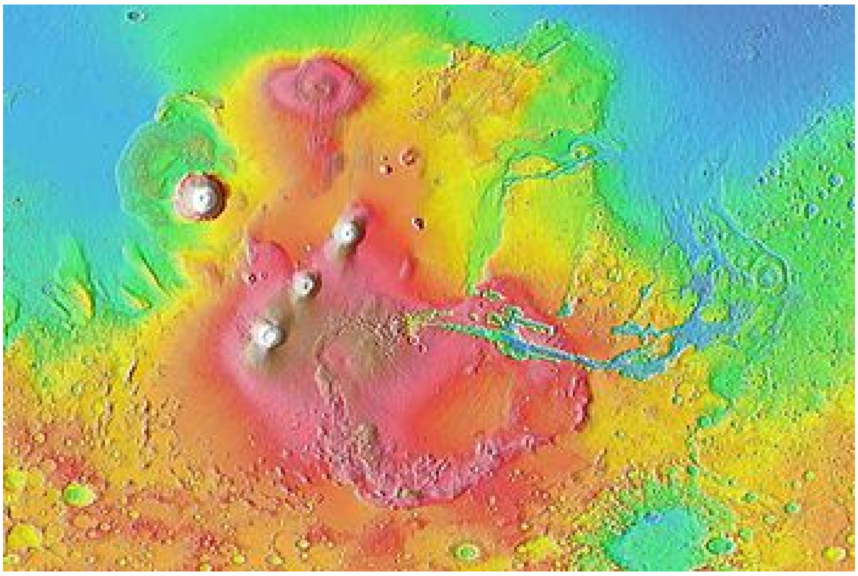
Planetary science

A first for geochronology: ages from Mars (*February 2014*)

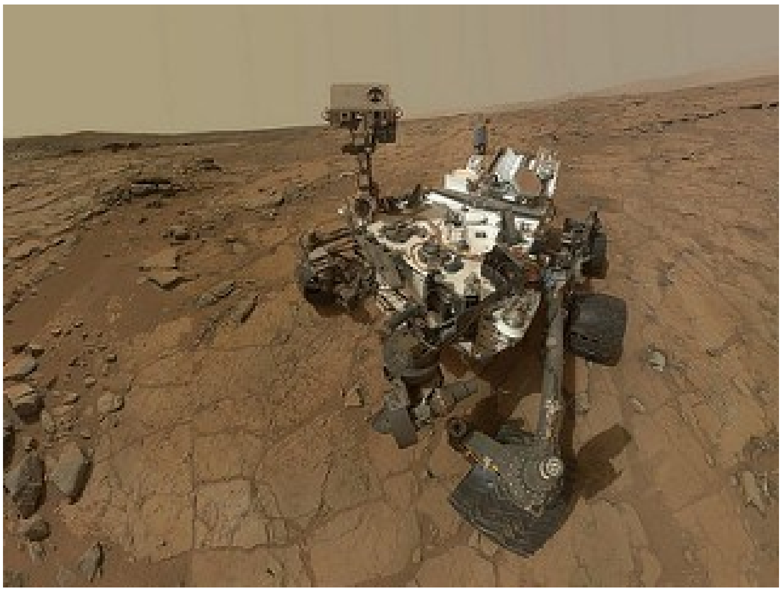
Remote sensing, including mapping of topographic elevation, and the recent exploits of three surface vehicles – the Spirit, Opportunity and Curiosity Rovers – have provided lots of data for a host of geological interpreters. Producing a time frame for Martian geological and geomorphological events has, understandably, been limited mainly to the use of stratigraphic principles. Various rock units and surface features can be placed in relative time order through simple stratigraphic principles, such as what sits on top of what and which features cut through pre-existing rock units or are masked by them. The most important guide up to now has been interpretation of the relations between impact craters and both rock units and other geomorphological features. The Inner Planets are assumed to have recorded about the same variation through time of the frequency and energies of bombardment, and that has been calibrated to some extent by radiometric dating of impact-related rocks returned from the Moon by the crewed Apollo missions. Some details of relative timings also emerge from craters cutting earlier ones. The only other source of Martian ages has been from rare meteorites (there are only 114 of them) whose stable isotope compositions are different from those of terrestrial rocks and more common meteorites. By a process of elimination it is surmised that they were flung from Mars as a result of large impacts in the past to land eventually on Earth. The oldest of them date back to 4.5 Ga, much the same as the estimated age of the earliest crystallisation of magmas on Earth.



Colourised relief map of the western hemisphere of Mars, showing Valles Marineris at centre and the four largest volcanoes on the planet

But all Martian stratigraphy is still pretty vague by comparison with that here, with only 4 time divisions based on reference to the lunar crater chronology and 3 based on evidence from detailed orbital spectroscopy and Rover data about the alteration of minerals on the Martian surface. Apart from meteorite dates there is very little knowledge of the earliest events, other than Mars must have had a solid, probably crystalline crust made of almost anhydrous igneous minerals. This was the 'target' on which much of the impact record was impressed: by analogy with the Moon it probably spanned the period of the Late Heavy Bombardment from about 4.1 to 3.7 Ga, equivalent to the Eoarchaean on Earth. That period takes its name – Noachian – from Noachis Terra ('land of Noah'), an intensely cratered, topographically high region of Mars's southern hemisphere, whose name was given to this large area of high albedo by classical astronomers. Perhaps coincidentally, the Noachian provides the clearest evidence for the former presence of huge amounts of water on the surface of Mars, whose erosional power formed the gigantic Valles Marineris canyon system. The rocky surface that the craters punctured is imaginatively referred to as the pre-Noachian. A major episode of volcanic activity that formed Olympus Mons and other lava domes is named the Hesperian (another legacy of early astronomical nomenclature). It is vaguely ascribed to the period between 3.7 and 3.0 Ga, and followed by three billion years during which erosion and deposition under hyper-arid conditions formed smooth surfaces with very few craters and rare evidence for the influence of surface water and ice. It is named, inappropriately as it turns out, the Amazonian.

Remote sensing has provided evidence of episodes of mineral alteration by water. Clay minerals have been mapped on the pre-Noachian surface, suggesting that aqueous weathering occurred during the earliest times. Sulfates occur in exposed rocks of early Hesperian age, suggesting abundant atmospheric SO_2 during this period of massive volcanicity. The last 3.5 billion years saw only the development of the surface iron oxides whose dominance led to Mars being nickname the 'Red Planet'.



A 'selfie' of Curiosity Rover drilling in Gale Crater (credit: Euclid vanderKroew)

A recent paper (Farley, K.A. and 33 others plus the entire Mars Science Laboratory 2014. In Situ Radiometric and Exposure Age Dating of the Martian Surface. *Science*, v. **343**, online; DOI: 10.1126/science.1247166) suggests that radiometric ages can be measured 'in the field', as it were, by instruments carried by the Curiosity rover. How is that done? Curiosity carries a miniature mass spectrometer and other analytical devices. Drilling a rock surface produces a powder which is then heated to almost 900°C for half an hour to drive off all the gases present in the sample. The mass spectrometer can measure isotopes of noble gases, notably ^{40}Ar, ^{36}Ar, ^{21}Ne and ^{3}He. Together with potassium measured by an instrument akin to an XRF, the ^{40}Ar yields a K-Ar age for the rock. A sample drilled from a fine-grained sedimentary rock in Gale Crater gave an age of 4.2 Ga, most likely that of the detrital feldspars derived from the ancient rocks that form the crater's wall, rather than an age of sedimentation. The values for ^{36}Ar, ^{21}Ne and ^{3}He provide a means for establishing how long the rock has been exposed at the surface: all three isotopes can be generated by cosmic-ray bombardment. The sample from Gale Crater gave an age of about 78 Ma that probably dates the eventual exposure of the rock by protracted wind erosion.

By themselves, these ages do not tell geologists a great deal about the history of Mars, but if Curiosity makes it through the higher levels of the sediments that once filled Gale Crater – and there is enough power to repeat the mass spectrometry at other levels – it could provide a benchmark for Noachian events. The exposure age, interesting in its own right, also suggests that sediments in the crater have not been exposed to cosmic-ray bombardment for long enough to have destroyed any organic materials that the science community longs for.

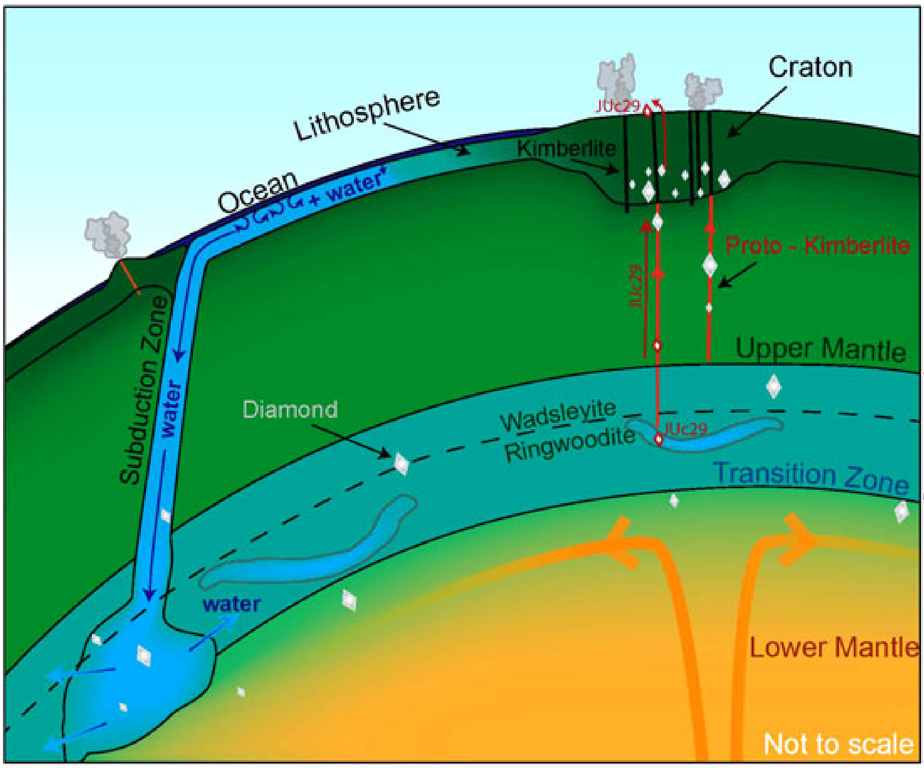
Damp Earth: hydrous minerals in deep mantle rock (*March 2004*)

A large number of water-oriented tropes have been applied to Earth for 'artistic effect', ranging from Waterworld to the Blue Planet, but from a geoscientific perspective H_2O in its many forms – liquid, solid, gas, supercritical fluid and chemically bound – has as much influence over the way the world works as do its internal heat production and transfer. Leaving aside surface processes, the presence of water has dramatic effects on the temperature at which rocks – felsic, mafic and ultramafic – begin to melt and deform and on the rates of important chemical reactions bound up with internal processes.

For a long while many geologists believed that the oceans were the product of water being transferred from the mantle by degassing through volcanoes so that the deep Earth has steadily been desiccated. But now it has become clear that such is the rate at which subduction can shift water back to the mantle that the entire volume of modern ocean water may have been cycled back and forth more than 3 times in Earth history (see *Subduction and the water cycle* Tectonics 2014). Besides, it is conceivable that accretion of cometary material up to about 3.8 Ga may have delivered the bulk of it.

An important aspect of the deep part of the water cycle concerns just how far into the mantle subduction can transport the dominant volatile component of our planet. Ultra high-pressure experimental petrology has reached the stage when conditions at depths more than halfway to the core-mantle boundary (pressures up to 50 GPa) can be sustained using diamond anvils surrounding chemical mixtures that approximate mantle ultramafic materials. Previously, it was thought that serpentinite, the hydrous mineral most likely to be subducted, broke down into anhydrous magnesium-rich silicates at depths around 1250 km. This would prevent the deepest mantle from gaining any subducted water and retaining any that it had since the Earth formed. A team of Japanese geochemists has discovered a hint that hydrous silicates can, through a series of phase changes, achieve stability under the conditions of the deepest mantle (Nishi, M. 2014. Stability of hydrous silicate at high pressures and water transport to the deep lower mantle. *Nature Geoscience*, v. **7**, p. 224-227; DOI: 10.1038/ngeo2074). From an approximate mantle composition their experiments yielded a yet to be named mineral (phase H or $MgSiH_2O_4$) that could remain stable in subducted slabs down to the core-mantle boundary. This development may help explain why the lowermost mantle is able to participate in plume activity through reduction in viscosity at those depths.

A parallel discovery concerns conditions at the base of the upper mantle; the 410 to 660 km mantle seismic transition zone. It comes from close study of a rare class of Brazilian diamonds that have been swiftly transported to the Earth's surface from such depths, probably in kimberlite magma pipes, though their actual source rock has yet to be discovered. These ultra-deep diamonds prove to contain inclusions of mantle materials from the transition zone (Pearson, D.G. and 11 others 2014. Hydrous mantle transition zone indicated by ringwoodite included within diamond. *Nature*, v. **507**, p. 221-224; DOI: 10.1038/nature13080). Australian geochemist Ted Ringwood pioneered the idea in the 1950s and 60s that the mantle transition zone might be due to the main mantle mineral olivine ($(Mg,Fe)_2SiO_4$) being transformed to structures commensurate with extremely high pressures, including one akin to that of spinel. Such a mineral was first observed in stony meteorites that had undergone shock metamorphism, and was dubbed ringwoodite in honour of its eponymous predictor. Yet ringwoodite had never been found in terrestrial rocks, until it turned up in the Brazilian diamonds thanks to Pearson and colleagues.



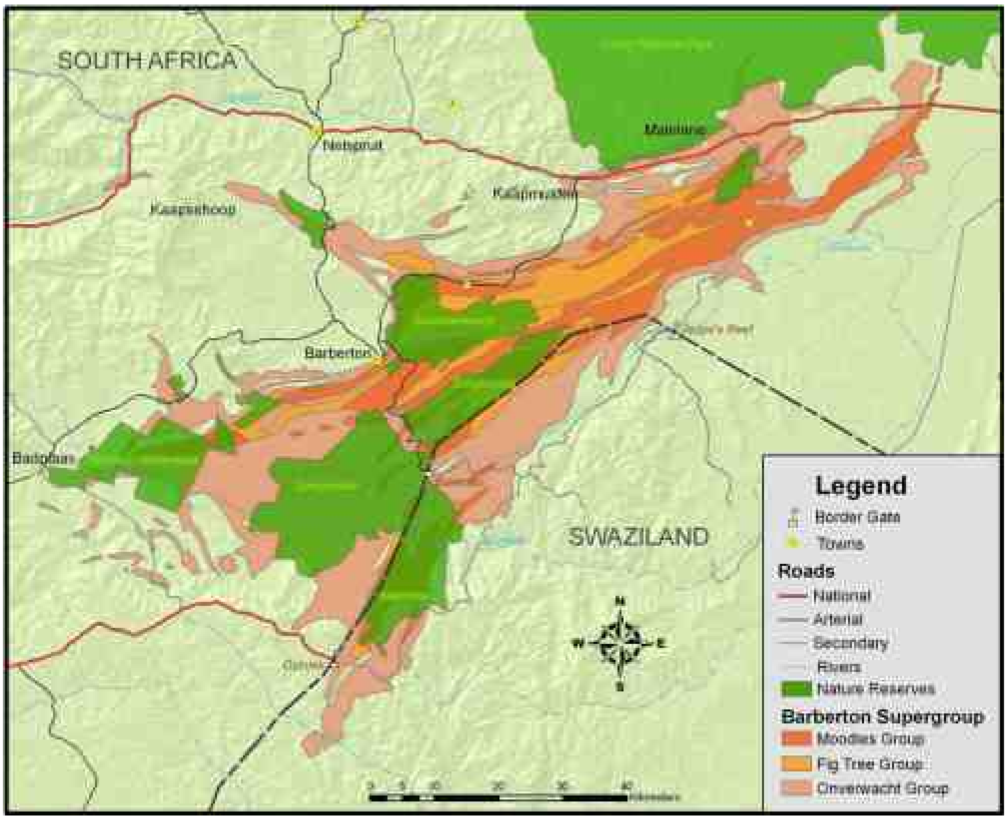
Partial cross-section of the Earth showing the where ringwoodite is stable in the mantle (Credit: Kathy Mather)

Earlier experimental work to synthesise ultra-deep minerals discovered that ringwoodite may contain up to 2% water (actually OH groups) in its molecular lattice: an astonishing thing for material formed under such extreme conditions. The ringwoodite inclusions in diamond show infrared spectra that closely resemble its hydrous form. From this it may be inferred that the 401-660 km transition zone contains a vast amount of water; roughly the same as in all the oceans combined, though the find is yet to be confirmed in a wider selection of diamonds. One of the puzzles about diamondiferous kimberlites is that the magma must have been rich in water and carbon dioxide. That can now be explained by volatile-rich materials at the depths where diamonds form, But that does not necessarily implicate the whole transition zone: there may be pockets ripe for kimberlitic magma formation in a more widely water-poor mantle.

Related articles: Keppler, H. 2014. Earth's deep water reservoir. *Nature* , v. **507**, p. 174-175; DOI: 10.1038/507174a. Rare Diamond Reveals Earth's Interior is All Wet (livescience.com)

Impacts in the early Archaean (*April 2014*)

From the days when advocates of impacts by extraterrestrial objects as explanations of geological features were widely regarded as 'whizz-bang artistes' a great many hats have probably been eaten, albeit in closely guarded privacy. In 1986, when beds of glassy spherules similar to those found in lunar soil and in the K-T boundary sequence were reported from early Archaean greenstone belts in Australia and South Africa, and deduced to have formed by an impact, the authors, Donald Lowe of Stanford University, USA and colleagues, were pounced on by those who thought they could plausibly explain the very odd rocks by unremarkable, Earthly processes. Subsequent work on their geochemistry overwhelmingly supported their formation by an impact of a large carbonaceous chondrite asteroid (see *Chromium isotopes and Archaean impacts* March 2003. And at one site, the Barberton Mountain Land greenstone belt in north-eastern South Africa, there was evidence for at least three such impacts formed in a 20 Ma period. In hindsight, given the lunar bombardment history that peaked between 4 and 3.8 Ga, early Archaean rocks were a great deal more likely to contain materials formed by giant impacts than less antiquated ones.



Barberton greenstone belt, South Africa (credit: Barberton World Heritage Site)

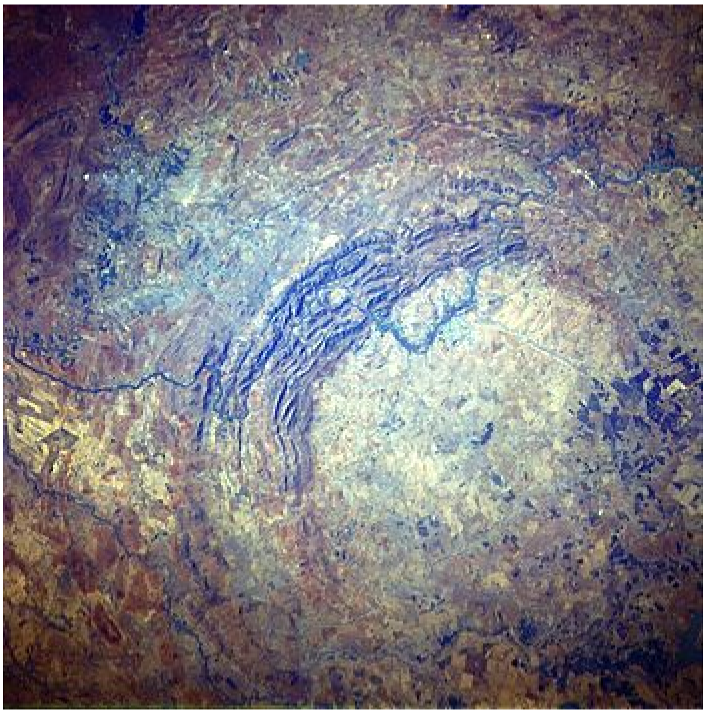
Lowe has been working steadily on his original idea since then, his enthusiasm drawing in others. The latest focus is on evidence for other likely consequences in the Archaean record of the vast power unleashed by incoming asteroids travelling at speeds around 15 km s^{-1} (Sleep, N.H. & Lowe, D.R. 2014. Physics of crustal fracturing and chert dike formation triggered by asteroid impact, ~3.26 Ga, Barberton greenstone belt, South Africa. *Geochemistry, Geophysics, Geosystems*, v. **15**, p-. 1054-1070; DOI: 10.1002/2014GC005229). The damage at Barberton not only produced spherule beds but opened fractures on the shallow sea bed into which liquefied sediments, including some spherules, were injected. These swarms of up to 10 m wide cherty dykes extend up to 100 m below what was then the sea floor strewn with impact spherules, and contain evidence of successive pulses of sediment injection.

Sleep and Lowe explain these dyke swarms as fractures caused by seismicity associated with a major impact. Their complexity suggests extreme shaking for upwards of 100 seconds; far longer than that from large, tectonic earthquakes. The fact that cracks opened to accommodate the sedimentary dykes indicates extension of the affected crust, which the authors suggest resulted from gravitational sliding of the shocked surface sediments down a gentle slope. Possibly the sediments, including the direct products of impact, the spherules, were swept into the cracks by currents associated with tsunamis induced by the impact.

Interestingly, the spherules and dykes formed upon crust largely formed of mafic to ultramafic lavas, yet volcanism following close on the heels of the impact event was of felsic composition. Did the impact trigger a shift locally from oceanic magmatism to that characteristic of island arcs; that is, did it start a new subduction zone?

Impact melts and their destination (*May 2014*)

The work done by an asteroid or a comet that hits the Earth is most obviously demonstrated by the size of the crater that it creates on impact, should it have survived erosion and/or burial by sediments. Since some of the work is done in flinging material away from the impact, the furthest point at which ejecta land is also a rough measure of the power of the hit. All this and much more derived from the kinetic energy of the object, which from Newton's laws of motion amounts to half the product of the body's mass and the square of its speed ($mv^2/2$). It's the speed that confers most energy; doubling the speed quadruples the energy. At a minimum, the speed of an object from far-off in space is that due to acceleration by the Earth's gravitational field; the same as Earth's escape velocity (about 11.2 km s^{-1}). In March 1989 Earth had a close encounter with Newton's laws writ large; an asteroid about 500 m across passed us with just half a million kilometres to spare. Moving at 20 km s^{-1} it carried kinetic energy of around 4×10^{19}J. Had it hit, all of this immense amount would have been delivered in about a second giving a power of 4×10^{19} W. That is more than two hundred times greater than the power of solar heating of the day-side of the Earth. A small part of that power would melt quite a lot of rock.



The Vredefort Dome impact structure in South Africa

As well as the glass spherules that are one of the hallmarks of impact ejecta on Earth and more so on the Moon's surface, some of the larger known impact craters are associated with various kinds of glassy rock produced by instantaneous melting. Some of this melt-rock occurs in thin dykes, but sometimes there is an entire layer of once molten 'country' rock at the impact site. One of the most spectacular is in the Manicougan crater in Quebec, Canada, where a 1 km thick impact-melt sheet dominates most of the 90 km wide structure. It is reputed to be the most homogeneous large rock mass known, being a chemical average of every rock type involved in the Triassic asteroid strike. Not all craters are so well endowed with an actual sheet of melt-rock. This has puzzled some geologists, especially those who studied the much larger (160 km) Vredfort Dome in South Africa, which formed around 2 billion years ago. As the name suggests this is now a circular topographic dome, probably due to rebound and erosional unloading. The structure extends to a depth of 20 km in the ancient continental lithosphere of the Kaapvaal craton. Vredfort has some large dykes of pseudotachylite but apparently no impact melt sheet. That has vanished, probably through erosion, but a relic has been found (Cupelli, C.L. *et al*. 2014. Discovery of mafic impact melt in the centre of the Vredfort dome: Archetype for continental residua of early Earth cratering? *Geology*, v. **42**, p. 403-406; DOI: 10.1130/G35297.1). One reason for it having gone undiscovered until now is that it is mafic in composition, and resembles an igneous gabbro intrusion. Isotope geochemistry refutes that mundane origin. It is far younger than the rocks that were zapped, and may well have formed as huge energy penetrated to the lower crust and even the upper mantle to melt a sizeable percentage of 2.7 to 3.0 Ga old mafic and ultramafic rock.

The same issue of *Geology* contains an article that also bears on the Vredfort Dome structure (Huber, M.S. *et al*. 2014. Impact spherules from Karelia, Russia: Possible ejecta from the 2.02 Ga Vredfort impact event. *Geology*, v. **42**, p. 375-378; DOI: 10.1130/G35231.1). Drill core samples from a Palaeoproterozoic limestone revealed millimetre-sized glass droplets containing excess iridium – an element at high concentration in a variety of meteorites. The link to Vredfort is the age of the sediments, which are between 1.98 and 2.05 Ga, neatly bracketing the timing of the large South African impact. Using reasonably well-constrained palaeogeographic positions at that time for Karelia and the Kaapvaal craton suggests that the glassy ejecta, if indeed they are from Vredfort, must have been flung over 2500 km.

Related article: Earth's Oldest and Biggest Crater Yields New Secrets (livescience.com)

Year Zero: the giant-impact hypothesis (*June 2014*)

On close examination, the light-coloured Highlands of the Moon look remarkably like an old sign by a North American road through hunting country: they are pocked by impact craters of every size. More than that, a lengthy period of bombardment is signified by the craters themselves being cratered to form a chaotic landscape dominated by interlocking and overlapping circular feature. In contrast the dark basaltic plains, called *maria* (seas), are pretty smooth albeit with some craters. They are clearly much younger than the Highlands. The discovery by Apollo astronauts that the older lunar Highlands are made almost exclusively of calcic plagioclase feldspar was a major surprise, requiring an astonishing event to explain them. Such anorthosites may form by flotation of low-density feldspar from a cooling and crystallising basaltic magma. Yet to form the bulk of the Moon's early crust from such materials requires not simply a deep magma chamber, but literally an ocean of molten material at least 200 km deep. The anorthosites also turned out to be far older than the oldest rocks on Earth, close to 4.5 billion years. The most likely explanation seemed to be that the melting resulted from a gargantuan collision between two protoplanets, the Earth's forebear and another now vanished. This would have melted and partially vaporised both bodies. After this discovery the Moon was widely believed to have formed from liquid and vaporised rock flung into orbit around what became the Earth.

Artist's depiction of a collision between two planetary bodies that formed the Moon

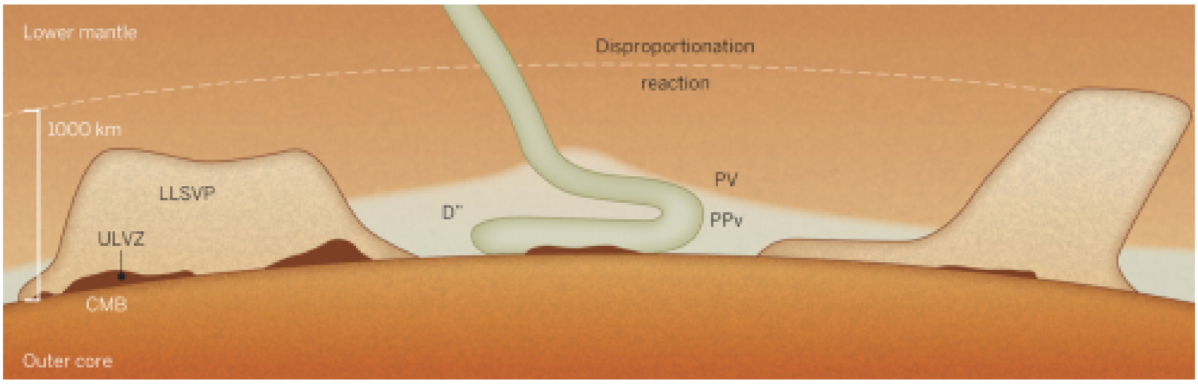
It is hard to escape such a catastrophic model for joint formation of the Earth and Moon shortly after planets of the Solar System had formed, but the hypothesis carries two major puzzles. First, Earth and Moon seem to have very similar, indeed almost the same chemistry: So what happened to the colliding planet? If it had been identical in composition to the proto Earth there is no problem, but a different composition would surely have left some detectable trace in a Moon-Earth geochemical comparison. Initial models of the collision suggested that the other planet (dubbed Theia) was about the size of Mars and should have contributed 70 to 90% of the lunar mass: the Moon-Earth geochemical difference should have been substantial The second issue raised in the early days of the hypothesis was that since the Moon seemed to be almost totally dry (at least, the first rock analyses suggested that), then how come the Earth had retained so much water?

For decades, after an initial flurry of analyses, the Apollo samples remained in storage. Only in the last 10 years or so, when the need to gee-up space exploration required some prospect of astronauts one more to be sent beyond Earth orbit, have the samples been re-examined. With better analytical tools, the first puzzle was resolved: lunar rocks do contain measurable amounts of water, so the impact had not entirely driven off volatiles from the Moon. The bulk geochemical similarity was especially puzzling for the isotopes of oxygen. Meteorites of different types are significantly ear-marked by their relative proportions of different oxygen isotopes, signifying to planetary scientists that each type formed in different parts of the early Solar System; a suggestion confirmed by the difference between those in meteorites supposedly flung from Mars and terrestrial oxygen isotope proportions. A clear target for more precise re-examination of the lunar samples, plus meteorites reckoned to have come from the Moon, is therefore using vastly improved mass spectrometry to seek significant isotopic differences (Harwartz, D. *et al*. 2014. Identification of the giant impactor Theia in lunar rocks. *Science*, v. **344**, p. 1146-1150; DOI: 10.1126/science.1251117). It turns out that there is a 12 ppm difference in the proportion of ^{17}Oin lunar oxygen, sufficient to liken Theia's geochemistry to that of enstatite chondrites. However, that difference may have arisen by the Earth, once the Moon had formed, having attracted a greater proportion of carbonaceous-chrondrite material during the later stages of planetary accretion by virtue of its much greater gravitational attraction. That would also account for the much higher volatile content of the Earth.

The new data do help to support the giant-impact hypothesis, but still leave a great deal of slack in the big questions: Did Theia form in a similar orbit around the Sun to that of Earth; was the impact head-on or glancing; how fast was the closure speed; how big was Theia and more besides? If Theia had roughly the same mass as the proto-Earth then modelling suggests that about half the mass of both Moon and Earth would be made of Theia stuff, giving the Moon and post-impact Earth much the same chemistry, irrespective of where Theia came from. Were William of Ockham's ideas still major arbiters in science, then his Razor would suggest that we stop fretting about such details. But continuing the intellectual quest would constitute powerful support for a return to the Moon and more samples.

What's happening at the core-mantle boundary? (*June 2014*)

The lithosphere that falls into the mantle at subduction zones must end up somewhere in the deep Earth; the question is, where and what happens to it. There are hints from seismic tomography of the mantle that such slabs penetrate as deep as the boundary between the lowermost mantle and the molten outer core. The lithosphere's two components, depleted mantle and oceanic crust, are compositionally quite different, being peridotitic and basaltic, so each is likely to be involved different petrological processes. As regards the physics, since seismic activity ceases below a depth of about 700 km neither entity behaves in a brittle fashion in the lower mantle. Such ductile materials might even pile up in the manner of intestines on the lithological equivalent of the abattoir floor; '*Bowels of the Earth'* as John Elder had it in his book of the same name.



Sketch of the lower 1000 km of the Earth's mantle (Credit: Williams 2014)

Pressure would make these recycled components mineralogically different, as indeed a relative light squeeze does in the upper mantle, where cold wet basalts become dry and denser eclogites thereby pulling more lithosphere down Wadati and Benioff's eponymous zones to drive plate tectonics. Decades old experiments at lower-mantle pressures suggest that mantle minerals recompose from olivine with a dash of pyroxene to a mixture of more pressure-resistant iron-magnesium oxide and perovskite ($(Mg,Fe)SiO_3$). Experiments in the early 21st century, under conditions at depths below 2600 km, revealed that perovskite transforms at the very bottom of the mantle (the D" zone) into layers of magnesium plus iron, silicon and oxygen. This is provisionally known as 'post-perovskite' (see *Post-perovskite unveiled* July 2010). The experiments showed that the transition releases heat. So, should oceanic lithosphere descend to the D" zone, it would receive an energy 'kick' and its temperature would increase. Conversely, if D"-zone materials rose to the depth of the perovskite to post-perovskite transition they would become less dense: a possible driver for deep-mantle plumes.

A new iron-rich phase stable in the bottom 1000 km of the mantle has recently emerged from experiments, and seems to result from perovskite undergoing a disproportionation reaction (Zhang, L. And 11 others 2014. Disproportionation of $(Mg,Fe)SiO_3$ perovskite in Earth's deep mantle. *Science*, v. **344**, p. 877-882; DOI: 10.1126/science.1250274). In the same issue of *Science* other workers using laser-heated diamond anvils have revealed that, despite the huge pressures, basaltic rock may melt at temperatures considerably below the solid mantle's ambient temperature (Andrault, D. *et al*. 2014. Melting of subducted basalt at the core-mantle boundary. *Science*, v. **344**, p. 892-895; DOI: 10.1126/science.1250466). Both studies help better understand the peculiarities of the deepest mantle that emerge from seismic tomography (Williams, Q. 2014. Deep mantle matters. *Science*, v. **344**, p. 800-801; DOI: 10.1126/science.1254399).

Huge blocks with reduced S-wave velocities that rise above the D" zone sit beneath Africa and the Pacific Ocean. There are also smaller zones at the core-mantle boundary (CMB) with shear-wave velocities up to 45% lower than expected. These ultralow-velocity zones (ULVZs) probably coincide with melting of subducted oceanic basalts, but the magma cannot escape by rising as it would soon revert to perovskite. Yet, since ultramafic compositions cannot melt under such high pressures the ULVSs indirectly show that subduction does descend to the CMB. Seismically defined horizontal layering in the D" zone thus may result from basaltic slabs whose ductility has enabled them to fold like sheets of lasagne as the reach the base of the mantle. Development of variants of the laser-heated diamond anvil set-up seem likely to offer insights into our own world's 'digestive' system at a far lower cost and with vastly more relevance than the growing fad for speculating on Earth-like planets that the current 'laws' of physics show can never be visited and on 'exobiology' that cannot proceed further than the extremes of the Earth's near-surface environment and the DNA double helix.

Trapping Martian life forms (*July 2014*)

No matter how optimistic exobiologists might be, the current approaches to discovering whether or not Mars once hosted life or – the longest shot of all – still does, are almost literally hit or miss. First the various teams involved try to select a target area using remotely sensed data to see if rocks or regolith have interacted with water; generally from the presence or absence of clay minerals and/or sulfates that hydrous alteration produces on Earth. Since funding is limited the sites with such ingredients are narrowed down to the 'best' – in the case of NASA's Curiosity rover to Gale Crater where a thick sequence of sediments shows occasional signs of clays and sulfates. But a potential site must also be logistically feasible with the least risk of the lander being lost. Even then, all that can be achieved in existing and planned mission is geochemical analysis of drilled and powdered samples. Curiosity's ambition is limited to assessing whether the conditions for life were present; not that it is or once was. Isotopic analysis of any carbon content to check for mass fractionation that may have arisen from living processes is something for a future ESA mission.

Neither approach is likely to prove the existence now or in far-off times of Martian life, though scientists hope to whet the appetite of those holding the purse strings. Only return of rock samples stands any realistic chance of giving substance to the dreams of exobiologists. But what to collect? A random soil grab or drill core is highly unlikely to provide satisfaction one way or the other. Indeed only incontrovertible remains of some kind of cellular material can slake the yearning. Terrestrial materials might provide a guide to (probably) robotic collectors. Kathleen Benison and Francis Karmanocky of West Virginia University have followed this up by examining sulfates from one of the least hospitable places on Earth; the salt flats (salars) of the high Andes of Chile (Benison, K.C. & Karmanocky, F.J. 2014. Could microorganisms be preserved in Mars gypsum? Insights from terrestrial examples. *Geology*, v. **42**, p. 615-618; DOI: 10.1130/G35542.1).

Evaporite minerals from Andean salars were precipitated from extremely acidic and highly saline lake water originating from weathering of surrounding volcanoes. Oddly few researchers have sought cellular life trapped in crystals of salt or gypsum, the two most common minerals in the high-elevation salt pans. Fluid inclusions in sedimentary halite (NaCl) crystals from as far back as the Triassic are known to contain single-celled extremophile prokaryotes and eukaryotes, but gypsum is more likely to be found on Mars. Benison and Karmanocky document a variety of cellular material from Chilean gypsum that has been trapped in the solid mineral itself or in fluid inclusions. This is the most likely means of fossilisation of Martian life forms, if they ever existed. The salar gypsum samples contain cells that can be cultured and thereby revived since several species can remain dormant for long periods. The authors suggest that transparent cleavage fragments of Martian gypsum could be examined at up to 2000 times magnification on future Mars landers. Finding convincing cells would see dancing in exobiology labs, and what if they should move…

Related articles: A Most Earthly Mineral on Mars (KQUD.org)

Planet Mercury and giant collisions (*July 2014*)

Mercury's sun-lit side from first MESSENGER flyby

Mercury is quite different from the other three Terrestrial Planets, having a significantly higher density. So it must have a considerably larger metallic core than the others – estimated to make up about 70% of Mercury's mass – and therefore has a far thinner silicate mantle. Another large body in the Inner Solar System, our Moon, is the opposite, having the greatest proportion of silicate mantle and a small core.

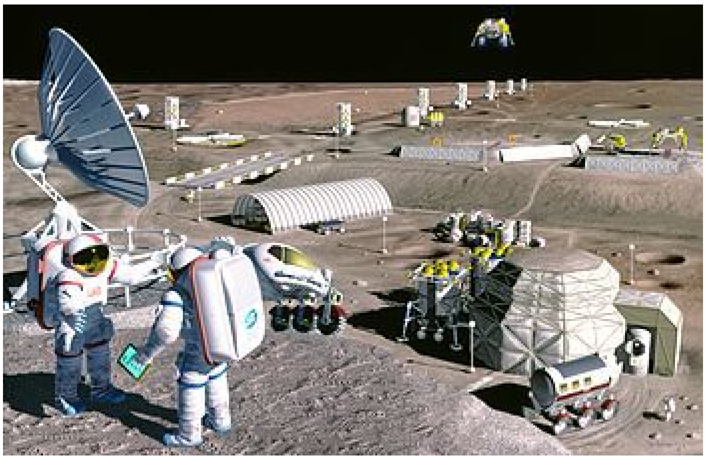
The presently favoured explanation for the Moon's anomalous mass distribution is that it resulted from a giant collision between the proto-Earth and a Mars-sized planetary body. Moreover, planetary theorists have been postulating that around 20 planetary 'embryos' accreted to form Venus and Earth, the final terrestrial event being the Moon-forming collision, with smaller Mars and Mercury having been derived from the two remaining such bodies. For Mercury to have such an anomalously large metallic core has invited mega-collision as a possible cause, but with such a high energy that much of its original complement of silicate mantle failed to fall back after the event. Two planetary scientists from the Universities of Arizona, USA, and Berne, Switzerland, have modelled various scenarios for such an origin of the Sun's closest companion (Asphaug, E. & Reuffer, A. 2014. Mercury and other iron-rich planetary bodies as relics of inefficient accretion. *Nature Geoscience*, published online, DOI: 10.1038/ngeo2189).

Their favoured mechanism is what they term 'hit-and-run' collisions in the early Inner Solar System. In the case of Mercury, that may have been with a larger target planet that survived intact while proto-Mercury was blasted apart to lose much of it mantle on re-accretion. To survive eventual accretion into a larger planet the left-overs had to have ended up in an orbit that avoided further collisions. Maybe Mars had the same kind of lucky escape but one that left it with a greater proportion of silicates.

One possible scenario is that proto-Mercury was indeed the body that started the clock of the Earth-Moon system through a giant impact. Yet no-one will be satisfied with a simulation and some statistics. Only detailed geochemistry of returned samples can take us any further. The supposed Martian meteorites seem not to be compatible with such a model; at least one would expect there to have been a considerable stir in planetary-science circles if they were. For Mercury, it will be a long wait for a resolution by geochemists, probably yet to be conceived.

Any excuse to return to the Moon (*August 2014*)

Humans first set foot on the Moon 45 years ago, yet by 42 years ago the last lunar astronaut left: by human standards manned lunar exploration has been ephemeral. Yet for several reasons – romantic and political – once again getting living beings onto other worlds has become an obsession to some, in much the same manner that increasing numbers of countries seem hell-bent in increasing the redundancy of equipment in orbit; redundant because many of the satellites being launched all do much the same thing, especially in the remote sensing field. It's all a bit like the choice between buying a Ferrari or hiring a perfectly serviceable vehicle when needed – prestige is high on the list of motivators. A new obsession is extraterrestrial mining and some very rich kids on the block are dabbling in that possibility: James Cameron of Aliens and Avatar fame (both films with space mining in the plot); a bunch of Google top dogs; billionaire entrepreneurs and oligarchs with cash to burn. Resource exploitation has also motivated Indian, Russian and Chinese interest in a return to the Moon, at least at an exploratory level.



NASA's proposed Moon colony concept from early 2001 (Credit: NASA)

The main prospective targets have been water, as a source of hydrogen and oxygen through electrolysis to make portable rocket fuel, and helium, especially its rare isotope ^{3}He, for use in fusion reactors. Helium is more abundant on the Moon than it is on Earth: only 300 grams of ^{3}He per year leaks out of the Earth's depths. On the Moon there may be as much as 50 parts per billion in its dusty regolith cover where it remains supercooled in areas of permanent shadow. But to get a ton of it would require shifting 150 million tons of regolith. A decade ago geologists suggesting that metals might be mined on the Moon – noble metals and rare-earth elements have been mooted (the latter's export currently embargoed by Earth's main producer China) – would have been laughing stocks, but now they get air time. Yet none of these materials occur on the Moon in the type of ore deposit found on Earth; if they did, the anomalous nature of such enrichments on a body devoid of vegetation would have ensured their detection already. Even if there were lunar ore bodies, anyone with a passing familiarity with resource extraction knows just how much waste has to be shifted to make even a super-rich deposit economic on Earth. Moreover, vast amounts of water are deployed in enriching the 'paying' metal to levels fit for smelting. For instance, while the rise in gold price since it was detached from a fixed link with paper money in 1971 has enabled very low concentrations to be mined. The methods involve grinding ore in water and then dissolving the gold in sodium cyanide solution, re-precipitating it on carbon made from coconut husks, re-dissolving and then precipitating the gold again by mixing the 'liquor' with zinc dust. Dry ore processing methods – based on density, magnetic and electrical properties – are hardly used in major mining operations nowadays.

The other, and perhaps most important issue with lunar or asteroid mining is that the undoubtedly high costs of whatever beneficiation process is deemed possible must be offset against income from the product; i.e. determined by market price on the home world which would have to be far higher than now. Such a rise in price would work to make currently uneconomic resources here worth mining, and anyone who believes that mining on the Moon would ever be competitive in that capitalist scenario risks being en route to the chuckle farm. Unless, of course, their motive is an exclusivist hobby par excellence and the bragging rights that accompany it – a bit like big game hunting, but the buzz coming from risking their billions rather than their lives.

But it turns out that a refocus on bringing stuff back from the Moon is not confined to floating stock on the financial markets. There are academic efforts to rationalise the Dan Dare (Pilot of the Future) spirit. There aren't many scientific journals with a level of kudos to match the Philosophical Transactions of the Royal Society, the first journal in the world exclusively devoted to science and probably the longest running since it was established in 1665 at the same time as the Royal Society itself. Recently one of its thematic issues dubbed ''Shock and blast: celebrating the centenary of Bertram Hopkinson's seminal paper of 1914' (Hopkinson, B. 1914. A method of measuring the pressure produced in the detonation of high explosives or by the impact of bullets. *Philosophical Transactions of the Royal Society A* v. **213**, p. 437-456; DOI: 10.1098/rsta.1914.0010) a paper appeared that examines the likelihood of fossils surviving the shocks of a major impact (Burchell, M.J. *et al*. 2014. Survival of fossils under extreme shocks induced by hypervelocity impacts. *Philosophical Transactions of the Royal Society A* v. **372**, 20130190; DOI: 10.1098/rsta.2013.0190).

The authors, based at the University of Kent, UK, used a high-velocity air gun to fire quite fragile fossils of diatoms frozen in ice into water at speeds up to 5.34 km s^{-1}. They then looked at solids left in the target to see if any recognisable sign of the fossils remained. Even at the highest energies of impact some diatomaceous material did indeed remain. Their conclusion was that meteorites derived by large impacts into planetary bodies, such as those supposedly from Mars or the Moon, could reasonably be expected to carry remnants of fossils from the bodies, had the impact been into sedimentary rock and that the bodies had supported living organisms that secreted hard parts. My first thought was that the paper was going to resurrect the aged notion of panspermia and a re-examination of the ALH84001 meteorite found in Antarctica claimed in 1996 to contain a Martian fossil (and believed by then US President Bill Clinton). Likewise it might be cited in support of the similar claim, made by panspermia buff Chandra Wickramasinghe, regarding fossils reputedly in a meteorite that fell in Sri Lanka on 29 December 2012: widely regarded as being mistaken. Yet Wickramasinghe's team reported diatoms in the meteorite!

The Martian meteorite ALH84001 shows microscopic features once suggested to have been created by life. (credit: Wikipedia)

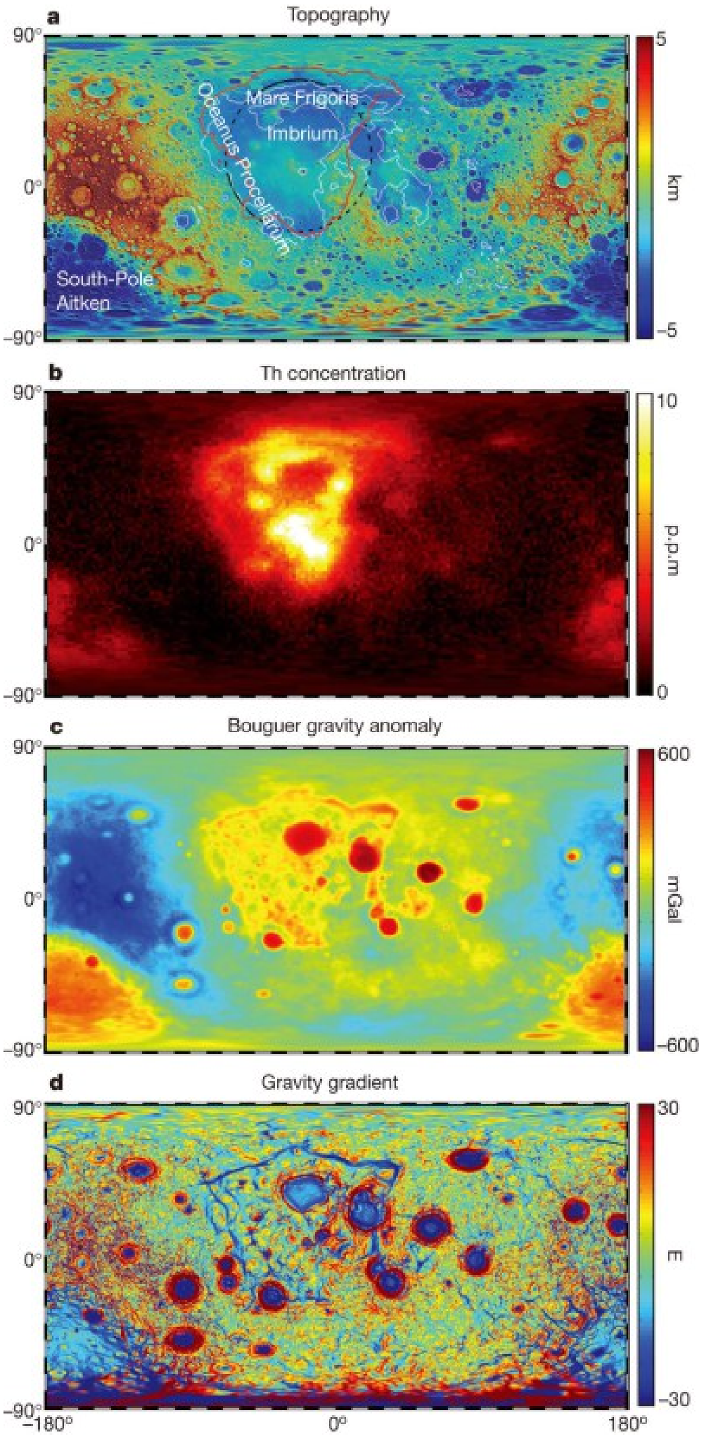
However, Burchell *et al*. have suggested that their results open up the possibility of meteorites on the Moon that had been blasted there from Earth might preserve terrestrial fossils. Moreover, such meteorites might preserve fossils from early stages in the evolution of life on Earth, since when both rocks and whatever they once contained have been removed by erosion or obliterated by deformation and metamorphism on our active planet. 'Another reason we should hurry back to the Moon' says Kieren Torres Howard of New York's City University…

Signs of lunar tectonics (*October 2014*)

Large features on the near side of the Moon give us the illusion of the Man-in-the-Moon gazing down benevolently once a month. The lightest parts are the ancient lunar highlands made from feldspar-rich anorthosite, hence their high albedo. The dark components, originally thought to be seas or *maria*, are now known to be large areas of flood basalt formed about half a billion years after the Moon's origin. Some show signs of a circular structure and have been assigned to the magmatic aftermath of truly gigantic impacts during the 4.1-3.8 Ga Late Heavy Bombardment. The largest *mare* feature, with a diameter of 3200 km, is Oceanus Procellarum, which has a more irregular shape, though it envelopes some smaller *maria* with partially circular outlines.

A key line of investigation to improve knowledge of the lunar *maria* is the structure of the Moon's gravitational field above them. Obviously, this can only be achieved at present by an orbiting experiment, and in early 2012 NASA launched one to provide detailed gravitational information: the Gravity Recovery and Interior Laboratory (GRAIL) whose early results I summarised in *A glimpse of thedeep Moon* in December 2012. GRAIL used two satellites orbiting in tandem, similar to the US-German Gravity Recovery and Climate Experiment (GRACE) launched in 2002 to measure variations over time in the Earth's gravity field. The GRAIL orbiters flew in a low orbit and eventually crashed into the Moon in December 2012, after producing lots of data whose processing continues.

The latest finding from GRAIL concerns the gravity structure of the Procellarum region (Andrews-Hanna, J.C. and 13 others 2014. Structure and evolution of the lunar Procellarum region as revealed by GRAIL gravity data. *Nature*, v. **514**, p. 68-71; DOI: 10.1038/nature13697) have yielded a major surprise. Instead of a system of anomalies combining circular arcs, as might be expected from a product of major impacts, the basaltic basin has a border made up of many linear segments that define an unusually angular structure.



The topography, radioactivity, and gravity structure of the Moon. Oceanus Procellarum is roughly at the centre. Note: the images cover both near- and far side of the Moon. (Credit: Andrews-Hanna et al 2014)

The features only become apparent from the gravity data after they have been converted to the first derivative of the Bouguer anomaly (its gradient). Interpreting the features has to explain the angularity, which looks far more like an outcome of tectonics than bombardments. The features have been explained as rift structures through which basaltic magma oozed to the surface, perhaps feeding the vast outpourings of *mare* KREEP basalts, rich in potassium (K), rare-earth elements (REE) and phosphorus (P). The Procellarum polygonal structure encompasses those parts of the lunar surface that are richest in the radioactive isotopes of potassium, thorium and uranium (measured from orbit by a gamma-ray spectrometer) – thorium concentration is shown in the figure.

Tectonics there may be on the Moon, but the authors are not suggesting *plate* tectonics but rather structures formed as a huge mass of radioactively heated lunar lithosphere cooled down at a faster rate than the rest of the outer Moon. Nor are they casting doubt on the Late Heavy Bombardment, for there is no escaping the presence of both topographic and gravity-defined circular features, just that the biggest expanse of basaltic surface on the Moon may have erupted for other reasons than a huge impact.

Related article: 'Strikingly Geometric' Shapes Hidden on Moon's surface (space.com)