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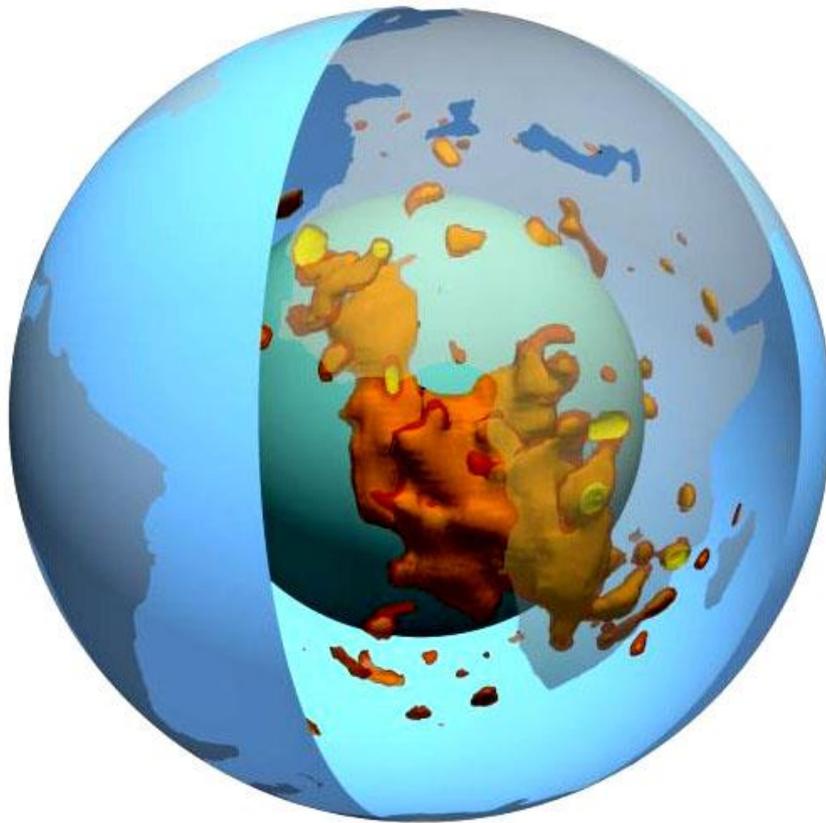
Lower-mantle blobs may reveal relics of event going back to the Hadean

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The World-Wide Standardised Seismograph Network (WWSSN) records the arrivals of waves generated by earthquakes that have passed through the Earth's interior. There are two types of these body waves: S- or shear waves that move matter at right angles to their direction of movement; compressional or P-waves that are a little like sound waves as materials are compressed and expanded along the direction of movement. Like sound, P-waves can travel through solids, liquids and gases. Since liquids and gases are non-rigid they cannot sustain shearing, so S-waves only travel through the solid Earth's mantle but not its liquid outer core. However, their speed is partly controlled by rock rigidity, which depends on the temperature of the mantle; the hotter the lower the mantle's rigidity.

Analysis of the S-wave arrival times throughout the WWSSN from many individual earthquakes enables seismologists to make 3-D maps of how S-wave speeds vary throughout the mantle and, by proxy, the variation of mantle rigidity with depth. This is known as [seismic tomography](#), which since the late 1990s has revolutionised our understanding of [mantle plumes](#) and [subduction zones](#), and also the overall structure of the deep mantle. In particular, seismic tomography has revealed two huge, blob-like masses above the core-mantle boundary that show anomalously low S-wave speeds, one beneath the Pacific Ocean and another at about the antipode beneath Africa: by far the largest structures in the deep mantle. They are known as 'large low-shear-wave-velocity provinces' (LLSVPs) and until recently they have remained the enigmatic focus of much speculation around two broad hypotheses: 'graveyards' for plates subducted throughout Earth history; or remnants of the magma ocean thought to have formed when another protoplanet impacted with the early Earth to create the Moon about 4.4 billion years ago.

Qian Yuan and Mingming Li of Arizona State University, USA have tried to improve understanding of the shapes of the two massive blobs (Yuan, Q. & Li, M. 2022. [Instability of the African large low-shear-wave-velocity province due to its low intrinsic density](#). *Nature Geoscience*, v. 15 DOI: 10.1038/s41561-022-00908-3) using advanced geodynamic modelling of the seismic tomography. Their work reveals that the Pacific LLSVP extends between 500 to 800 km above the core-mantle boundary. Yet that beneath Africa reaches almost 1000 km higher, at 1300 to 1500 km. Both of them are less rigid and therefore hotter than the surrounding mantle. In order to be stable they must be considerably denser than the rest of the mantle surrounding them. But, because it reaches much higher above the core, the African LLSVP is probably less dense than the Pacific one. A lower density suggests two things: the African blob may be less stable; the two blobs may have different compositions and origins.



Three-dimensional rendition of seismic tomography results beneath Africa. Mantle with anomalously low S-wave speeds is shown in red, orange and yellow. The faint grey overlay represents the extent of surface continental crust today – Horn of Africa at right and Cape Town at the lower margin – the blue areas near the top are oceanic crust on the floor of the Mediterranean Sea. (Image credit: Mingming Li/ASU)

Both the Pacific Ocean floor and the African continent are littered with volcanic rocks that formed above mantle plumes. The volcanic geochemistry above the two LLSVPs differs. African samples show signs of a source enriched by material from upper continental crust, whereas those from the Pacific do not. Yuan and Li suggest that the enrichment supports the 'plate graveyard' hypothesis for the African blob and a different history beneath the Pacific. The 3-D tomography beneath Africa (see above) shows great complexity, perhaps reflecting the less stable nature of the LLSVP. Interestingly, 80 % of the pipe-like African kimberlite intrusions that have brought diamonds up from mantle depths over the last 320 Ma formed above the blob.

But why are there just two such huge blobs of anomalous material that lie on opposite sides of the Earth rather than a continuous anomaly or lots of smaller ones? The subduction graveyard hypothesis is compatible with the last two distributions. In a 2021 conference presentation the authors suggest from computer simulations that the two blobs may have originated at the time of the Moon's formation after a planetary collision (Yuan, Q. *et al.* 2021. [Giant impact origin for the large low shear velocity provinces](#). *Abstracts for the 52nd Lunar and Planetary Science Conference*: Lunar and Planetary Institute, Houston). Specifically, they suggest that the LLSVPs originated from the mantle of the other planet (Theia) after its near complete destruction and

melting, which sank without mixing through the magma ocean formed by the stupendous collision. Yet, so far, no geochemists have been bold enough to suggest that there are volcanic rocks of any age that reveal truly exotic compositions inherited from deep mantle material with such an origin. If Theia's mantle was dense enough to settle through that of the Earth when both were molten, it would be sufficiently anomalous in its chemistry for signs to show up in any melts derived from it. There again, because of a high density it may never have risen in plumes to source any magma that reached the Earth's surface ...

Note added later: Simon Hamner's Comment about alternative views on seismic tomography has prompted me to draw attention to [something I wrote 19 years ago](#)

Rare meteorite gives clues to the early history of Mars

PUBLISHED ON [July 25, 2022](#)

Apart from the ages and geochemistry of a few hundred zircon grains we have no direct evidence of what the earliest crust of the Earth was like. The vast bulk of the present crust is younger than about 4 billion years. The oldest tangible crustal rocks occur in the 4.2 billion year (Ga) old [Nuvvuagittuq greenstone belt](#) on Hudson Bay. The oldest zircon grains have compositions that suggest that they formed [during the crystallisation of andesitic magmas](#) about 4.4 Ga ago about 140 Ma after the Earth accreted. But, according to an idea that emerged decades ago, that does not necessarily represent the earliest geology. Geochemists have shown that the bulk compositions of the Earth and Moon are so similar that they almost certainly share an early history. Rocks from the lunar highlands – the light areas that surround the dark basaltic maria – collected during the Apollo missions are significantly older (up to 4.51 Ga). They are made mainly of calcium-rich feldspars. These anorthosites have a lower density than basaltic magma. So it is likely that the feldspars crystallised from an all-enveloping 'magma ocean' and floated to form an upper crust on the moon. Such a liquid outer layer could only have formed by a staggering input of energy. It is believed that what became the Moon was flung from the Earth following collision with another planetary body as vapour, which then collapsed under gravity and condensed to a molten state (see: [Moon formed from vapour cloud](#); January 2008). Crystallisation of the bulk of anorthosites has been dated to between 4.42 to 4.35 Ga (see: [Moon-forming impact dated](#); March 2009). The Earth would likely have had a similar magma ocean produced by the impact ([a much fuller discussion can be found here](#)), but no tangible trace has been discovered, though there is subtle geochemical evidence.

The surface geology of Mars has been mapped in great detail from orbiting satellites and various surface Rovers have examined sedimentary rocks – one of them is currently collecting samples for eventual return to Earth. Currently, the only materials with a probable Martian origin are [rare meteorites](#); there are 224 of them out of 61 thousand meteorites in collections. They are deemed to have been flung from its surface by powerful impacts to land fortuitously on Earth. It is possible to estimate when they were ejected from the effects of cosmic-ray bombardment to which they were exposed after ejection, which produces radioactive isotopes of a variety of elements that can be used in dating. So far, those analysed were flung into space no more than 20 Ma ago. Meteorites

with isotopic 'signatures' and mineral contents so different from others and from terrestrial igneous rocks are deemed to have a Martian origin by a process of elimination. They also contain proportions of noble gases (H, Ne, Ar, Kr and Xe) that resemble that of the present atmosphere of Mars. Almost all of them are mafic to ultramafic igneous rocks in two groups: about 25 % that have been dated at between 1.4 to 1.3 Ga; the rest are much younger at about 180 Ma. But one that was recovered from the desert surface in West Sahara, NW Africa (NWA 7034, nicknamed 'Black Beauty') is unique. It is a breccia mainly made of materials derived from a sodium-rich basaltic andesite source, and contains much more water than all other Martian meteorites.



The 'Black Beauty' meteorite from Mars (NWA 7035) with a polished surface and a 2 mm wide microscope view of a thin section: the pale clasts are fragments of pyroxenes and plagioclase feldspars; the rounded dark grey clast is a fine-grained basaltic andesite. (Credits: NASA; Andrew Tindall)

If you would like to study the make-up of NWA 7035 in detail you can explore it and other Martian meteorites by visiting the [Virtual Microscope](#) devised by Dr Andrew Tindall and Kevin Quick of the British Open University.

The initial dating of NWA 7034 by a variety of methods yielded ages between 1.5 to 1.0 Ga, but these turned out to represent radiometric 'resetting' by a high-energy impact event around 1.5 Ga ago. Its present texture of broken clasts set in a fine-grained matrix suggests that the breccia formed from older crustal rock smashed and ejected during that impact to form a debris 'blanket' around the crater. Cosmogenic dating of the meteorite indicates that the debris was again flung from the surface of Mars at some time in the last 10 Ma to launch NWA 7034 beyond Mars's gravitational field eventually to land in northwest Africa. But that is not the end of the story, because increasingly intricate radiometric dating has been conducted more recently.

'Black Beauty' contains rock and mineral fragments that have yielded dates as old as 4.48 Ga. So the breccia seems to have formed from fragments of the early crust of Mars. Indeed it represents the oldest *planetary* rock that has ever come to light. Some meteorites (carbonaceous chondrites) date back to the origin of the Solar System at around 4.56 Ga ago, and were a major contributor to the bulk composition of the rocky planets. However, the material in NWA 7034 could only have evolved from such primordial materials through processes taking place within the mantle of Mars. That was

very early in the planet's history: less than 80 Ma after it first began to accrete. It could therefore be a key to the early history of all the rocky planets, including the Earth.

There are several scenarios that might account for the composition of NWA 7034. The magma from which its components originated may have been produced by direct partial melting of the planet's mantle shortly after accretion. However, experimental partial melting of ultramafic mantle suggests that andesitic magmas would be unlikely to form by such a primary process. But other kinds of compositional differentiation, perhaps in an original magma ocean, remain to be explored. Unlike the Earth-Moon system, there is no evidence for anorthosites exposed at the Martian surface that would have floated to become crust once such a vast amount of melt began to cool. Some scientists, however, have suggested that to be a possibility for early Mars. Another hypothesis, by analogy with what is known about the earliest Archaean processes on Earth, is [secondary melting of a primordial basaltic crust](#), akin to the formation of Earth's early continental crust.

Only a new robotic or crewed mission to the area from which NWA 7034 was 'launched' can take ideas much further. But where on Mars did 'Black Beauty' originate? A team from Australia, France, Cote d' Ivoire, and the US have used a range of Martian data sets to narrow down the geographic possibilities (Lagain, A., and 13 others 2022. [Early crustal processes revealed by the ejection site of the oldest martian meteorite](#). *Nature Communications*, v. 13, article 3782; DOI 10.1038/s41467-022-31444-8). The meteorite contains a substantially higher content of the elements thorium and potassium than do other Martian meteorites. Long-lived radioactive isotopes of K, Th and U generate gamma-ray emissions with distinctly different wavelengths and energy levels. Those for each element have been mapped from orbit. NWA 7034 also has very distinct magnetic properties, and detailed data on variations on the magnetic field intensity of Mars have also been acquired by remote sensing. Images from orbit allow relative ages of the surface to be roughly mapped from the varying density of impact craters: the older the surface, the more times it has been struck by projectiles of all sizes. These data also detect of craters large enough to have massively disrupted Martian crustal materials to form large blankets of impact breccias like NWA 7034. That is, 'targets' for the much later impact that sent the meteorite Earthwards. Using a supercomputer, Lagain *et al.* have cut the possibilities down to 19 likely locations. Their favoured source is the relatively young Karratha crater in the Southern Hemisphere to the west of the Tharsis Bulge. It formed on a large ejecta blanket associated with the ancient (~1.5 Ga) 40 km wide Khujirt crater.

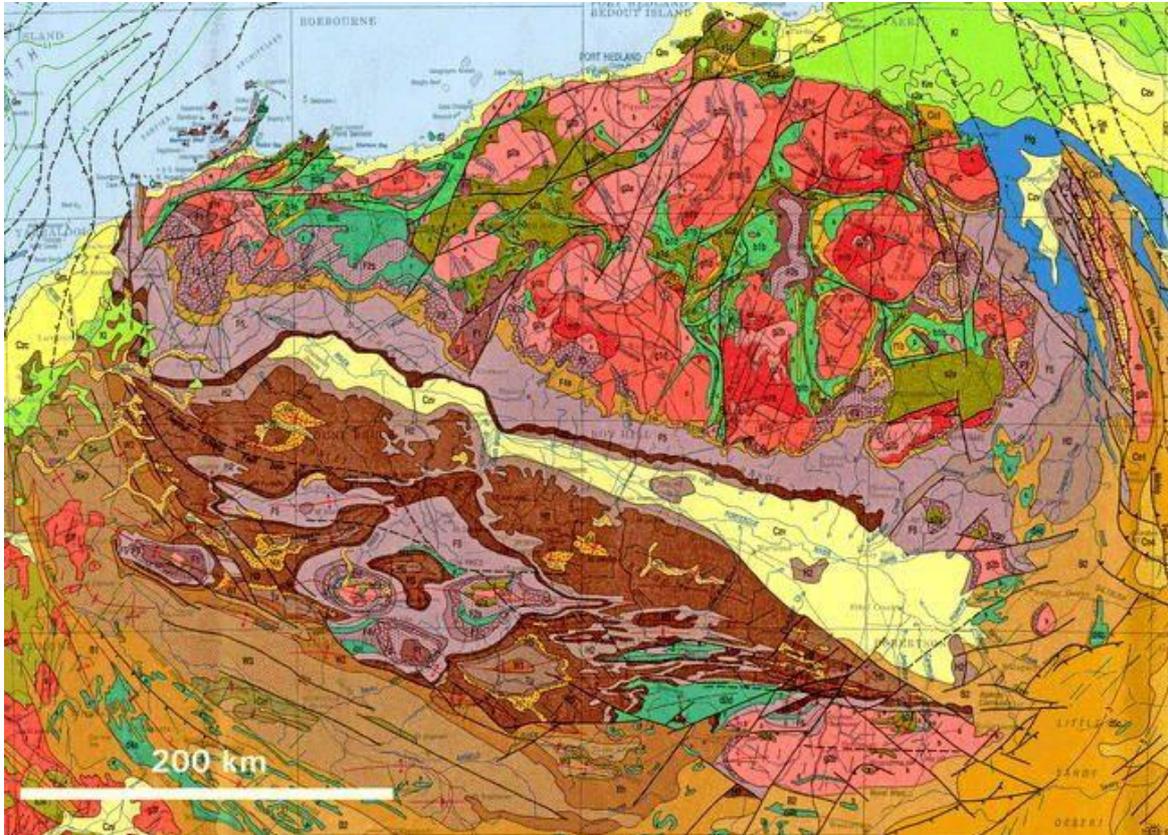
Interesting, but sufficiently so to warrant an awesome bet in the form of a mission budget?

Did giant impacts trigger formation of the bulk of continental crust?

PUBLISHED ON [August 18, 2022](#)

Earth is the only one of the rocky Inner Planets that has substantial continental crust, the rest being largely basaltic worlds. That explains a lot. For a start, it means that almost 30 percent of its surface area stands well above the average level of the basaltic ocean basins – more than 5 km – because of the difference in density between continental and oceanic lithosphere. Without continents and the inability of subduction to draw them back into the mantle Earth would remain a water-world as it is

thought to have been during the Hadean and early Archaean Eons. The complex processes involved in geochemical differentiation and the repeated reworking of the continents through continual tectonic and sedimentary processes has further enriched parts of them in all manner of useful elements and chemical compounds. And, of course, the land has had a huge biosphere since the Devonian period that subsequently helped to draw down CO₂ well as evolving us.



The distinctive Archaean granite-greenstone terrain of the Pilbara craton of Western Australia. TTG granites are shown in reds in the form of domes, which are enveloped by metamorphosed sediments and mafic-ultramafic volcanics in khaki and emerald green. Other colours signify post Archaean rocks. (Credit: Warren B. Hamilton; Earth's first two billion years. GSA, 2007)

It has been estimated that during the Archaean (4.0 to 2.5 Ga) around 75% of continental crust formed. Much of this Archaean crust is made up of sodium-rich granitoids: grey tonalite-trondhjemite-granodiorite (TTG) gneisses in the main. Their patterns of trace elements strongly suggest that their parent magmas formed by partial melting at shallow depths (25 to 50 km). Their source was probably basalts altered by hydrothermal fluids to amphibolites, unlike the post-Archaean dominance of melting associated with subducted slabs of lithosphere. Yet most of the discourse on early continents has centred on [when plate tectonics began](#) and [when they became strong enough](#) to avoid disruption into subductible 'chunks'. Yet 10 years ago geochemists at the University of St Andrews in Scotland used hafnium and oxygen isotopes in Archaean zircons to suggest that the first [continents grew very quickly in the Hadean and early Archaean](#) at around 3.0 km³ yr⁻¹, slowing to an average of 0.8 km³ yr⁻¹ after 3.5 Ga. In 2017 Geochemists working on one of the oldest cratons in the Pilbara region of Western Australia developed a new, [multistage model for early crust formation](#) that did not have a subduction component. They proposed that high degrees of mantle melting first produced a mafic-ultramafic crust of [komatiites](#), which became the source for

a 3.5 Ga mafic magma with a geochemistry similar to those of modern island-arc basalts. If a crust of that composition attained a thickness greater than 25 km and was itself partially melted at its base, theoretically it could have generated TTG magma and Archaean continental crust. Three members of that team from Curtin University, Western Australia, and others have now contributed to formulating a new possibility for early continent formation (Johnson, T.E. *et al.* 2022. [Giant impacts and the origin and evolution of continents](#). *Nature*, v. 608, p. 330–335; DOI: 10.1038/s41586-022-04956-y).

Tim Johnson and colleagues base their views on oxygen isotopes in Archaean zircon grains from the Pilbara. The zircons' O-isotopes fall into three kinds of cluster: low ^{18}O that indicate a hydrothermally altered source; intermediate ^{18}O suggesting a mantle source; high ^{18}O signifying contamination by metasedimentary and volcanic rocks. The first two alternate in the 3.6 to 3.4 Ga period; 4 clusters with mantle connotations occupy the 3.4 to 3.0 Ga range; a cluster with supracrustal contamination follows 3.0 Ga. This record can be reconciled agreeably with the geological and broad geochemical history of the Pilbara craton. But there is another connection: the [Late Heavy Bombardment](#) (LHB) recognised on most rocky bodies in the Solar System.

Bodies with much more sluggish internal processes than the Earth have preserved much of their earliest surfaces and the damage they have suffered since the Hadean. The Moon is the best example. Its earliest rocks in the lunar Highlands record a vast number of impact craters. Their relative ages, deduced from older ones being affected by later ones, backed up by radiometric ages of materials produced by impacts, such as melt spherules and basaltic magmas that flooded the [lunar maria](#), revealed the time span of the LHB. The maria formed between 4.2 and 3.2 billion years ago and the damage done then is shown starkly by the dark maria that make up the 'face' of the Man in the Moon. The lunar bombardment was at a maximum between 4.1 and 3.8 Ga but continued until 3.5 Ga, dropping off sharply from its maximum effects. Earth preserves no tangible sign of the LHB, but because it is larger and more massive than the Moon, and both have always been in much the same orbit around the Sun, it must have been subject to impacts on a far grander scale. Projectiles carry kinetic energy that enables them to do geological work when they impact: $\frac{1}{2} \times \text{mass} \times \text{speed}^2$. The minimum speed of an impact is the same as the target's escape velocity – 2.4 km s^{-1} for the Moon and 11.2 km s^{-1} for the Earth. So the energy of an object hitting the Earth would be 20 times more than if it struck the lunar surface. Taking into account the Earth's larger cross sectional area, the amount of geological work done here by the LHB would have been as much as 300 times greater than that on Earth's battered satellite.

The Earth's early geological history was rarely seen in that context before the 21st century, but that is the framework plausibly adopted by Johnson and colleagues. Archaean sediments in South Africa contain several beds of impact spherules older than 3.2 Ga, as do those of the Pilbara. The LHB also left a geochemical imprint on Earth in the form of anomalous isotope proportions of tungsten in 3.8 Ga gneisses from West Greenland (See: [Tungsten and Archaean heavy bombardment](#) and [Evidence builds for major impacts in Early Archaean](#); respectively, July and August 2002). Johnson *et al.* suggest a 3-stage process for the evolution of the Pilbara craton: First a giant impact akin to the lunar Maria that formed a nucleus of mafic-ultramafic crust from shallow melting of the mantle; its chemical fractionation to produce low-magnesium basalts; and in turn their melting to form TTG magmas and thus a continental nucleus. They conclude:

'The search for evidence of the Late Heavy Bombardment on Earth has been a long one. However, all along it seems that the evidence was right beneath our feet.'

I agree wholeheartedly, but would add that, until quite recently, many scientists who referred to extraterrestrial influences over Earth history were either pilloried or lampooned by their peers as purveyors of 'whizz-bang' science. So, many 'kept their powder dry'. The weight of evidence and a reversal of wider opinion over the last couple of decades has made such hypotheses acceptable. But it has also opened the door to less plausible notions, such as an impact cause for [sudden climate change](#) and even for mythological catastrophes such as the [destruction of Sodom and Gomorrah!](#)

See also: Timmer, J. 2022. [Did giant impacts start plate tectonics?](#) *arsTechnica* 11 August 2022.