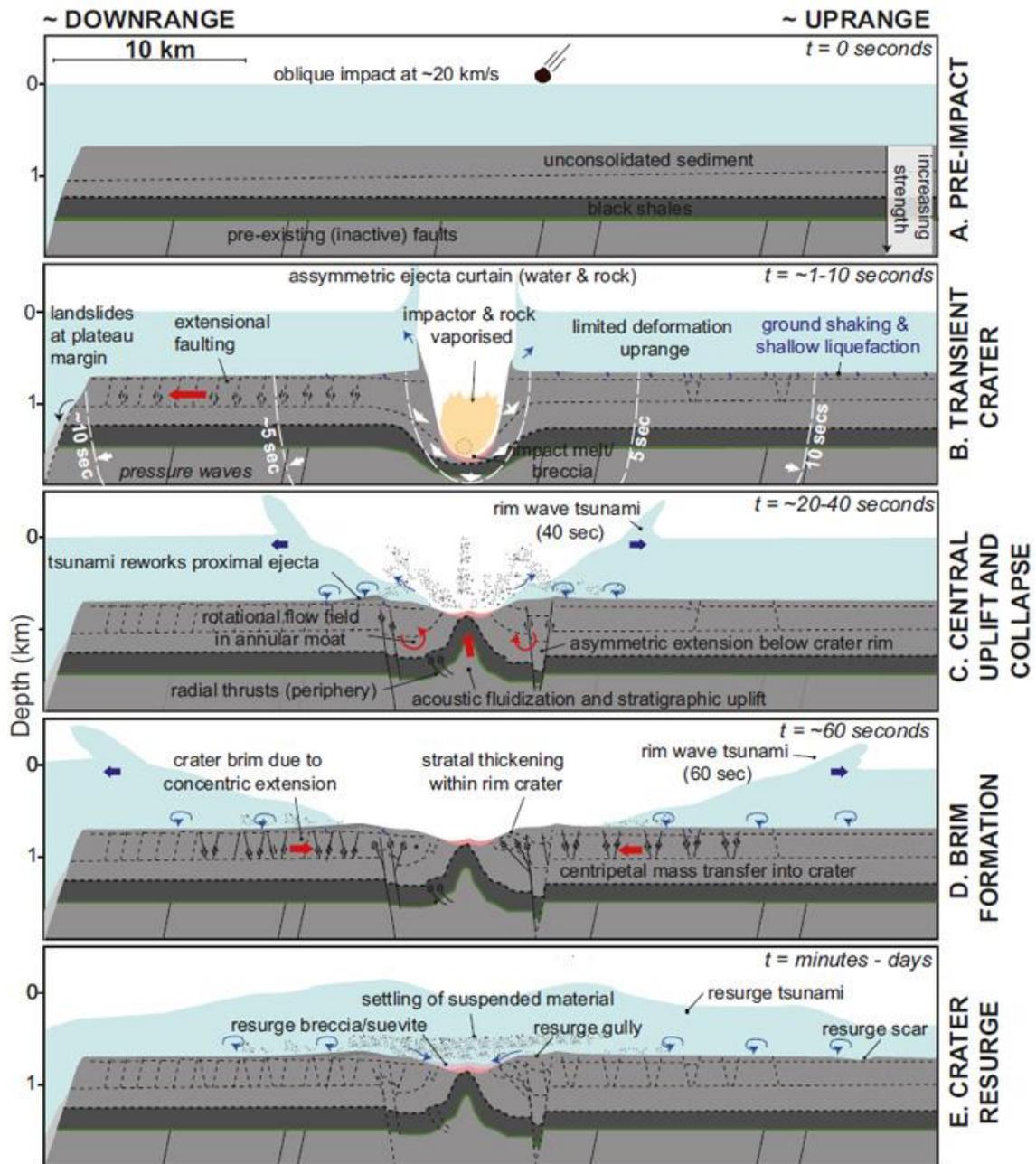
widespread liquefaction of nearby Cretaceous sedimentary strata and that the crater had been filled by sediments shortly after it formed. Yet the data were too fuzzy for an astronomical catastrophe to be absolutely certain: similar structures can form from the rise of bodies of rock salt, which is less dense than sediments and will dissolve on reaching the seabed. The owners of the seismic data donated a much larger collection from a grid of survey lines. Processing of such seismic grids turns the collection of individual two-dimensional sections into a 3D regional data set showing the complete shape of subsurface structures. Seismic data of this kind enables more detailed structural and lithological interpretation of both cross section and plan views. They enable sedimentary layers to be 'peeled' back to examine the crater at all depths, in much the same manner as CT and MRI scans reveal the inner anatomy of the human body.



Map of faults around the Nadir crater at a level in the 3D seismic data that was about 200 m below the sea bed at the time of the impact. (Credit: Nicholson, et al. 2024, Fig 6)

Uisdean Nicholson and a larger team have now published their findings from the 3D seismic data that show the structure in unique detail (Nicholson, U., and 6 others 2024. [3D anatomy of the Cretaceous–Paleogene age Nadir Crater](#). *Communications Earth & Environment* v. 5,

article number 547; DOI: 10.1038/s43247-024-01700-4). Nadir crater was affected by spiral-shaped thrust faults that suggest it was formed by an oblique impact from the northeast by an object around 450 m across, probably travelling at 20 km s^{-1} at 20 to 40° to the surface. Seconds after excavation uplift of deeper sediments was a response to removal of the load on the crust. The energy was sufficient to vaporise both sediment and impactor within a few seconds, the to drive drive seawater outwards in a tsunami about half a kilometre high, which in about 30 seconds exposed the incandescent crater floor. In the succeeding minutes hours and days liquefied sea water sloshed in and out of the crater, repeated tsunami resurgence forming gullies on its flanks and transporting sediment mixed with glass ([suevite](#)) flowed to refill the crater.



Time line for the Nadir impact, derived from detail shown by 3D seismic data. (Credit: Nicholson, et al. 2024, Fig 7)

There is no means of assigning any of the K-Pg extinctions to the Nadir crater, just that it happened at roughly the same time as Chicxulub. But it is the first impact crater to reveal the processes involved through complete coverage by high-resolution 3D seismic data. The majority of the roughly 200 craters are on the continental surface, and were thus ravaged to some extent by later erosion. Yet of the influx of hypervelocity objects through time at least 70% must have struck the oceans, but only 15 to 20 are known. That may reflect the fact that much deeper water could have buffered even giant impacts from affecting the oceanic crust beneath the abyssal plains, whose average depth is about 4 km. Only a small proportion of the continental shelves deemed to contain petroleum reserves have been explored seismically. Chicxulub itself has been drilled, but only two seismic reflection sections have crossed its centre since its discovery, although earlier 3D data from petroleum exploration cover its outermost northern parts. More detail is available for Nadir and its lower energy did not smash its structural results, unlike Chicxulub. So, despite Nadir's smaller size, fortuitously it gives more clues to how such marine craters formed. It looks to be an irresistible target for drilling.