Planetary science

So, when did the core form? (*January 2009*)

Sometime early in its history the Earth underwent two gigantic redistributions of its chemistry: a gargantuan collision that formed the Moon; separation of a metal plus sulfide core from a silicate remainder. These 'set the scene' for all subsequent geological (and perhaps biological) evolution. The current theory about core formation stems from a marked disparity between Hf-W and U-Pb geochronology of the mantle. The first suggests a metal-secreting event about 30 Ma after formation of the Solar System – tungsten is siderophile and would have become depleted in the mantle following segregation of a metallic core. The second points to lead partitioning into a sulfide mass descent to the core around 20-100 Ma later; assuming that lead is chalcophile. The key to explaining the disparity and validating the dual core formation hypothesis lies in establishing just how chalcophile lead is, relative to other metals that are present in the mantle (Lagos, M. *et al*. 2008. The Earth's missing lead may not be in the core. *Nature*, v. **456**, p. 89-92; DOI: 10.1038/nature07375). The German and Russian geochemists set up experiments to determine directly the partition coefficients of lead and the other 'volatile' elements cadmium, zinc, selenium and tellurium between metal, sulfide and silicate melts at mantle pressures. They found that Pb and Cd are moderately chalcophile and lithophile, but never siderophile; Zn favours silicate melts, and is exclusively lithophile under mantle conditions; Se and Te are both chalcophile and siderophile, so would enter the core in both molten sulfide and metal.

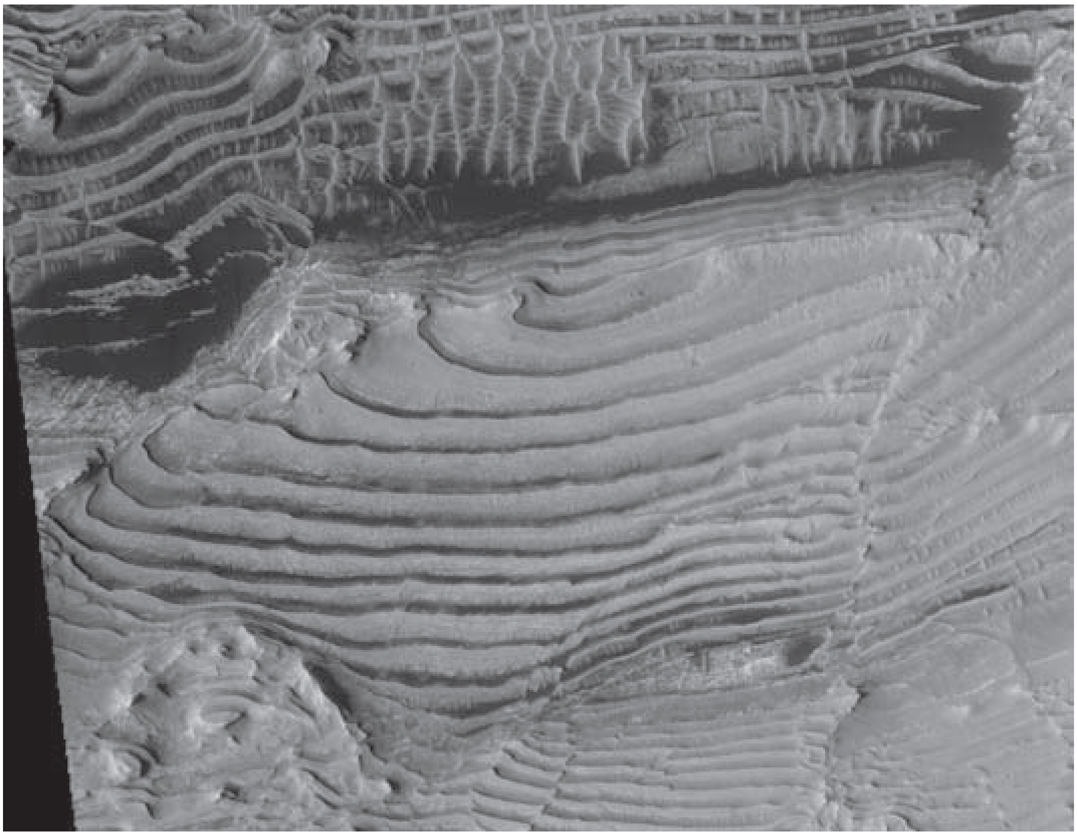
The measured partition coefficients give a basis for comparing the relative proportions of the volatile elements estimated in the mantle with those predicted by the two-event model of core formation. This elegant approach strongly suggests that sulfide or iron-nickel metal segregation from the mantle to the core can explain neither the mantle abundances of the five 'volatile' elements nor the lead-isotope ratios in the mantle. It even questions the existence of terrestrial sulfur in the core. The postulated Moon-forming mega-impact alone could have produced the measured geochemical features of the mantle as a result of vaporisation of 'volatile' elements.

Mantle heat transfer by radiation (*January 2009*)

After some early speculation about efficient heat transfer in the mantle by radiation, it became generally accepted that convection and conduction dominate at depth in the Earth. Yet the Stefan-Boltzmann law has the radiant energy flux of a body increasing proportionally to the fourth power of its absolute temperature. So at deep mantle temperatures of up to 4300 K radiation ought to be significant unless mantle minerals become opaque at high pressures. Mantle mineralogy is dominated by iron-magnesium silicates that adopt the perovskite structure. High-pressure experiments with perovskites reveal surprisingly high transparency to visible and near-infrared radiation (Keppler, H. *et al*. 2008. Optical absorption and radiative thermal conductivity of silicate perovskite to 125 gigapascals. *Science*, v. **322**, p. 1529-1532; DOI: 10.1126/science.1164609). It seems that a higher than expected radiative contribution to heat transfer should stabilise large plume structures in the zone above the core-mantle boundary.

Cycling on Mars (*January 2009*)

High-resolution remotely sensed data (HiRISE) from the Red Planet is free of charge to registered investigators (it did cost quite a bit to acquire), whereas the Earthly equivalent costing would set you back at least US$25 per square kilometre (for Quickbird. They are wonderfully clear, as Mars's thin atmosphere causes no haze except during dust storms. They are also in stereo, providing both 3-D views and digital terrain elevation data with a precision of 1 m. HiRISE data have revealed detail equivalent to that from aerial photos of Earth taken from about 5 km above. Not surprisingly, they show a lot of geology, including an area around 500 to 1000 km^2 with clear signs of layered sediments (Lewis, K.W. *et al*. 2008. Quasi-periodic bedding in the sedimentary rock record of Mars. *Science*, v. **322**, p. 1532-1535; DOI:10.1126/science.1161870).



Rhythmic bedding on Mars (Credit: Lewis *et al*. 2009; Fig. 1)

Where large craters have exposed sequences in their walls it is possible to measure bedding thickness and count individual strata. In Becquerel crater the layering is very regular, comprising two size ranges around 3.6 and 37 m, the second being made up of several of the first sized layers. The two sets of thickness remain consistent through about 300 m of section, so probably represent cyclical processes on Mars. The most likely driving forces are rotational and orbital, as they are for the Earth's Milankovich climatic pacing. The 10:1 ratio between the two frequencies of bedding is twice that dominating the Milankovich time series (rotational precession and orbital eccentricity). One possibility for the Martian cycles is the estimated variation of orbital eccentricity on 120 ka, 1.2 Ma and 2.4 Ma timescales, although axial tilt changes through tens of degrees; far more than does that of the Earth's rotational axis. Thankfully, the authors stick to variations in wind-driven sedimentation to explain the bedding cycles. Changes in insolation on Mars would affect condensation and evaporation of CO_2 ice at the poles, and consequently the density of the atmosphere and its ability to move and deposit sediment. Less fortunately, they suggest water must have been involved to lithify the layers. That hardly seems necessary on a planet with low atmospheric pressure, as unconsolidated wind-blown loess in western China maintains the integrity of its layering with little cementation.

Moon-forming impact dated (*March 2009*)

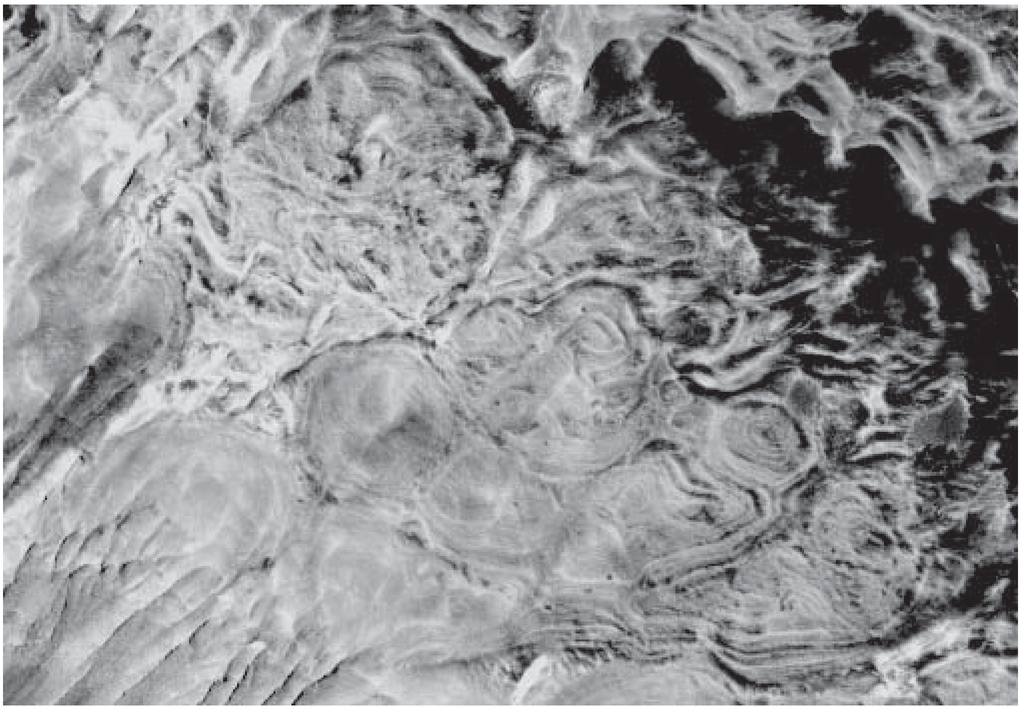
One of the major discoveries that arose from the lunar samples returned by the Apollo astronauts was that the pale-coloured lunar highlands were made almost entirely of calcium-rich plagioclase feldspar: they are made of anorthosite. In the early 1970s Joe Smith of the University of Chicago realised that the only way vast amounts of such single-mineral igneous rocks could have formed was by massive fractional crystallisation. Low-density feldspar must have floated on top of what had been literally a magma ocean. Although Smith did not put forward the idea that a molten moon had formed through a giant collision between the Earth and a passing Mars-sized planet, it was his concept that pointed strongly in that direction. Inevitably, much of the Earth would also have been melted by such a monstrous catastrophe – material that eventually became the Moon had probably been vaporised before condensing to form our satellite.

The Apollo samples are still objects of research, especially as new analytical methods develop. One such new method is the dating of single, tiny zircons; even of their individual zones. Later impacts on the Moon formed a variety of breccias, samples of which are handy as they include fragments of many rock types in one specimen. One of these has helped zero-in on just when the magma ocean began to crystallise (Nemchin, A. *et al*. 2009. Timing of crystallization of the lunar magma ocean constrained by the oldest zircon. *Nature Geosciences*, v. **2**, p. 133-136; DOI: 10.1038/NGEO417). In fact advanced mass spectrometry dated 41 tiny spots in a single half-millimetre zircon grain, revealing a spectrum of ages between <4.35 Ga and a maximum of 4.417 ± 0.006 Ga. The oldest marks the minimum age for the start of crystallisation of the molten Moon and thus for the impact that formed the Moon. For comparison, the earliest material found on Earth – also a zircon but one transported in sediment to become part of a much younger sandstone – is 4.404 Ga old. The authors suggest that the bulk of the lunar highland crust had solidified within 100 Ma of the collision

Did mantle chemistry change after the late heavy bombardment? (*September 2009*)

During the Hadean the Inner Solar System was subject to a high flux of asteroidal debris, culminating in a dramatic increase in the rate of cratering on planetary surfaces between 4.0 and 3.8 Ga known as the late heavy bombardment. It left a subtle mark in tungsten isotopes of the Earth's continental crust that formed during and shortly after the cataclysm (see Tungsten and Archaean heavy bombardment, August 2002). It has also been suggested that it enriched the mantle in elements, such as those of the platinum group, that have an affinity for metallic iron, a major constituent of many meteorites. The most likely rocks of the Archaean crust to show hints of such enrichment are ultramafic lavas known as komatiites, though to have formed by high degrees of partial melting of plumes rising from deep in the Archaean mantle. Komatiites from their type locality in South Africa and from the Pilbara area of Western Australia do indeed suggest that there was significant effects (Maier, W. D. *et al*. 2009. Progressive mixing of meteoritic veneer into the early Earth's deep mantle. *Nature*, v. **460**, p. 620-623; DOI: 10.1038/nature08205). The Finnish-Australian-Canadian team found that the older komatiites (3.2-3.4 Ga) contain less platinum-group elements (PGE) than do those from the later Archaean and early Proterozoic (2.0-2.9 Ga). This they ascribe to a surface layer of meteoritic debris gradually being mixed into the mantle by convection. In their discussion they suggest that once the Earth's core formed (almost certainly very soon after the Moon-forming event at 4.45 Ga) it effectively leached all PGE from the lower mantle, and could only have achieved higher concentrations by mixing of later meteoritic debris. Their results suggest that this went on through the Hadean, but reached its acme and then stabilised in the late Archaean once the earlier Archaean alien debris had been churned in.

And now; salt domes on Mars (*September 2009*)



Features reminiscent of salt diapirism in Hebes Chasma on Mars. The image is about 3 km wide. (Credit: Adams *et al*. 2009; Fig. 2c)

The front cover of the August 2009 issue of *Geology* could be mistaken for an exaggerated oblique aerial view of part of Iran's Zagros Mountains, well known for their dissected salt domes. It is, however, a simulation of an aerial oblique using digital elevation data from the Valles Marineris area on Mars (Adams *et al*. 2009. Salt tectonics and collapse of Hebes Chasma, Valles Marineris, Mars. *Geology*, v. **37**, p. 691-694; DOI: 10.1130/G30024A.1). Hebes Chasma is a roughly oval, steep-sided depression the margins of which show clear signs of some kind of erosion. However, the depression has no outlet, so looks quite bizarre by terrestrial standards: and it is not the only such feature. At its core is a pericline of material that was formerly buried deeper than the flanks of the chasma, which are pretty much horizontal. Unlike the larger, nearby Valles Marineris, Hebes Chasma cannot have formed by erosion of the surface by a huge mass of flowing water, yet 100 thousand cubic kilometres of rock has simply disappeared. Explaining such a gigantic, weird feature taxes the imagination, but the authors do come up with a hypothesis. They reckon that the 10^5 km^3 of material became some kind of thin, briny slurry during an early Martian heating event, which drained downwards into a vast aquifer. For that to happen demands a thick, subsurface layer of dirty ice that melted, and an extremely porous substrate able to channel away the escaping muddy brine. How the pericline formed is not explained, except that it appears in a lab model made of sand, glass beads and ductile silicone polymer, when the silicone drained out through slots in the model's base. There is plenty of evidence that the surroundings of the chasma collapsed spectacularly, and if the pericline formed by the rising of low-density material dominated by ductile salts (or ice) then it is a likely story. But where did the 100 thousand km^3 of gloopy brine go? Even if there is a crewed mission to Mars, to land anywhere near Valles Marineris would be suicidal, it is so precipitous. So, this is yet another Martian mystery that will linger in a febrile kind of way.

'Follow the water' (*November 2009*)

Two millennia ago an anonymous Roman wrote, 'The first provision of any civilised society, after a code of law, is a reliable source of clean water'. Planetary and life scientists might well like the adage for themselves: the sentiment applies nicely to active planetary tectonics and to the origin and survival of all conceivable life forms. The Earth has plenty of water at the surface and also deep in the mantle. Without the second, the main mantle mineral olivine would be too stiff for the mantle to convect. Heat would build up within until magma formed in great abundance and emerged with a dreadful growl, as it did on Venus about 750 million years ago to repave the entire planet. It simply isn't possible to think of answering the questions, 'When did plate tectonics begin and life emerge?' – let alone 'How?' – without first addressing where the Earth's water came from and when our home world become so richly endowed.

In a very practical sense, these are the most important issues in geochemistry. Francis Albarède, of the École normale supérieure de Lyon, President of the European Association for Geochemistry and the first geochemist to deploy a multicollector, inductively coupled, plasma-source mass spectrometer, is a fitting person to review where the subdiscipline stands on them. His views appeared as a 'Progress' (a rare kind of *Nature* article) in the 29 October 2009 issue of *Nature* (Albarède, F. 2009. Volatile accretion history of the terrestrial planets and dynamic implications. *Nature*, v. **461**, p. 1227-1233; DOI: 10.1038/nature08477). The article casts doubt on the long-held views that when the Moon formed after a giant impact on the Earth, both bodies lost huge masses of volatiles, including water, and that Earth's water-rich nature stemmed from repeated bombardment by volatile-rich comets up to about 3800 Ma.

Geochemical data are now available from a comet (Hyakutaki) and it contains twice the amount of deuterium relative to hydrogen that is in terrestrial seawater. The D/H ratio of carbonaceous chondrite meteorites is more Earth-like, and these primitive objects seem a more likely water source than comets. But did cataclysmic formation of the Earth-Moon system dehydrate both bodies and drive off other volatile matter? Planets and smaller bodies formed by gravitational accretion of solids that condensed from the initially hot gas or nebula that dominated the proto-solar system. Experiments show that condensation of the elements occurs in three discrete temperature ranges, separated by ranges in which few elements condense. Above around 1300 K the most refractory elements condensed, including oxides of some elements (Ca, Fe, Mg, Si) that now make silicate minerals, including the dominant mantle mineral olivine. Between 900-1200 K the alkali metals and some of the elements (chalcophile) that readily combine with sulfur emerged in solid form. In the third step from 500-800 K the more volatile chalcophile elements, including lead, and halogens condense, leaving four (Hg, O, N, C) that can take on solid form only below about 300 K. Interestingly, the proportions of volatile elements relative to refractory ones in the Earth, Moon and Martian meteorites are very low compared with those in carbonaceous chondrites. It is likely that volatile elements only accreted to the Inner Planets in small amounts before being swept to the outer reaches by an intense solar wind as the Sun was powering up, i.e. before nebular temperatures had fallen below about 1000 K. From that stems the inescapable conclusion that none of these planets were endowed with much water in their earliest forms.

Proportions of the lead isotopes ^{206}Pb and ^{204}Pb from terrestrial sulfide mineral deposits define a near-perfect linear relationship with the ages of mineralisation, from which an age can be estimated for the time the element lead appeared on Earth. That age is 4400 Ma; about 110 Ma younger than the actual age of the planet, and matches apparent ages derived from I-Xe and Pu-Xe decay schemes; iodine and xenon are volatile elements. This strongly supports the idea that 500-800 K condensates arrived late, and other evidence indicates that they and water ice were delivered by carbonaceous chondrite material falling towards the Sun from far beyond the orbits of the giant planets, once the early solar wind had lessened. That is, the Earth's oceans formed very early in its history, and the mantle gained its water from them once hydrated lithosphere could founder deep into the evolving mantle by subduction. Albarède also summarises fascinating new ideas about the different course followed by Venus and Mars from essentially the same starting point. His 'Progress' is not difficult to read, and by marking the start of a new consensus in planetary evolution is of vital interest to all Earth scientists

Extraterrestrial water is also the subject of a Great Quest by NASA and other space agencies, though sadly an attempt on 9 October to prove that there is ice on the lunar surface, by hurling a US$79 million spacecraft at an obscure polar crater, produced no sensible results. Ironically, a couple of weeks later, three papers appeared in *Science* that document passive remote sensing evidence that the Moon contains a lot more water than long assumed (the most revealing is: Pieters, C.M. and 28 others 2009. Character and spatial distribution of OH/H_2O on the surface of the Moon seen by M^3 on Chandrayaan-1. *Science*, v. **326**, p. 568-572; DOI: 10.1126/science.1178658). The Apollo samples astonished geologists when they proved to be almost completely anhydrous, any signs of minor hydration being ascribed to contamination after collection. The Moon Mineralogy Mapper (M^3) aboard India's first lunar mission Chandrayaan is a hyperspectral imaging device that operates in the visible to SWIR range of EM wavelengths (0.4 – 3.0 mm). That range includes SWIR wavelengths beyond 2.4 mm where OH^-, water and water ice have large absorption features that are masked in terrestrial remote sensing by the high moisture content of Earth's atmosphere. Pieters *et al*. attempted to model hydroxyl and water content in the lunar surface, and discovered significant amounts (a few tenths of a percent) in the polar regions. That they got results when the Moon was fully illuminated by the Sun suggests that this is not due to ice hidden from heating in shadows, but to minerals that contain molecularly bound water and hydroxyl ions. That begs the question of how the water got there. One possibility is the late arrival of volatile condensates as above, another that it is due to hydrogen (protons) from the solar wind reducing iron in silicate minerals to metallic iron and combination with the oxygen released. Expect loud hurrahs from devotees of Star Trek and NASA because one prerequisite of civilised society seems to be there on the Moon. But judging from the bureaucracies involved in space, getting the funds to use it will not be easy.