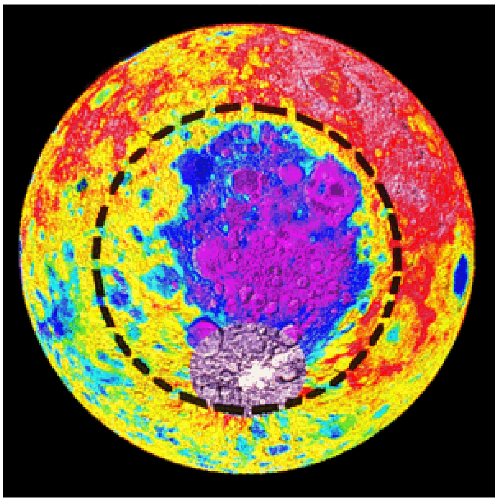
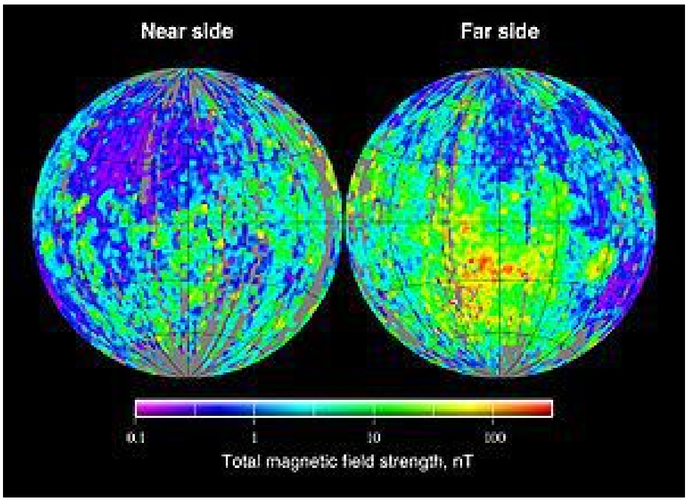
Planetary science

Two smoking barrels on the Moon (*March 2012*)

The South Pole and the farside of the Moon contain, at 2500 km across and 13 km deep, the largest impact structure in the Solar System: the South Pole-Aitken (SPA) basin. Being partly camouflaged by many later craters up to several 100 km across, typical of the lunar far side and the lunar highlands in general, the SPA basin formed early in the Moon's cratering history, and is unlike the mare basins of the near side that are filled with basalt lavas. The light colour of the lunar highlands into which the SPA basin was excavated signifies that they are dominated by almost pure feldspar in the form of anorthosite rock. These anorthosites are prime evidence for the former melting of much if not all of the Moon at the time of its formation: low-density feldspar with a very high melting point could only have accumulated with the degree of purity of anorthosite if early-formed crystals floated to the top of the magma ocean.





Left - Elevation map of the lunar South Pole-Aitken basin (NASA/SDIO probe Clementine mission) – red, the highest elevations, magenta and blue – lowest. Right - Total magnetic field strength at the surface of the Moon (NASA Lunar Prospector mission)

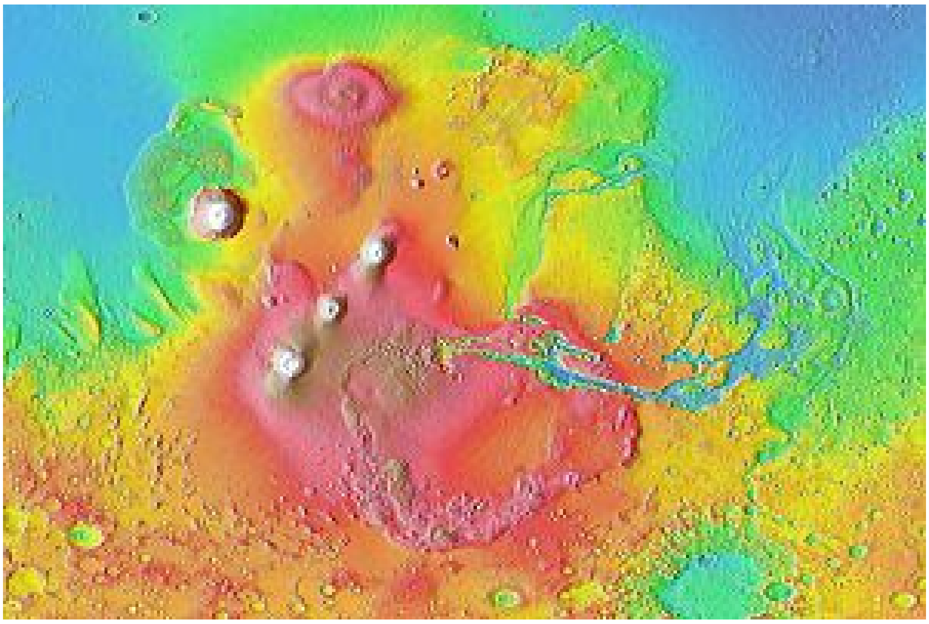
The other feature of feldspars is that they are among the least magnetic of minerals, so it came as a surprise that the northern rim of the SPA basin is studded with positive magnetic anomalies (Wieczorek, M.A. *et al*. 2012. An impactor origin for lunar magnetic anomalies. *Science*, v. **335**, p. 1212-1215). Lunar samples returned by the Apollo Programme are consistently lacking in all but the weakest remanent magnetism, suggesting that the Moon either never had a magnetic field or if it did the field was extremely weak. Even if it did once have a magnetic field, the anomaly patterns are small with high amplitude and reminiscent of a target hit by a shotgun blast. Similar anomalies are scattered on the near side.

The SPA basin is elliptical, suggesting that the projectile responsible for it struck at an oblique angle. The far=side magnetic anomalies cluster exactly where impact modelling would suggest for debris displaced by impact from a northward travelling body. The interpretation arrived at by Mark Wieczorek of the Parisian Institut de Physique du Globe and colleagues from MIT and Harvard University in the US is that the anomalies mark landing sites for large fragments of an easily magnetised, iron-rich asteroid that excavated the basin. Moreover, the same impact might explain magnetic anomalies much further from the basin, on the lunar near side. The remaining mystery is how fragments of the impactor came to be magnetised. The impact would have ensured their being heated well above the temperature of the Curie point at which even the most magnetically susceptible materials lose their magnetisation. The most likely possibility is that the fragments attained their magnetised state at a time when the moon did have a core-generated magnetic field, albeit weak.

Related articles: Moon's magnetic material may have come from an asteroid (latimes.com); NASA video guide to the Moon – http://lunarscience.nasa.gov/articles/video-a-tour-of-the-moon/; NASA video of lunar evolution – http://lunarscience.nasa.gov/articles/video-evolution-of-the-moon/

Valles Marineris: a big sag or a wrench for Mars (*July 2012*)

In the Solar System topographic features don't come larger than Valles Marineris on Mars. At between 5 to 10 kilometres deep and extending along a fifth of the planet's circumference, it makes the Grand Canyon and the Gorge of the Nile look puny.



Colour- relief map of the Mars's Tharsis bulge Valles Marineris at right centre (Credit: NASA/GSFC)

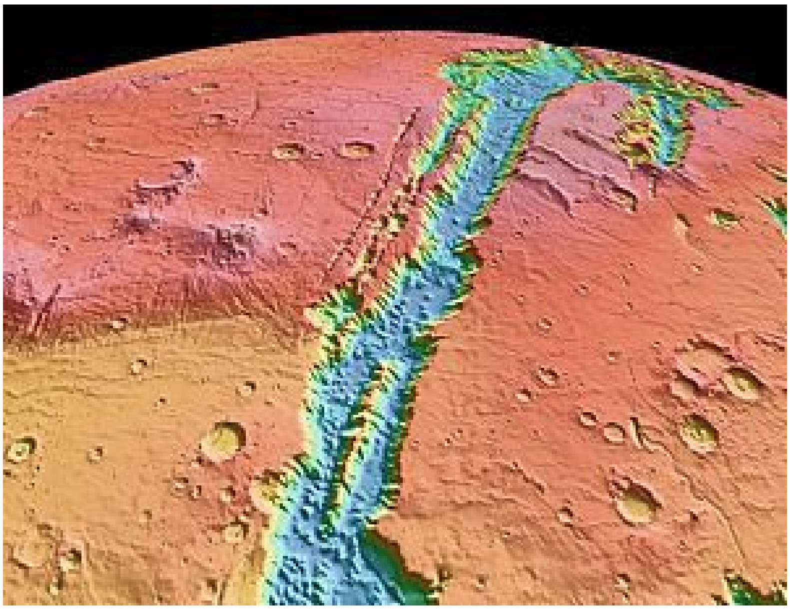
The base and margins of this stupendous valley contains all manner of evidence for erosion, huge landslips and signs of collapse into voids in Mars's crust. Much of the erosion on Mars seems to have stemmed from catastrophic floods several billion years ago, though whether they were all of water or if some were volcanic in origin is being debated (Leverington, D.W. 2011. A volcanic origin for the outflow channels of Mars: Key evidence and major implications. *Geomorphology*, v. **132**, p. 51-75; DOI: 10.1016/j.geomorph.2011.05.022. Atkinson, N. 2012. Did Water or Lava Carve the Outflow Channels on Mars? *Universe Today*, (29 March 2012))

It is difficult to imagine anything other than some kind of fault control over the almost straight, roughly east-west trend of Vales Marineris, but the scale suggests an unmatched scale of tectonics. It has long been thought that the massive canyon resulted from extensional rifting that created a major weakness etched out by later erosion and/or collapse into huge subsurface voids in the crust. Yet there is little sign of commensurately large faults, through there are some. However, the structure is an integral part of yet another superlative. It is on the eastern flank of the mighty Tharsis bulge on which several humongous volcanoes, including Mons Olympus, developed: perhaps there is a causal link between the two dominating features.

Jeffrey Andrews-Hanna of the Colorado School of Mines in the US has tried to model the bulge-chasm pair, coming to the conclusion that there is little sign of major extension. The finale of his study zeroes-in on the possibility of dominant subsidence producing the structure (Andrews-Hanna, J.C. 2012. The formation of Valles Marineris: 3. Trough formation through super-isostasy, stress, sedimentation, and subsidence. *Journal of Geophysical Research*, v. **117**, E06002, DOI: 10.1029/2012JE004059).

In this model, the Tharsis bulge and its associated volcanic province rose so high that on the scale of the planet it must have created a large positive gravitational anomaly. This remains for the most part, but in the Valles Marineris region the crust is now either in isostatic balance or has large negative gravity anomalies, complicated by the fact that the very carving of the canyon system must have resulted in some uplift through unloading. For a while the whole bulge was supported in this gravitationally unstable state by the strength of the Martian lithosphere, and most of it is still in a state of disequilibrium.

Andrews-Hanna's novel view is that a small amount of extension allowed residual magma to rise in linear zone along the eventual length of Valles Marineris as dykes. Andrews-Hanna does not mention the possibility that the magmatism may have melted crustal layers of ice to produce the abundant evidence of flooding and water erosion. The magmas and their heating effect reduced the strength of the lithosphere, locally removing support for the huge load, which subsided. By creating greater slope on the surface of Tharsis the subsidence would have become a focus for both erosion and sedimentation, the increased sedimentary load adding to the subsidence to give the present stupendous depth of the canyons and chasms.



Simulated westwards oblique view of Valles Marineris (Credit: NASA/GSFC)

But this isn't the only model for the canyon system. An Yin of the University of California used a combination of remote sensing data from Mars Reconnaissance Orbiter and Mars Odyssey to perform detailed lithological and structural mapping along Valles Marineris(Yin, A. 2012. Structural analysis of the Valles Marineris fault zone: Possible evidence for large-scale strike-slip faulting on Mars. *Lithosphere*, v. **4** DOI: 10.1130/L192.1). What emerged were several fault zones up to 2000 km long. Instead of an expected extensional sense of movement they are strike-slip faults, with displacements of the order of 100 km in a left-lateral sense. Yin's model is that the canyon system bean as a zone of transtensional deformation: very different from that of Andrews-Hanna. It also begs the question of the underlying tectonic processes, because strike-slip zone on Earth are usually associated with distributed stress from plate tectonics.

For an entertaining, if sometimes bizarrely speculative tour of the Martian landscape, check out Symbols of an Alien Sky Episode 2 on YouTube

The oldest impact structure (*July 2012*)

Various lines of evidence, such as sedimentary deposits of glass spherules and shocked minerals, or signs of unusual isotopic chemistry (see Ejecta from the Sudbury impact April 2005 and Evidence builds for major impacts in Early Archaean August 2002) point to the predicted intensity of meteorite or comet bombardment of the early Earth, and evidence is growing for some events that had global effects. Yet no actual impact sites from the Archaean Eon have been found, until recently. That is not entirely unexpected because erosion during the last few billion years will have removed all trace of the characteristic surface craters. But perhaps there is cryptic evidence in Archaean terrains for the deeper influence of impacts: after all, the depth of penetration of large meteoritic 'missiles' would have been of a similar order to their diameter where shock structures in minerals would slowly anneal and impact-generated melts would crystallise slowly enough to masquerade as plutonic igneous rocks. Close to the Arctic Circle in SW Greenland Archaean gneisses are associated with a roughly 200 km wide geomagnetic anomaly and regionally curvilinear features in the geology that suggest a series of concentric closed structures over a 100 km diameter area centred on a zone of extensively fractured, brecciated and remelted rock (Garde, A.A. *et al*. 2012. Searching for giant, ancient impact structures on Earth: The Mesoarchaean Maniitsoq structure, West Greenland. *Earth and Planetary Science Letters,* v. 337, p. 197-210). Adam Garde and colleagues from the Greenland Geological Survey, Cardiff University UK and Lund University Sweden focused on the central part of these anomalies where gneisses are extensively brecciated with signs of annealed shock-induced lamellae in quartz, feldspar melting and fluidization of highly comminuted mylonites. They ascribe this assemblage of features on a variety of scales to the effects of a major meteorite impact on 25 km deep continental crust. The metamorphic complex contains the famous Amitsoq Gneisses that once had the status of the world's oldest rocks at around 3.8 Ga, but is dominated by migmatites formed around 3.1 Ga that are akin to the Nuuk Gneisses from further south.

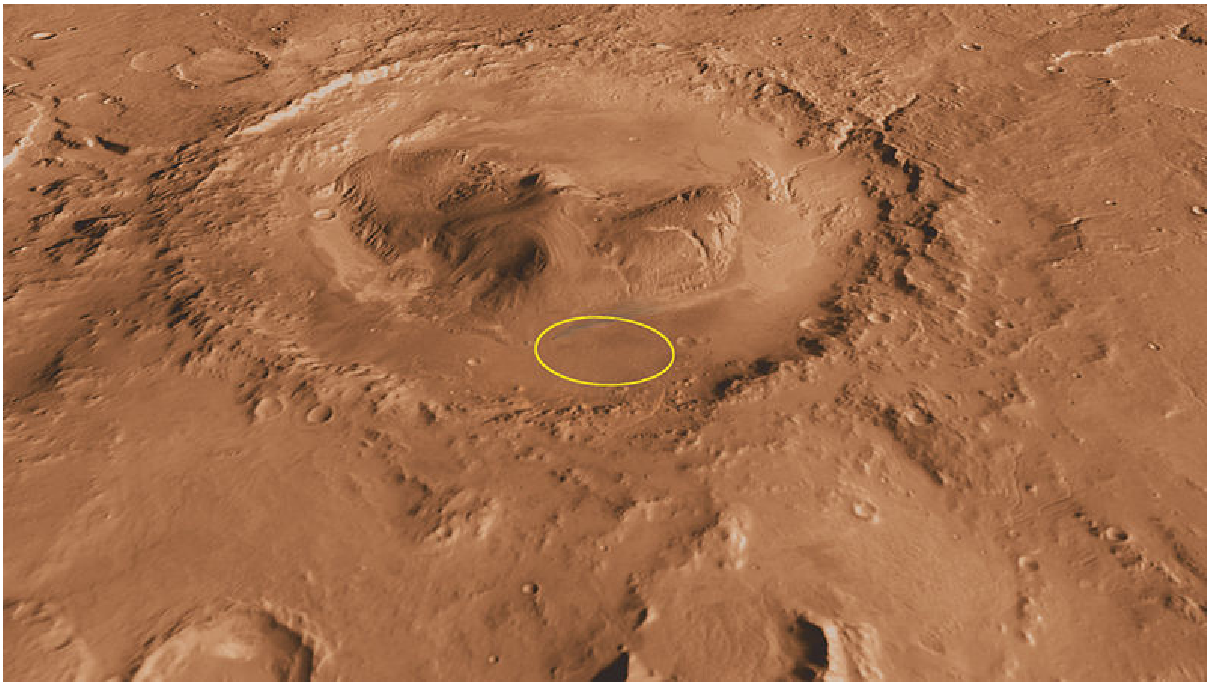
The possible signs of a deeply penetrating impact are cut through by small ultramafic intrusions, zircons from which yield $^{207}Pb/^{206}Pb$ ages between 3.01 and 2.98 Ma, confirming the structures' Mesoarchaean age. An interesting and unanswered question concerns the origin of these magmas together with marginally younger, voluminous granites. Were the ultramafic magmas generated by high degrees of partial melting of mantle as a result of the immense energy of impact? Having temperatures well above those of basaltic melts, could the ultramafic intrusions in turn have induced crustal melting within the depths of a large impact basin?

Gale crater: The Martian 'sexy beast' (*July 2012*)

Why is 'Curiosity' the latest Mars rover aimed to land at Gale Crater? It seems to have been filled with stratified sediments deposited in the crater over perhaps as long as two billion years after it formed by a meteorite impact. The sediments now occur as a relic of later aeolian erosion at the centre of the crater in the form of a large mound that Curiosity is designed to climb and sample. The big attraction is the detection of clays and sulfate minerals in the sediments using multispectral remote sensing. They clearly suggest the influence of water in the formation of the sediments, hence the suggestion that they are lake sediments. On that assumption, Gale Crater is hoped to be a fruitful site for seeking signs of former biological processes: given the technical circumstances of the mission it is deemed the best site there is on Mars for NASA's Mars Science Laboratory.

Artist's concept of NASA's Mars Science Laboratory (Curiosity). (Credit: NASA-JPL)

Sulfates on Mars have excited geologists enormously, along with their companion clays, because they signify the influence of abundant acid water in the breakdown of Martian primary igneous rocks from which the sediments have undoubtedly been derived. Their formation is undoubtedly the geoscientific 'sexy beast' of the last four or five years. Given multi-channel remotely sensed data – and Mars labs are awash with them from several previous missions – sulfates are easy to detect from their distinctive reflectance spectra so there has been abundant pay-back for geologists involved with the Red Planet. But there is water and there is…water. It is hoped to be proved that the depositional medium was standing water or at least abundant subsurface aqueous fluids, which may have lingered for long enough for living organisms to have formed. But there is a possibility that sulfates can form, and so too clays, by superficial weathering processes beneath a humid atmosphere.



An oblique view of Gale crater showing the landing site (yellow ring) and the mound of layered rocks that NASA's Curiosity rover will investigate. (Credit: NASA-JPL)

Erwin Dehouck and team of US and French geochemists set out experimentally to recreate conceivable atmospheric and climatic conditions from Mars's early history to mimic weathering processes (Dehouck, E. *et al*. 2012. Evaluating the role of sulfide-weathering in the formation of sulfates or carbonates on Mars. *Geochimica et Cosmochimica Acta*, v. **90**, p. 47-63; DOI: 10.1016/j.gca.2012.04.057). The experiment involved liquid water and hydrogen peroxide (detected in Mars's present atmosphere and probably produced photochemically from water vapour) in contact with a CO_2 atmosphere. Martian surface conditions were simulated by evaporation of H_2O and H_2O_2 to mix with dominant CO_2, which allowed 'dew' to form on the experimental samples. The samples consisted of ground up olivine and pyroxene, important mineral constituents of basalt – feldspar was not used. – mixed with the iron sulfide pyrrhotite, commonly found in terrestrial basalts and meteorites judged to have come from Mars. Samples of each pure mineral and mixtures with the sulfide were left in the apparatus for four years and then analysed in detail.

Even in such a short exposure the silicate-sulfide mixtures reacted to produce sulfate minerals –hexahydrite ($MgSO_4\_6H_2O$), gypsum ($CaSO_4\_2H_2O$) and jarosite($KFe_3(OH)_6(SO_4)_2$), together with goethite (FeOOH) and hematite (Fe_2O_3). Without the presence of sulfides, the silicate minerals barely broke down under the simulated Martian conditions but did produce traces of magnesium carbonate. The sulfate bearing assemblages look very like those reported from many locations on Mars. The acid conditions produced by weathering of sulfides to yield sulfate ions are incompatible with preservation of carbonates, as the experiment indicates. However, there are reports of Martian sediments that do contain abundant carbonate minerals.

The researchers' conclusions are interesting: "These results raise doubts on the need for a global acidic event to produce the sulfate-bearing assemblages, suggest that regional sequestration of sulfate deposits is due to regional differences in sulfide content of the bedrock, and pave the way for reevaluating the likelihood that early sediments preserved biosignatures from the earliest times”. Weathering by dew formation seems quite adequate to match existing observations.

Where did Earth’s water come from? (*August 2012*)

Comet Hyakutake and a carbonaceous chondrite meteorite

Because they can be so large, consist mainly of water ice and since there are probably a great many lurking in the outer reaches of the solar system, impacting comets have long been thought to have delivered the water that makes the Earth so dynamic and capable of hosting complex life. Remote-sensing studies of the isotopic composition of water in one comet (Hartley 2) caused great excitement in 2011 by showing that its ratio of deuterium to hydrogen was very similar to that of Earth’s ocean water. Other D:H ratios have recently been published from a suite of meteorites gleaned from the surface of Antarctic ice (Alexander, C.M.O’D. *et al*. 2012. The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science*, v. **337**, p. 721-723; DOI: 10.1126/science.1223474). These meteorites are carbonaceous chondrites thought to be the source of much of the solid material in planets of the Inner Solar System. To cut short a long and closely argued case, it seems that the CI-type chondrites’ water is isotopically quite different from that in analysed comets, knocking another popular hypothesis on the head; that comets and carbonaceous chondrites formed in the same part of the Solar System.

Since hydrocarbons in comets – known from interplanetary dust particles – contain hydrogen with a far richer complement of its heavy isotope deuterium than does cometary water ice, the crashing of entire comets onto planets such as the Earth would not produce the observed terrestrial D:H ratio even though their water ice alone does match it. Alexander and US, British and Canadian colleagues conclude what seems to be a unifying explanation whereby CI chondritic solids and volatiles alone would have been able to form the Inner Planets and their various complements of water by initial accretion. Comets as a second-stage source, in this account, are relegated to mere curiosities of the Solar System with little role to play other than occasional big impacts that may, or may not, have influenced evolution by the power that they delivered not through their chemistry.

Are Martian clays magmatic in origin? (*September 2012*)

The remote detection of spectral features in the infrared that suggest abundant clay minerals on the surface of Mars is the basis for a widely-held view that Mars may once have had moist climatic conditions that encouraged life to form (see *The Martian 'sexy beast'* above*)*. The presence of clays, along with suggestive landforms, has also been used to speculate that Mars once harboured long-lived lakes and perhaps even a huge ocean on its northern hemisphere, between 3.7 to 4.1 Ga. It was the presence of clays that pitched NASA's recently arrived Curiosity Rover at the Gale crater and its central *Aeolis Mons*. The latter, also known as Mount Sharp, preserves about 5 km of layered rocks, the lowest of which are clay-rich and hypothesised to be sediments laid down in a lake that filled the crater. Provided Curiosity operates according to plan, we will know soon enough whether or not the layered rocks of Mount Sharp are indeed sediments, but an article suggests another explanation than weathering for the production of abundant clay minerals on Mars (Meunier, A. *et al*. 2012. Magmatic precipitation as a possible origin of Noachian clays on Mars. *Nature Geoscience*, v. **5**, p. 739-743; DOI: 10.1038/NGEO1572).

Layered rocks on the flanks of Mount Sharp in Gale crater from Curiosity's Mastcam

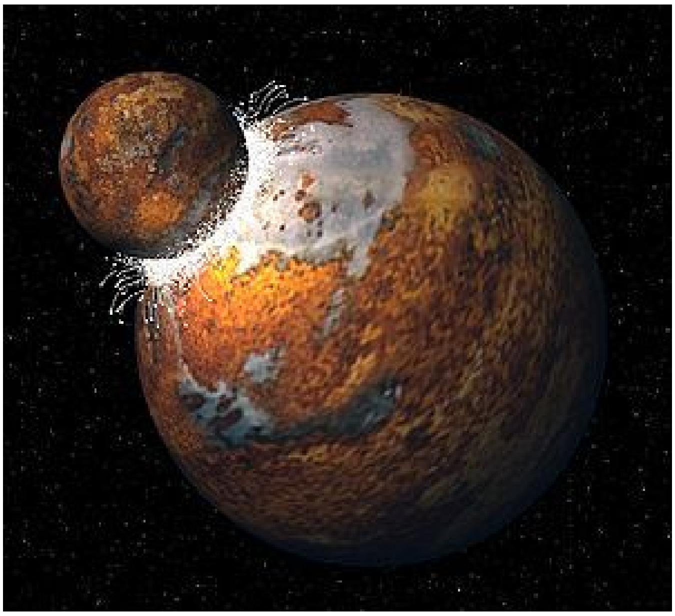
The French-US team provides evidence from terrestrial lavas that abundant iron- and magnesium-rich clays, known as smectites, may form at a late stage during crystallization of magma. If magma contains water – and most magmas do – as more and more anhydrous silicates crystallise during cooling water builds up in the remaining liquid. Once silicate crystallisation is complete there remains a watery fluid capable of reacting with some of the silicates to form clay minerals; a process often referred to as pneumatolysis. How much clay is formed depends on the initial water content of the magma. Pneumatolysis operates on hot lava, whereas weathering occurs at ambient temperature provided the climate is able to support liquid water at the surface. Mars is currently far too cold for that, and ideas of a wet surface environment earlier in the planet's history demand an explanation for a much warmer climate. Clay minerals do not appear to be present in Mars's younger rocks, so Meunier and colleagues suggest that as the planet's mantle evolved early water-rich magmas were gradually replaced by ones with less water: interior Mars was gradually de-gassed and its magmas lost the ability to alter minerals that crystallised from them.

Now, clay minerals are extremely resistant to change except through high-temperature metamorphism. Once formed they can be blown around – Mars has probably always been a very windy place – to end up in aeolian sediments that are plentiful on Mars. Also, if occasionally water flowed on the surface perhaps by subsurface water venting suddenly, fine-grained pneumatolytic clays would easily be picked up, concentrated as flow speed lessened and deposited in waterlain sedimentary layers. A dilemma that faces the Curiosity science team is what significance to assign to clays in sediment layers, when they no longer provide unequivocal evidence of weathering. But will the resistant layers on Mount Sharp turn out to be pneumatolytically altered lava flows?

Note added 28 September 2012: The first scientific triumph of the Curiosity Rover is imagery of sediments in what had been suggested to be an alluvial fan washed into Gale crater. They show gravels with rounded pebbles.

Related articles: Curiosity Rover Steps Right Into Ancient Riverbed on Mars (wired.com); Hynek, B. 2012. Uninhabitable martian clays? *Nature Geoscience*, v. **5**, p. 683-684; DOI: 10.1038/ngeo1560.

New twist on lunar origin (*October 2012*)



Artistic impression of the moon-forming giant impact. (credit: Wikipedia)

Although a few would-be space faring countries have ambitions, a post-Apollo crewed mission to the Moon is unlikely for quite a while. Yet moon-struck curiosity goes on: currently there is a surge in re-examining the lunar samples brought back more than 40 years ago. The Lunar Sample Laboratory Facility in Houston holds about a third of a ton of rock and regolith. I suppose part of the reason why lunar rocks are being re-analysed – in fact some for the first time – is because new or improved methods are available, but frustration among a growing community of planetary geochemists having little more than meteorites to peer at probably plays a role as well. Since Hartman and Davis first suggested it, the giant impact theory for the Moon's origin has dominated geochemical ideas. Its most tangible aspect is that of a magma ocean, floated plagioclase crystals from its fractional crystallisation probably having formed the glaring white lunar highlands composed of anorthosite. More subtle are ideas about what happened to the Mars-sized planet that did the damage to Earth and flung vaporised rock into orbit to accrete into the new Moon, and the effects of the stupendous energy on the geochemistry of all three bodies. Directed at all that is new research on isotopes of zinc (Paniello, R.C. *et al*. 2012. Zinc isotope evidence for the origin of the Moon. *Nature*, v. **490**, p. 376-379; DOI: 10.1038/nature11507).

The focus on zinc is because it is easily vaporised compared with more refractory materials, such as calcium an titanium, and as well as being 'volatile' it has five naturally occurring isotopes with relative atomic masses of 64 (the most abundant), 66, 67, 68 and 70. In general, isotopes of an element behave in slightly different ways during geological and cosmological processes, which changes their proportions in the products; a process known as 'mass-fractionation'. Paniello and colleagues from Washington University, Missouri and the Scripps Institution of Oceanography, California USA found that lunar rocks are enriched in the heavier isotopes of zinc yet depleted in total zinc compared with terrestrial rocks and meteorites supposed to have come from Mars. Unlike those two planets the Moon's zinc deviates from its abundance relative to other elements recorded by chondritic meteorites. This zinc depletion tallies with volatile loss from incandescent vapour blurted from the colliding planets. But it doesn't help with the detailed predictions from the giant-impact model. A variety of scenarios suggest that the Moon should be made from remnants of the inbound impactor's mantle, yet studies of other elements' isotopes indicate that the Moon is rather Earth-like. But not those of zinc, so it looks like they have to be explained by a complete rethink of the whole hypothesis (Elliott, T. 2012. Galvanized lunacy. *Nature*, v. **490**, p. 346-7; DOI: 10.1038/490346a).

Related article: The genesis of the Moon (geologyrocks blog)

A glimpse of the Hadean (*November 2012*)

There is something deeply unsatisfying, even untidy, about a planetary history from which the first half billion years is more or less a blank. Every likely stone has been turned and every isotope hurled as a curve-ball through a mass spectrometer in the quest for either direct evidence of Hadean events or an acrid whiff that lingers in later matter. All, that is, except for one…

Formed in a proposed supernova that may have helped trigger formation of the Sun and Solar System, ^{150}Gd quickly decayed to produce ^{146}Sm, which itself had a half-life of about 68 Ma. That is too short for any significant trace of that radioactive rare-earth element to remain in terrestrial rocks, but its daughter isotope ^{142}Nd bears witness to its former existence. Checking the proportion of ^{142}Nd against the heavier ^{144}Nd is a means of assessing isotopic fractionation according to atomic mass between a solid source of a magma, and between residual magma and solids that crystallised from it.

A popular and well-supported view of the Hadean is that shortly after accretion of the Earth a stupendous impact left a deep 'ocean' of magma and flung off mass that produced the Moon. Solidification of that ocean, which would have involved denser minerals sinking and lighter ones rising to higher levels, has been suggested to have resulted in differentiation of the mantle into two portions, one enriched, the other depleted; an event on which the entire later geochemical history of our planet has depended. Should either part of the mantle melt again, the igneous rocks that would result should carry a neodymium isotope signature of one or the other. Little sign of either emerges from studies of igneous rocks younger than 2.5 Ga, but older rocks from Greenland that go back to 3.8 Ga demonstrate that almost all of them melted from the Hadean depleted mantle. Without rocks carrying $^{142}Nd/^{144}Nd$ ratios signifying the other side of the more ancient mantle division, an enriched source, the grand idea was flawed. But this one-sidedness appears now to have been balanced by other Archaean igneous rocks (Rizo, H. *et al*. 2012. The elusive Hadean enriched reservoir revealed by ^{142}Nd deficits in Isua Archaean rocks. *Nature*, v. **491**, p. 96-100; DOI: 10.1038/nature11565).

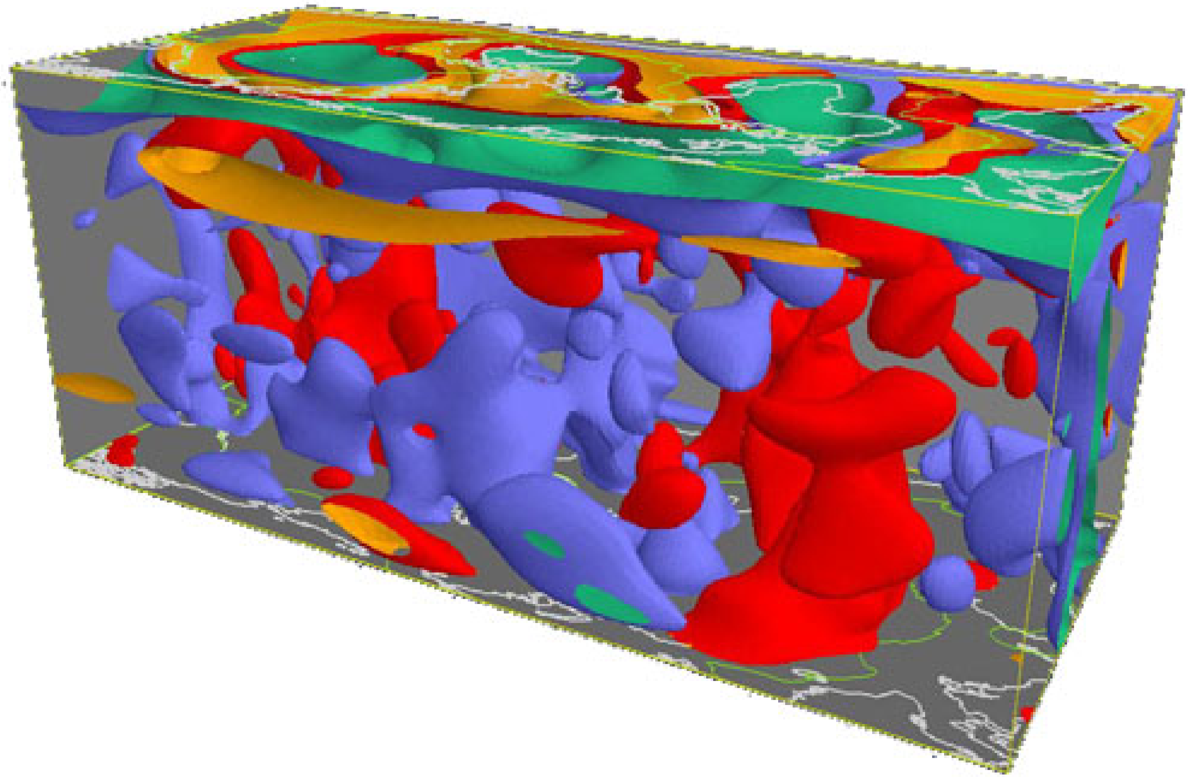
3.8 billion year-old Amitsoq gneisses, West Greenland (Image credit: Stephen Moorbath)

The analysed rocks are interesting for another reason, for they are 3.4 Ga old basalt dykes that cut through the more ancient west Greenland crust. They are the first evidence of a brittle crust that cracked under tension to be followed by mantle-derived magma. Some members of the Ameralik dyke swarm show just the isotopic signature predicted for the enriched member of the postulated fundamental mantle division. However, for some yet to be recognised reason, few post-Archaean rocks show any sign of widespread mantle heterogeneity. Such matters could be addressed with greater confidence only after mass spectrometry allowed precise discrimination between isotopes of a whole variety of both common and rare elements. That was not so long ago, so a rich trove of future revelations can be anticipated.

Related article: Greenland rocks provide evidence of Earth formation process (phys.org)

Probing the Earth's mantle using noise (*December 2012*)

It goes without saying that it is difficult to sample the mantle. The only direct samples are inclusions found in igneous rocks that formed by partial melting at depth so that the magma incorporated fragments of mantle rock as it rose, or where tectonics has shoved once very deep blocks to the surface. Even if such samples were not contaminated in some way, they are isolated from any context. For 20 years geophysicists have been analysing seismograms from many stations across the globe for every digitally recordable earthquake to use in a form of depth sounding. This seismic tomography assesses variations in the speed of body (P and S) waves according to the path that they travelled through the Earth.



Global seismic tomogram (Mercator projection with north at front face) dividing the mantle into 'warm' and 'cool' regions (Credit: Cornell University Geology)

Unusually high speeds at a particular depth suggests more rigid rock and thus cooler temperatures whereas hotter materials slow down body waves. The result is images of deep structure in vertical 2-D slices, but the quality of such sections depends, ironically, on plate tectonics. Earthquakes, by definition mainly occur at plate boundaries, which are lines at the surface. Such a one-dimensional source for seismic tomograms inevitably leaves the bulk of the mantle as a blur. But there are more ways of killing a cat than drowning it in melted butter. All kinds of processes unconnected with tectonics, such as ocean waves hitting the shore and interfering with one another across the ocean basins, plus changes in atmospheric pressure, especially those associated with storms, also create waves that pass through the solid Earth in a similar fashion to seismic ones.

Such aseismic energy produces the background noise seen on any seismogram. Even though this noise is way below the energy and amplitude associated with earthquakes, it is continuous and all pervading: the cumulative energy of many natural processes. Given highly sensitive modern detectors and sophisticated analysis, much the same kind of depth sounding is possible using micro-seismic noise, but for the entire planet and at high resolution. Rather than imaging speed variations this approach can pick up reflections from physical boundaries in the solid Earth. Surface micro-seismic waves exactly the same as Rayleigh and Love waves from earthquakes have already been used to analyse the

Mohorovičić discontinuity between crust and upper mantle as well as features in the continental crust; indeed the potential of noise was recognized in the 1960s. But the deep mantle and core are the principle targets, being far out of reach of experimental seismic surveys using artificial energy input. It seems they are now accessible using body-wave noise (Poli, P. *et al*. 2012. Body-wave imaging of Earth's mantle discontinuities from ambient seismic noise. *Science*, v. **338**, p. 1063-1065; DOI: 10.1126/science.1228194).

Poli and colleagues used a temporary network of 42 seismometers laid out in Arctic Finland to pick up noise, and sophisticated signal processing to separate surface waves from body waves. Their experiment resolved two major mantle discontinuities at ~410 and 660 km depth that define a transition zone between the upper and lower mantle, where the dominant mineral of the upper mantle – olivine – changes its molecular state to a more closely packed configuration akin to that of the mineral perovskite, which is thought to characterize the lower mantle. Moreover, they were able to demonstrate that the 2-step shift to perovskite occupies depth changes of about 10-15 km. Applying the method elsewhere doesn't need a flurry of new closely-spaced seismic networks. Data are already available from arrays that aimed at conventional seismic tomography, such as USArray that deploys 400 portable stations in area-by-area steps across the United States (see *The march of the seismometers* November 2009).

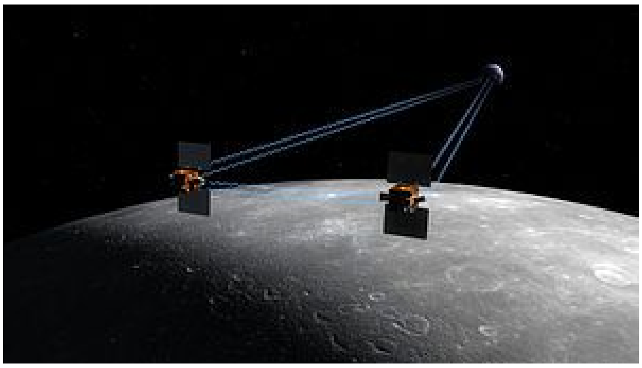
It is early days, but micro-seismic noise seems very like the dreams of planetary probing foreseen by several science fiction writers, such as Larry Niven who envisaged 'deep radar' being deployed for exploration by his piratical hero Louis Wu. Trouble is, radar of that kind would need a stupendous power source and would probably fry any living beings unwise enough to use it. Noise may be a free lunch to the well-equipped geophysicist of the future.

Related articles

Prieto, G.A. 2012. Imaging the deep Earth. *Science* (Perspectives), v. **338**, p. 1037-1038; DOI: 10.1126/science.1231290.

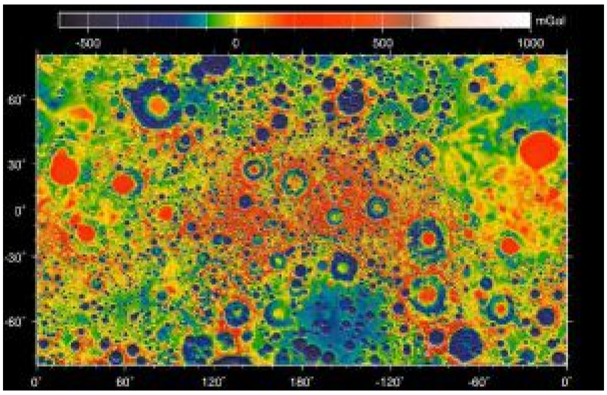
A glimpse of the deep Moon (*December 2012*)

Charting the variation in gravitational potential across a planet provides a measure of the distribution of mass beneath its surface. That depends on both the planet's actual shape and on internal variations in rock density. The Earth's gravity has been mapped with varying degrees of precision, depending on sample spacing, by surface measurements using gravimeters. Doing gravity surveys from space cannot be so direct, however. One ingenious approach for the gravitational field over the oceans is to measure the mean height of the ocean surface using radar beams from a satellite. Since this is affected by variations in the gravitational field, partly due to bathymetry and partly because of varying density beneath the ocean floor, removing the calculable bathymetric effect leaves a gravitational signal from the underling lithosphere and deeper mantle. The first satellite to illuminate the Earth with radar microwaves, Seasat, gradually built up such a gravitational map of the deep Earth over a period of 105 days in 1978, which was followed up by other satellites such as the ERS series and Topex-Poseidon.



Artistic rendition of the GRAIL satellites in lunar orbit

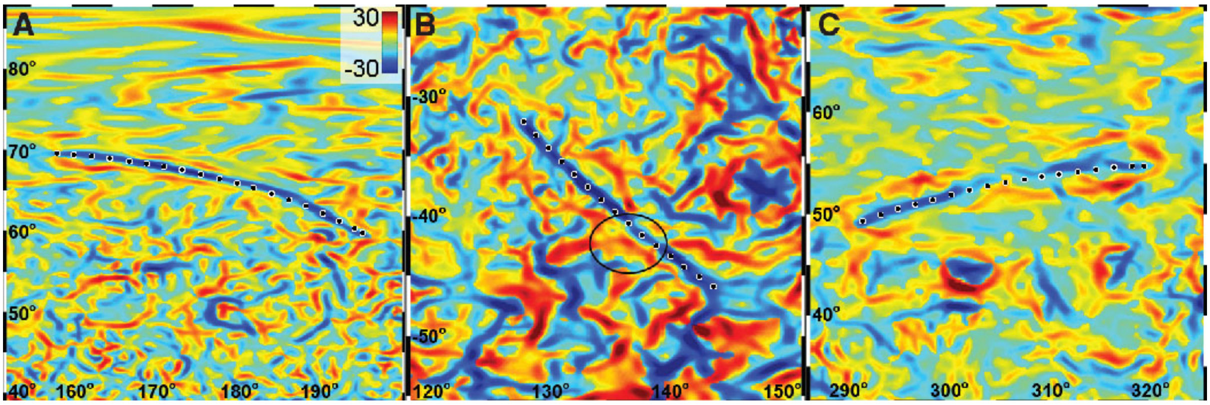
It is not so easy to map gravity precisely above a solid planetary surface, but through the GRACE experiment this can be done by measuring very precisely the distance between a pair of satellites that follow the same orbit. As the gravitational field changes so too does the separation between the tandem of satellites; an increase in gravity pulls the satellites closer together and *vive versa*. GRACE has provided some fascinating data, such as estimates of the withdrawal of groundwater from large sedimentary basins (see *Groundwater depletion measured from orbit* Physical resources September 2009) and shrinkage of ice caps (see *Micro-gravity data chart shrinking ice caps* Remote sensing November 2009). However, GRACE is limited in its resolution of gravitational anomalies by the fact that Earth has an atmosphere above which such tandems must be parked in orbit to avoid burning up. The higher the orbit, the more degraded is the resolution. This effect is much less for Mars and non-existent for the Moon.



Gravity field of the moon as measured by NASA's GRAIL mission. The far side of the moon is at the centre, whereas the nearside (as viewed from Earth) is at either side. (credit: NASA/ARC/MIT)

A sister experiment to GRACE has been orbiting the Moon since September 2011: the Gravity Recovery and Interior Laboratory (GRAIL). First the tandem orbited at 55 km, then 22 and for a brief period 11 km, before running out of thruster fuel on 17 December 2012 and crashing into the lunar surface. Results from the highest orbit resolve lunar gravity to 13 km cells, recently reported on-line in three papers (Zuber, M.T. and 16 others 2012. Gravity field of the Moon from the Gravity Recovery and Interior Laboratory (GRAIL) Mission. *Science*, v.**339**, p. 668-671; DOI: 10.1126/science.1231507. Wieczorek, M.A. and 15 others 2012. The crust of the Moon as seen by GRAIL. *Science*, v. **339**, p. 671-675; DOI: 10.1126/science.1231530. Andrews-Hanna, J.C. and 18 others 2012. Ancient igneous intrusions and early expansion of the Moon revealed by GRAIL gravity gradiometry. *Science*,

v. **339**, p. 675-678; DOI: 10.1126/science.1231753). From crater gravitational signatures due to variations in surface topography it seems that the early bombardment of the lunar surface far exceeded previous assumptions. Impact effects dominate the GRAIL data at this resolution, but 2% of the information relates to structures hidden at depth.



500 km linear anomalies in the Moon's far-side gravitational field. (credit: NASA/JPL-Caltech/CSM)

There are linear gravity anomalies extending over hundreds of kilometres, which may be huge igneous intrusions in the form of dykes; perhaps reflections of influences of early extensional tectonics in the Moons lithosphere. Estimates point to this having been due to an up to 5 km increase in the lunar radius, probably as a result of thermal changes. The dominant feature of the lunar surface is not the near-side flat basaltic maria, visually prominent as they are, but the far more rugged lunar highlands which stand far higher because of the lower density of their constituent feldspar-rich anorthosites. GRAIL permitted a bulk estimate of the density of highland crust that turned out to be substantially lower, at 2550 kg m^{-3} – compared with 2600-2700 for granite and 2800-3000 for basalt – than originally estimated from samples returned by the Apollo mission. This forces a reassessment of the thickness of highland crust from 50-60 km to between 34 and 43 km, with a near-surface layer that has a porosity of around 12%, probably resulting from its awful battering. A thinner highland crust than previously assumed presents a bulk geochemical picture that need not be more enriched in 'refractory' elements, such as aluminium and calcium, than is the Earth.

Such unanticipated results from the low-resolution mode of the GRAIL experiment have its science team excited at prospects from the sharper 'pictures' that will arise from the lower altitude orbits.