Planetary science

Moon formed from vapour cloud (*January 2008*)

The Moon is generally believed to have formed from the debris ejected when a body (nicknamed Theia) about the size of Mars struck the partly formed Earth a glancing blow. That cataclysmic event can be considered to have marked the start of geochemical evolution of both Earth and Moon. From a purely mechanical standpoint, it seems almost inevitable that the Moon is made mainly from debris supplied by the offending small planet. Yet Earth and Moon have profound geochemical similarities, the most remarkable being their now similar blend of oxygen isotopes. Meteorite studies suggest that oxygen isotopes varied widely in the early Solar System, probably differing according to distance from the Sun. That suggests that the Earth-Moon similarity is somewhat odd, unless the impacting planet formed in the same part of space as the Earth itself, i.e. in a very similar orbit. However, that is as mechanically unlikely as the Moon being a chunk of Earth flung off by the impact.

A new explanation for shared oxygen isotopes is based on a model for the collision that involves the vaporisation of much of the outer Earth and Theia (Pahlevan, K. & Stevenson, D.J. 2007. Equilibration in the aftermath of the lunar-forming giant impact. *Earth and Planetary Science Letters*. v. **262**, p. 438–449). High temperature vapour would have involved sufficient turbulence for the geochemical signatures of both Earth and Theia to have been mixed efficiently. The Moon would then have condensed from a disk of orbiting vapour of this mixed composition, most of the Earth re-accreting in a molten state too. Thus both bodies would have begun their evolution with deep magma oceans. The light-coloured, highland part of the Moon is thought to be a relic of the flotation of plagioclase crystals that floated to the top of its magma ocean as it began to cool; the lunar highlands are made of anorthosite and are at least 4.4Ga old. So far no tangible sign of such relics of early fractionation have appeared in the Earth's geological record. Pahlevan and Stevenson's model indicates that only between 100 to 1000 years would have elapsed from impact to appearance of the moon as a tangible body.

See also: Halliday, A.N. 2007. Isotopic lunacy. *Science*, v. **450**, p. 356-357; DOI: 10.1038/450356a.

Another angle on the mysteries of the Hadean (*January 2008*)

Geochemists will be celebrating the end of 2007 after a steady growth in knowledge about times before formation of the first real rocks, albeit of a proxy nature. The latest addition stems from the isotopes of the rare-earth element neodymium. Its heaviest isotope ^{144}Nd is a direct product of nucleosynthesis in supernova star explosions The middleweight isotope ^{143}Nd is well-known as the daughter product of the decay of one unstable isotope of a sister element, samarium (^{147}Sm, half-life 1.06 x 10^5 Ma). The Sm-Nd dating method, based on this decay, has been an important means of dating ancient mafic and ultramafic rocks and examining the geochemistry of their source rocks in the mantle for over 20 years. The lightest isotope is also a daughter of radioactive decay but would have formed from short-lived ^{146}Sm (108 Ma half life). Potentially, ^{142}Nd in old rocks can be used to judge processes in the Hadean mantle as ^{146}Sm would have declined rapidly in the early Solar System – none is detectable nowadays. In meteorites it reveals complexities in the early differentiation of their parental planetesimals, and lunar studies show that too was subject to fractionation. That something odd happened in the early Earth became apparent when it was discovered that modern crust and mantle had more radiogenic ^{142}Nd than the chondritic meteorites thought to have been the building blocks for the Earth. A study of neodymium isotopes in the two largest old chunks of continental crust – the Archaean gneisses of SW Greenland and Western Australia – revealed yet more (Bennett, V.C. *et al*. 2007. Coupled ^{142}Nd-^{143}Nd isotopic evidence for Hadean mantle dynamics. *Science*, v. **318**, p. 1907-1910; DOI: 10.1126/science.1145928).

The two blocks are different as regards their neodymium, and this suggests that a fundamental chemical division of the Earth's mantle took place during the Hadean, which lasted for the next billion years at least. Yet another long-held idea about the Earth's origin seems condemned to the status of myth. It had been assumed that the early Earth was well-mixed as a result of its accretion from countless planetesimals – it doesn't really matter if they included different varieties because accretion would have been such a chaotic process. Discovering whether the now-established mantle fractionation resulted during accretion or after a cataclysmic collision with another world formed the Earth-Moon system is set to be the next challenge for students of the Hadean. It will probably be argued that this requires yet more samples to be brought from the Moon…

Deep geothermal processes (*March 2008*)

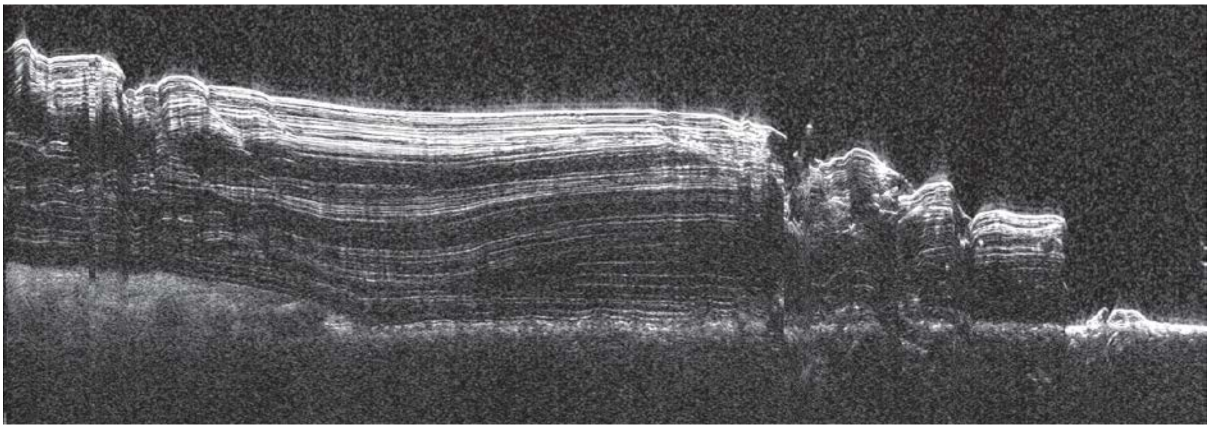
Advances in seismic tomography of the mantle, greater knowledge of mineralogical phase changes right down to its base and modelling of processes within the core have revolutionised ideas on the physical aspects of deep mantle processes that contribute to convection and magmatism. The thermal features of the deep Earth are of crucial importance, so it is excellent to see a timely review of how heat moves at and around the core-mantle boundary (CMB) (Lay, T. *et al*. 2008. Core-mantle boundary heat flow. *Nature Geoscience*, v. **1**, p. 25-32; DOI: 10.1038/ngeo.2007.44). The review gives a readable means of catching up with developments, using simple and not too speculative diagrams. You can find plenty about temperatures and physical properties at the CMB, the various contributions to heat flow and their magnitudes, and the significance of the newly discovered transformation of the deep mantle 'catch-all' mineral perovskite to another phase, post-perovskite. Heat that flows from the core into the lower mantle, as much as a third of the total current surface flux of about 45 terawatts, must make a profound contribution to convection in the core and thus to the geomagnetic dynamo. But there is a temperature contrast at the CMB of 500 to 1800 degrees that surely must affect physical processes in the deepest mantle, such as the initiation of mantle plumes. A puzzling new discovery is of ultra-low seismic velocities in the bottom few tens of kilometres of mantle, which Thorne Lay, John Herlund and Bruce Buffett discuss. Finally, the whole of Earth history encapsulates the evolution of heat flow, which underpins the dynamics of our planet. The historically complex interplay between evolving sources of heat – inherited from Earth accretion and Moon formation; radiogenic sources, and physical and chemical phenomena that are played out as the core evolves – should be curricular issues for all Earth scientists.

Complexities of the deep mantle (*July 2008*)

The use of seismic signals from many receiving stations to probe physical properties of the Earth tomographically is producing increasingly sharp results from the deep mantle. In a fascinating review of the state of that art, combined with results of high-pressure experiments that throw light on deep mantle changes in mineralogy and density, Edward Garnero and Allen McNamara of Arizona State University present some stunning graphics (Garnero, E.J. & McNamara, A.K. 2008. Structure and dynamics of Earth's lower mantle. *Science*, v. **320**, p. 626-627; DOI: 10.1126/science.1148028). Their scope is global, and dominated by thermochemical upwelling plumes and superplumes, zones towards which whole-mantle convection has swept dense material, and some indication of a connection between the two huge phenomena. It seems there are also pockets of magma close to the core-mantle boundary, which are hinted at by abnormally low shear-wave velocities.

Astonishing stratigraphy of the north pole of Mars (*July 2008*)

Since, so far as we know, not a single sentient being has set foot on the Martian surface the title of this item might seem strange; but it is true. One of the features of microwave radiation is that it is capable of penetrating through solid surfaces and imaging the subsurface, given the right conditions. This phenomenon is best exploited by ice, and ground-penetrating radar is routinely used for sounding Earths glaciers and ice caps. To a lesser extent sedimentary layers can be penetrated, provided they are very dry. Radar is also an extremely useful remote-sensing tool with which to examine surfaces, and no planetary mission would be complete without some kind of radar instrument. The US Mars Reconnaissance Orbiter carries a radar system targeted at just such penetration – the Shallow Radar or SHARAD.



SHARAD radargram of deformed stratigraphy beneath the North Pole of Mars (Credit: Phillips *et al*. 2008; Fig. 3)

SHARAD is operated along traverses and provides cross sections of the subsurface that look very like seismic sections, with structure picked out by reflecting surfaces. Crossing the north polar ice cap of Mars, SHARAD reveals a simple layered sequence (Phillips, R.J. and 26 others 2008. Mars north polar deposits: stratigraphy, age and geodynamical response. *Science*, v. **320**, p. 1182-1185; DOI: 10.1126/science.1157546). Nonetheless the layering is interesting as it reveals what appear to be cyclical processes involved in the ice cap's evolution; perhaps by ~million-year periodicity in Mars's obliquity or orbital eccentricity. The radar transparency of the north polar region is probably down to almost pure ice, around 1 km thick. Therein lie clues to another Martian feature: its lithosphere is very strong and thick. That conclusion stems from the lack of any significant annular topographic bulge around the ice cap. Kilometre thick ice on Earth would result in a measurable feature of that kind, due to displacement of the underlying asthenosphere. The post-glacial relaxation of such a bulge that once lay to the south of the British ice cap is responsible for the drowning of valleys in SW England especially, and measurable subsidence of southern Britain today.

See also: Kerr, R. 2008. Layers within layers hint at a wobbly Martian climate. *Science*, v. **320**, p. 867; DOI: 10.1126/science.320.5878.867.

How to spot impact sites that others have missed (*July 2008*)

Unlike the surfaces of several other planetary bodies, the Earth's surface is not peppered with obvious impact craters. That is because our planet is active tectonically and in terms of weathering, erosion and sedimentary deposition. Craters here quickly get 'ironed-out' or buried. Yet there is no way that the Earth could have escaped the episodic rain of objects large and small that results from gravitational perturbation of asteroids and comets by the complex motions of the giant planets. Finding signs of past impacts adds to knowledge of their effects on life, for example, as well as on the processes that accompany 'mountains that fall from the sky': it is a damn sight cheaper than doing the field work on the Moon or Mars.

Shatter cones in limestone from Ohio, USA. (Credit: Wooster Geologists)

Astonishingly, a large impact site straddling a major highway in New Mexico escaped detection until recently (Fackelman, S.P. *et al*. 2008. [Shatter cone and microscopic shock-alteration evidence for a post-Paleoproterozoic terrestrial impact structure near Santa Fe, New Mexico, USA. *Earth and Planetary Science Letters*, v. **270**, p. 290-299; DOI: 10.1016/j.epsl.2008.03.033). The clue that something swift and terrible had occurred in New Mexico during the late Precambrian were strange structures in road cuttings that looked like cartoons of Christmas trees. They consist of multiple cone-shaped features nested together in masses up to 2 m long and 0.5 m across. Other processes can form these strange structures, but finds of shocked minerals and signs of melting in the rocks affected by the cones confirmed a suspicion of a nearby impact structure. Shatter cones can easily be overlooked by geologists who have never seen such features before. The fact that those in New Mexico occur in recent road cuttings helped the authors spot them. At known impact sites shatter cones occur exclusively within the zone of uplift at the centre of complex craters. Those in New Mexico occur over an area about 3 km across, suggesting a minimum size for the now vanished crater of 6-13 km across.

Oh dear; water on the Moon…again (*September 2008*)

The accepted wisdom about the Moon is that it is and always has been supremely dry. That notion stems from analyses of every single solid rock brought back by the Apollo astronauts, and the probability that the Moon formed from incandescent vapour blasted into orbit by a giant collision between the original Earth and an errant planet as big as Mars. Water and indeed most volatile elements and compounds ought to have been driven off the orbiting gas and debris that coalesced to form the Moon around 4.5 Ga ago. Most people believe that more or less everything the astronauts dragged back to Houston has been analysed: not so. There are millions of glass beads that constitute a sizeable fraction of the lunar regolith. Some of these turn out to be volatile rich, and may have been blown out by early lunar volcanism (Saal, A.E. *et al*. 2008. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. *Nature*, v. **454**, p. 192-195; DOI: 10.1038/nature07047). If the glasses are volcanic in origin, that implies there is water in the Moon's mantle. So, you might ask, how come the Moon is not a vibrant place rather than being as dead as a doorknob? The Earth is so interesting partly because it is a wet planet. The Moon has very little in the way of heat production, so even if its mantle contained hydrous phases, it cannot reach basalt solidus temperatures unless energy is delivered mightily by impacts. That did happen around 4 Ga, when the lunar *maria* formed and became floored by gigantic floods of basalt. Yet those basalts are extremely dry, thereby posing a bit of a question for Saal and his colleagues.

See also: Chaussidon, M. 2008. The early Moon was rich in water. *Nature*, v. **454**, p. 170-172; DOI: 10.1038/454170a.

At last, 4.0 Ga barrier broken (*November 2008*)

Since the 1960s when Stephen Moorbath of the University of Oxford determined a date of 3.8 Ga for metamorphic rocks in West Greenland that Vic McGregor of the Geological Survey of Greenland had discovered, pushing the age of tangible rocks towards that of the Earth itself has been slow. Indeed, geologists found only one geological terrain that pushed the 'vestige of a beginning' significantly back in time beyond the famous Isua rocks: the Acasta Gneiss east of Great Slave Lake in northern Canada, dated at just over 4 Ga. In fact in the 30 years between Moorbath's Greenland date and that for the Acasta Gneiss, stratigraphers seem to have become resigned to a maximum 3.8 Ga age for rocks, and the start of the Archaean was set at that age. All earlier time, some 750 Ma of it, became known as the Hadean – a hellish time from which nothing had survived. Some geochemists perked up with the discovery in the late 1980s by Australians Bill Compston and Bob Pidgeon of 17 zircon grains, sifted from a much younger sandstone, that formed up to 4.4 Ga ago; but they tell us very little about the early world. What had become the lost cause of seeking pre-4 Ga rocks, has suddenly become revitalised with the discovery of a voluminous suite of rocks that are 200 million years closer to Earth's origin in the eastern part of Arctic Canada (O'Neil, J. *et al*. 2008. Neodymium-142 evidence for Hadean mafic crust. *Science*, v. **321**, p. 1828-1831; DOI: 10.1126/science.1161925).

The rocks are part of a recently mapped greenstone belt on the east shore of Hudson Bay, which contains a variety of mafic igneous rocks along with metasedimentary banded iron formations and cherts. The most dominant of the mafic rocks has yielded a ^{146}Sm-^{142Nd} isochron age of almost 4.3 Ga, and they are intruded by mafic and ultramafic sills dated at around 4.0 Ga. The older meta-igneous rock's geochemistry suggests that it formed by partial melting of undepleted mantle rocks to produce magmas similar to those forming at modern convergent plate margins. Its major element variability, reflected in very diverse metamorphic mineral assemblages, suggests it to have originally formed as a mafic pyroclastic rock. It would be hard to prove that the BIFs and cherts are the same age in such a structurally complex belt, but that they are as old as the dated material is a distinct possibility. In that case they push back tangible evidence for surface water a great deal more convincingly than the arcane isotopic evidence derived from the oldest known zircons (see *Zircon and the quest for life's origin* *Palaeobiology* May 2005). That such a substantial piece of very old crust has turned up a record age owes a great deal to advances in the Sm-Nd dating technique; the use of ^{146}Sm decay to ^{142Nd} (1/2 life of ~10^8 years), rather than the more readily addressed ^{147}Sm to ^{143}Nd decay (1/2 life of ~10^{11} years). This proof of concept may unleash a reappraisal of rocks that seem to be the oldest relative to others in Precambrian shields on every continent. It may eventually become possible to show that, apart from its cataclysmic experience that formed the Moon and probably a global magma ocean shortly after accretion, the Earth was by no means a totally hellish period during the 'Hadean'.

Two Archaean birds with one stone (*November 2008*)

There are two major issues concerning the Archaean mantle: was the mantle hotter than it is now; was it in a reduced or oxidised state? The first has implications for Archaean plate tectonics. If loss of the higher radioactive heat produced in the mantle was accomplished by processes similar to those today, i.e. dominantly by mid-ocean volcanism the Archaean geotherm would have been similar to today's and plate tectonics would have been similar. If this means of heat loss could not cope, then temperatures would increase more rapidly with depth, with implications for the style of plate tectonics, especially subduction. A mantle with reducing conditions would be expected to emit reduced gases, such as methane, as well as carbon dioxide, to produce a reducing atmosphere. If oxidising conditions prevailed, then CO_2 would be a dominant emission to the atmosphere. There have been arguments over these two aspects of the Archaean for decade, but now they may have been resolved (Berry, A.J. *et al*. 2008. Oxidation state of iron in komatiitic melt inclusions indicates hot Archaean mantle. *Nature*, v. **455**, p. 960-963; DOI: 10.1038/nature07377).

One factor alone allowed the arguments to damp down: A 2.7 Ga ultramafic lava flow from Zimbabwe preserved a pristine sample of the original magma in the form of small glass blobs trapped in olivine. Measured proportions of Fe(II) and Fe(III) in a melt indicate those in its source, and hence the redox state of the source, mantle peridotite. The Zimbabwe melt inclusions are similar in this respect to those found in modern mid-ocean ridge basalts; they show a high degree of reduction. In turn that suggests that the melting that formed them was almost anhydrous, otherwise dissociation of water would have added oxygen that would have upped the content of Fe(III) in the melt. Experiments show that the degree of anhydrous partial melting of peridotite needed to form ultramafic magma is compatible only with temperatures around 1700ºC, about 400 degrees hotter than those that form modern basalt magma. Significant volumes of the late Archaean mantle, and by extension that of earlier times, had to have been a great deal hotter than it is today.