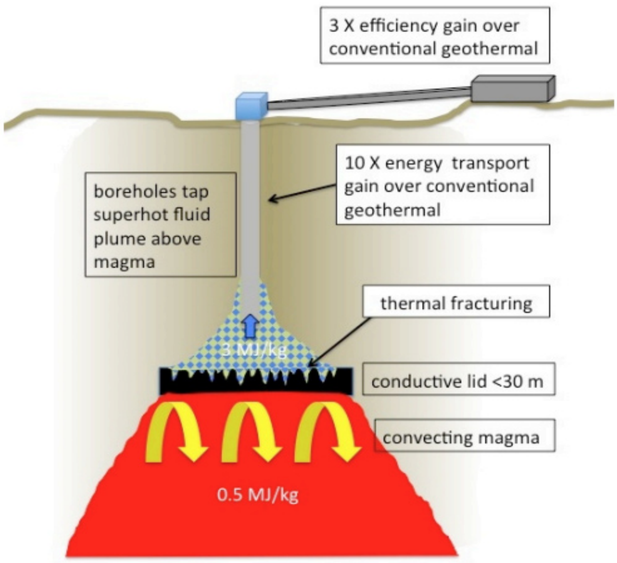
GEOBROWSER

Limitless Energy from Iceland?

Iceland is renowned for its volcanic eruptions, the latest example being the spectacular fire-fountaining and basalt outflows from the fissures that opened this year between the Blue Lagoon and the town of Grindavik, on the southwestern Reykjanes peninsula. Iceland is also a world leader in renewable energy generation, so one might expect that geothermal heat would be its most utilised source. It was indeed first exploited over a thousand years ago by Viking settlers, but today it lags behind hydropower, which accounts for about 70 percent of the country's energy output. The current geothermal use is for heating buildings, which started in 1930 and now links 90% of homes by extensive piped systems. But in north-east Iceland there is a source of potentially limitless energy that is a step closer to being realised at the Krafla geothermal facility.

Located close to a 25 km-diameter highly active rhyolite shield volcano, this plant currently generates electricity from 'conventional' boreholes which tap heated underground water to drive steam-powered turbines. By 2026, however, it is hoped that the Krafla Magma Testbed (KMT) project will begin work on a borehole which, with care, will tap into the actual margin of the volcano's magma chamber, some 1.3 miles below the surface. This will take advantage of a magma's high energy density and an environment in which the heat is delivered by convection, rather than indirectly by groundwater (*Eichelberger et al, GRC Transactions, 2018*). Drilling into a magma chamber seems inherently dangerous, but boreholes indicate that rather than consisting of the expected partially-melted 'mush', the magma carapace is remarkably solid. The samples retrieved indicate rapid quenching of both the rhyolitic magma (to obsidian) and melted wallrock, suggesting that convective overturn within the magma is actually cooling the roof zone. The conclusion is that magma and the suprajacent hydrothermal system are separated by a very thin, but crucially solid, conductive zone. Fluid circulation will still play an important role here, but the heat will be transferred by thermal fracturing rather than hydrofracturing above a convecting magmatic heat source. This should result in a close, and hopefully safe connection between the magmatic and the superheated hydrothermal portions of the system. The drilling technique was pioneered at Krafla in 2009 and involves cementing a steel casing into the well with a perforated section at the bottom, closest to the magma. This allows heat to slowly build, eventually producing superheated steam that can rise up through the well.

There will be hurdles to overcome but also some beneficial spin-offs, for example in the field of eruption prediction, and the sciences associated with rock behaviours in molten and near-molten Earth. Crucially, however, this near-magma super-hot geothermal source (SHGS) will produce wells up to an order of magnitude more powerful than existing sites. The more 'conventional' Krafla facility already supplies electricity to several aluminium smelting plants attracted by an abundant supply of cheap energy, but if the new project is successful, new markets could open up. With support from Landsvirkjun, Iceland's state-owned energy company, this could involve the resurrection of long-planned ambitions to directly export geothermally-sourced electricity via submarine cables to interconnectors linking grids in the UK and mainland Europe. The potentially cheap and limitless nature of such energy would attract nations who need clean and renewable sources of energy to fulfil Kyoto protocol targets. There are some practical difficulties to overcome though: it is estimated that with the world's current cable manufacturing capacity it would require 6 years to construct the 1170 kilometres required to reach Scotland, and given today's tensions in Europe such a supply source would be vulnerable to sabotage. Alternatively, energy could be processed and 'packaged' in Iceland to produce clean fuels for export to Europe and the rest of the world, thus creating a viable mass market. Hydrogen produced from sea-water through electrolysis is one possibility, and although many believe that a world hydrogen market is still decades away, urgency created by the rapidity of climate change may change all this.



Depiction of power generation from 'magma energy' (Source: Eichelberger et al, 2018)

World's largest geode

For decades the Almeria Province in south-eastern Spain has been a major holiday destination much frequented by sun-seeking northern Europeans. But not too far from the beaches there is a geological wonder that could be straight out of a science fiction film. The walk-in geode In Pulpí is the world's largest, measuring eight metres wide, two metres high and two metres deep.

The Almeria geode (Source: BBC Travel website)

The geode was originally discovered in the Mina Rica mine, which started during a local 'silver rush' and operated from 1873 to 1969. The much-sought for minerals are hosted in Triassic limestone, but in this case the early miners were disappointed when they encountered a large cavity with heavy crystals that were difficult to remove and not profitable. It was not until 1999 that the geode was re-discovered by geologists, and the site was eventually opened to the public in 2019 (see *andalucia.com website for location.*)

Research into the geode is still being conducted, but one suggestion is that the source material for the crystals lay outside the mineralised limestone host-rock, and is more likely to have been associated with the sedimentary gypsum and salt deposits found in other parts of the Almeria Triassic province. Heated fluids leached calcium and sulphate from these strata, re-precipitating them in fractured limestones as slowly growing, very large and remarkably transparent anhydrite crystals. It is tempting to conclude that the heat necessary for this process was provided by volcanoes active between about 8 and 15 million years ago, and which now form the spectacular scenery of the nearby Cabo de Gata Natural Park. However, the researchers are currently more inclined towards a younger date for crystal growth, between about 600 000 and 2 million years ago, so geode formation was not obviously related to that volcanism.

Finding Theia

It seems unlikely, but seismological investigations into deep Earth structure may now be throwing light on the very earliest development of our planet, going as far back as the formation of the protoplanets from the solar nebula about 4.6 billion years ago. This was a time of utter chaos when protoplanets were growing by accretionary growth, had no fixed orbits and so were prone to collision. One of these events is embodied in an astrogeology hypothesis for the formation of the Moon first proposed in 1946 by the Canadian geologist Reginald Daly. Named as the *giant-impact hypothesis* during the 1970s, the theory goes that the proto-Earth collided with a Mars-sized dwarf planet of the same orbit soon after the Solar System had formed. The kinetic energy generated by the collision turned both the proto-Earth and Theia into a fused molten mass, and the left-over material subsequently accreted to form the Moon, possibly within about 40 years of the collision. This could be regarded as a 'good' catastrophe: firstly, because it may have knocked the Earth into its current orbital position within the sun's habitable zone, where benign temperatures allow water to exist. Secondly, the Earth-Moon gravitational system accounts for the former's axial tilt, giving us the seasons, as well as the tides. The impactor planet is appropriately called Theia, after the mythical Greek Titan who was the mother of Selene, the goddess of the Moon.

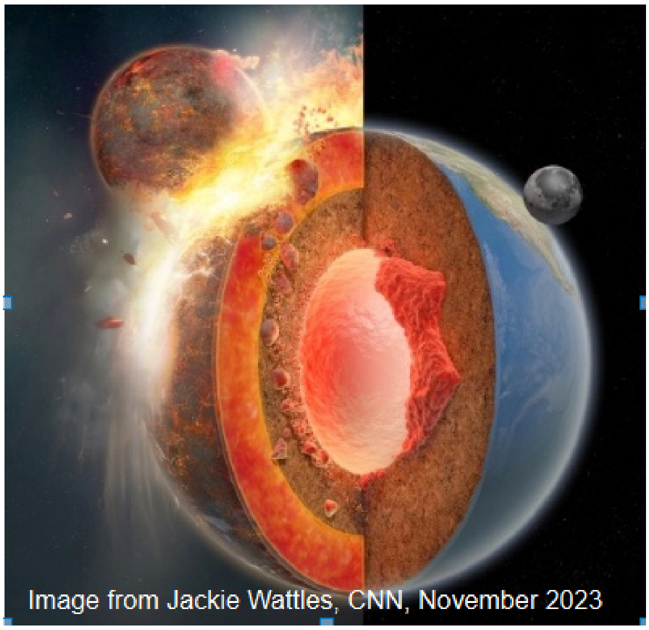


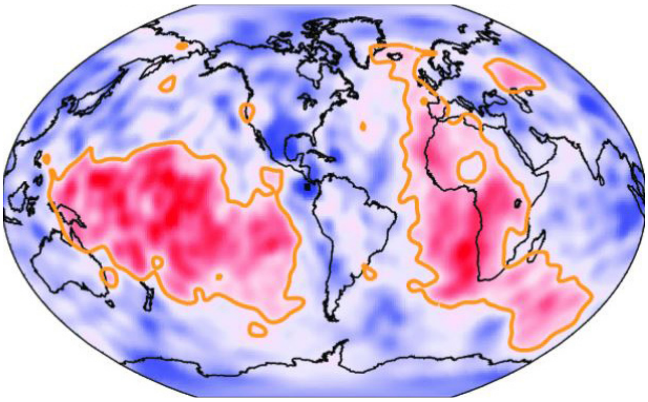
Image from Jackie Wattles (CNN, November 2023) depicting the Earth-Theia collision. Note that the Moon had not formed at this point in time.

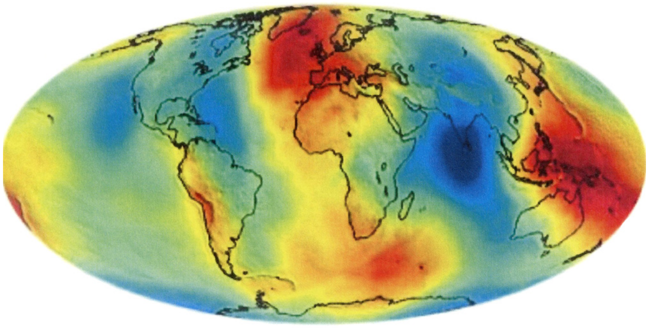
One might expect that in the 4 billion or so years since the supposed impact occurred, the Earth's mantle would have been re-processed and homogenised many times over, not least by the constant operation of plate tectonics involving subduction and ocean-floor spreading. But the mantle is not entirely homogeneous, as Deep-Earth seismic studies have shown, and an article by Q Yuan and others in the journal *Nature* for November, 2023 seeks to explain some particular seismic anomalies, or 'blobs', in the lowermost mantle, by suggesting that they are the actual remnants of Theia. These continent-sized entities were revealed by global seismic tomography surveys in the 1980s and have been called large low-velocity provinces (LLVPs). They evidently have sharp margins and are made up of material that is 2 to 3.5 per cent denser than the surrounding mantle. On the basis of impact simulations using a convecting mantle model, Yuan *et al* have shown that following collision, dense, iron-rich masses of Theia impactor material tens of kilometres in size could plausibly have sunk downwards to the outer boundary of the core where they amalgamated into LLVPs. Theia mantle rocks could have withstood the Earth's 4.5 billion years of evolution, thus retaining their identity, because of their higher density compared to Earth's mantle.

Yuan expects much controversy and heated debate over such a novel concept, which he describes as an hypothesis needing further research before it is proved. He speculates that because lunar sampling suggests that the Earth and Moon are made of material that could have originated from Theia and the proto-Earth, there could also be evidence of similar materials in the Moon's mantle, so this could furnish an additional line of research by lunar scientists. Admittedly there have been many other Earth-bound theories for the origin of LLVPs, one being that they may simply be thick fragments of oceanic crust that have sunk, or been subducted, into the mantle. But some tantalizing lines of corroboration for the Theia hypothesis are appearing: for example, the higher density of the LLVP mantle fragments implies a higher iron oxide composition, which would also be consistent with the isotope geochemistry of lunar samples, as well as that of certain oceanic island basalts overlying the LLVPs.

...Theia's ghostly presence?

The discovery of LLVPs underlines the fact that the Earth's mantle is anything but homogeneous, despite billions of years of constant re-processing. This is mirrored by the fact that the Earth's shape, or its geoid, is not regular, but is somewhat distorted or lumpy. This is because the geoid is everywhere perpendicular to the pull of gravity, and this influence is not always consistent because at great depths some parts of the Earth are denser than others. In the merged images comparing the distribution of the mantle LLVPs with 'bulges in the Earth's geoid', there appears to be some correspondence between the two anomalies. So although much still remains to be proved about LLVPs, could it be that after all these years it is Theia that is exerting an influence over modern topography?





Comparison between (top image) the distribution of LLVPs, their boundaries indicated by the thick orange line (Source: Geoscientist Feature, April 2019) and (lower image) geoid 'lumpiness' in yellow and red colours (Source: 'Space in images', ESA 2003)

Back cover photographs

Desert landforms carved into the Lower Palaeozoic sandstones around Al Ula, in northwestern Saudi Arabia (clockwise from the top): Rainbow Arch, just north of Al Ula; Al Naslh, the 'split rock' zeugen south of Tayma, and the Nabataean Tomb of Lihyan at Maada'in Saleh in Al Ula; The Mahajah arches, carved in fins far to the east of Al Ula; The sandstone plateau above Al Ula; The towers of Al Ghrameel, north of Al Ula (photos by Tony Waltham).