Planetary science

Zircons and early continents no longer to be sneezed at (*February 2006*)

Dating of detrital zircon grains found in ~3 Ga old Archaean sediments from Western Australia first pushed known geological time beyond the previously impenetrable 4 Ga barrier. The record now goes back to around 4.4 Ga, 95% of the age when the Earth and the Solar System came into being (4.55 Ga). There has been much written about the oxygen isotopes in this tiny number of resistant minerals regarding whether or not they originated in a crust permeated by liquid water. Because zircon is a mineral most usually associated with rocks of granitic composition, the very presence of extremely old ones seems to suggest that some degree of fractionation of primitive basaltic magmas must have taken place in the Hadean to form highly evolved magmas. But did actual continental material arise so early? Processes in island arcs can generate evolved magmas in which zirconium is moderately enriched. If such a host for the pre-4 Ga zircons was small in volume, it may have been easily recycled back to mantle depths, yet would enough zircons have been eroded from it to yield those preserved in sediments a billion years younger? It is possible to probe the processes involved in zircon formation by using the extremely sluggish radioactive decay of an isotope of the rare-earth element lutetium. The half-life of the ^{176}Lu to ^{176}Hf decay scheme (~37 Ga) is far longer than the time since the Big Bang, so detecting changes in the proportion of ^{176}Hf to other hafnium isotopes is a tough nut to crack, the more so as ^{176}Lu is very rare indeed.

A consortium of geochemists from Australia, the US, France and the UK have used the famous Jack Hills zircons to test the widely believed hypothesis that substantial continental crust has only emerged since 4 Ga ago (Harrison, T.M. *et al*. 2005. [Heterogeneous Hadean hafnium: evidence of continental crust at 4.4 to 4.5 Ga](#). *Science*, v. **310**, p. 1947-1950; DOI: 10.1126/science.1117926). They found that deviations of ^{176}Hf/^{177}Hf from those assumed to characterise the bulk Earth (in fact the proxy of chondritic meteorites) show large variations in the zircons. Some of the deviations are negative, which is consistent with the very early formation of continental crust – perhaps from very soon after the Earth formed. On the other hand, some zircons show positive deviations, a sign that the mantle was depleted, also pointing to crust forming events. The authors boldly suggest that such anomalies refer to a very early geochemical upheaval in the Earth, that likely produced continental material. But the 4 Ga barrier for whole rocks seems clearly to suggest that none remains: either it was all subducted away, or was only a tiny fraction from which the Jack Hills zircons miraculously emerged on their long journey to a final resting place.

Commenting on the paper, Yuri Amelin of the Canadian Geological Survey, points out that no one agrees on the true composition of the bulk Earth (Amelin, Y. 2005. [A tale of early Earth told in zircons](#). *Science*, v. **310**, p. 1914-1915; DOI: 10.1126/science.1121536). Other isotopic evidence raises the spectre of our planet having accreted from a mixture of geochemically different meteorite types, and has never mixed thoroughly. Moreover, zircons are notorious for being compositionally zoned, as a result of being able to survive engulfment in later magmas from which new layers of zircon grow. The measurement of ^{176}Hf/^{177}Hf ratios is so difficult that only whole zircons give useful results, but those data hide the variations among the zones. Finally, he points out that studies of the ^{176}Hf/^{177}Hf in

post 4 Ga basalts – and therefore the mantle from which they were derived - show that there is a clear divergence from chondritic meteorites that began around 4 Ga, the start of the record of existing continental rocks. In the kindest way, Amelin casts doubt on the sense in studies of such tiny relics of the Earth's distant past.

See also: Valley, J.W. *et al*. 2006. Comment on ''Heterogeneous Hadean Hafnium: Evidence of Continental Crust at 4.4 to 4.5 Ga''. *Science*, v. **312**, p 1139: DOI: 10.1126/science.1125301. Harrison, T.M. *et al*. 2005. Response to Comment on "Heterogeneous Hadean hafnium: evidence of continental crust at 4.4 to 4.5 Ga". *Science*, v. **312**, p. 1139; DOI: 10.1126/science. 1125408


Puffing up the Moon (March 2006*)*

Since George Bush announced that US manned planetary missions are back on the agenda, albeit in an uncertain future for NASA, barely a month goes by without some kind of scientific justification for a return to the 'good old days'. The latest as regards future lunar missions was in the 1 April 2006 of *New Scientist*, as a special report 'It's time to go back'. It seems there are unique opportunities that the Moon presents for a range of scientific work (Chandler, D.L. 2006. The ultimate lab. *New Scientist*,1 April 2006 issue, p. 33-37). The lunar far side, being shielded from radio noise from Earth, is well suited to deploying an array of miniature radio telescopes. Half a dozen 1 m dishes spread over 20 km could simulate an enormous dish. The lack of an atmosphere suggests ideal stable conditions for optical telescopes, although being on a body with a large gravitational attraction would expose instruments to meteor flux. The lunar South Pole is said to look good for science. For a start, there is a 5 km peak always lit by the Sun for continuous solar power, as well as data relay back to Earth. Nearby is the deep Shackleton crater that is never lit, and is immensely cold; ideal for an infrared telescope, and maybe harbouring water ice to support a manned lunar base.

The Apollo missions returned sufficient rock and soil samples to whet planetary scientists' appetites. They answered a lot of questions, and did revolutionise issues of planetary origins, evolution and bombardment history, yet they raised other interesting questions. Answering geological questions from the rocks of other worlds depends a great deal on luck, and the few small sites visited by the Apollo astronauts undoubtedly left out a great deal. What is needed, it seems is a 'Serendipity Base'. The best one would be a deep crater with steep, rocky sides, and there is one that seems just right. The Aitken basin is 12 km deep and exposes a layered structure in its walls.

Perhaps the greatest attraction is the fact that anything that falls on the Moon remains in its pristine state for all time, provided it is not buried by accumulated meteoritic dust and impact ejecta. The Moon could be a really happy hunting ground for meteorite specialists, although finding interesting ones on the dull, grey surface might pose problems – you can tell a meteorite on Earth, if you search ice sheets, deserts and saline flats, by their contrast with the background. There is a very odd notion, however, that well-preserved ejecta from impacts on the Earth and other planets that found their way to the lunar surface might hold the keys to the origin of life (Ward, P. 2006. House of flying fossils. *New Scientist*, 1 April 2006 issue, p. 38-41). The reasoning goes like this: like the Moon, all planets in the Solar System have for 4.55 Ga been whacked by impacts, which must have flung debris outside their gravitational attraction. Having a strong gravitational field itself, the Moon must have

swept up a sizeable representative sample of all such debris hurtling around the Solar System. Some of the biggest impacts – again as revealed by the lunar surface – were early in planetary evolution. Debris from them would therefore be samples of materials before they had been affected by later geological processes on their parent planets. Analyses of particles in the Apollo samples indicate that perhaps 3 kg of the third of a tonne of material is non-lunar, of which a few grams might be from Earth.
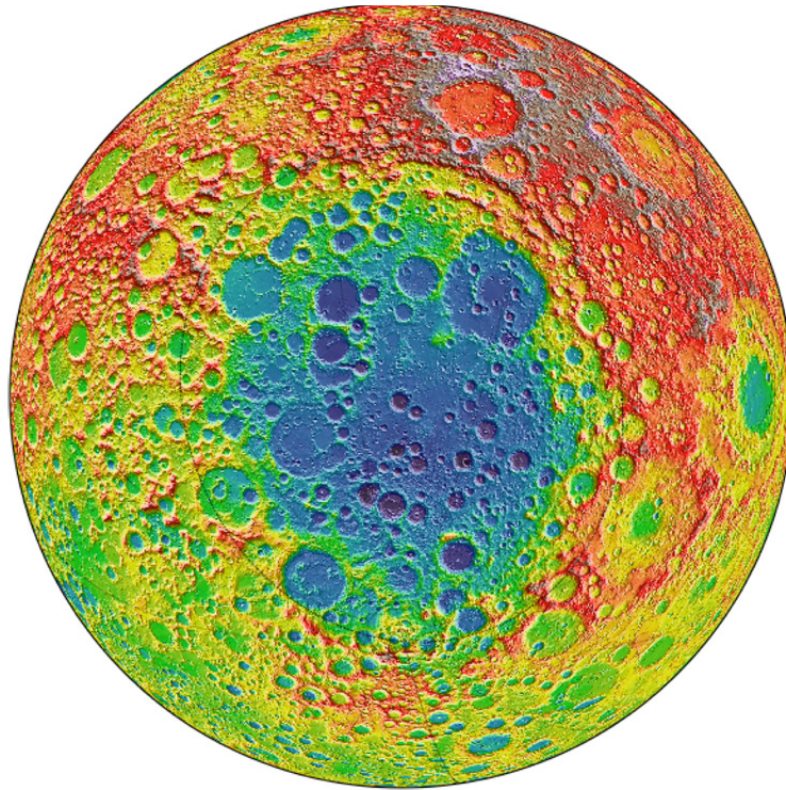

The Aitken Basin at the lunar South Pole. Bluish magenta lowest, brown highest elevations.
(Credit: NASA)

Terrestrial geology effectively stops once we go back to about 4 Ga, besides which very old rocks on Earth have been subject to all manner of chemical, erosive, tectonic and metamorphic influences. That is the reason why incontrovertible fossils and geochemical evidence for life have yet to be found before 3 Ga at the earliest. There are whiffs of earlier life, which people choose to believe or otherwise, but the potential for dispute fuels continual debate. But escaped ejecta from Hadean impacts on the Earth wouldn't have been altered so much. They could be dated, and thereby tell geoscientists about the earliest crust, now vanished apart from a few minute grains of pre-4 Ga zircons. Most attractive is the possibility that they could harbour well-preserved organic materials that are traces of the very earliest life forms or their complex precursor chemicals. But would they survive the impacts that produced them? Although impacts from objects as small as 100 m could fling debris beyond the Earth's pull without heating it too much, Hadean impacts would have had awesome energy because the colliders were huge, as witness the mare basins on the Moon that are over 100 km across. Much of the debris from those lunar big hits is in the form of once melted glasses, and the holes that they left filled with magma generated by the huge energies involved. Some meteorites do preserve their original magnetization, which suggests they never reached temperatures above the Curie points of the minerals responsible for it. Ward cites this evidence in support of once living materials being able to

survive in ancient terrestrial ejecta that almost certainly will lie on the lunar surface. But he uses it to say that meteorite internal temperatures must have stayed below 100°C: the Curie point for common magnetic minerals is around 600°C. Given the date of publication, might we be reading of a pudding with too much egg? Whatever, the origin, if not the meaning of life exerts more pull on science purse strings than the prospect of gold nuggets hiding in shadowed craters…

Yet another weird world (*March 2006*)
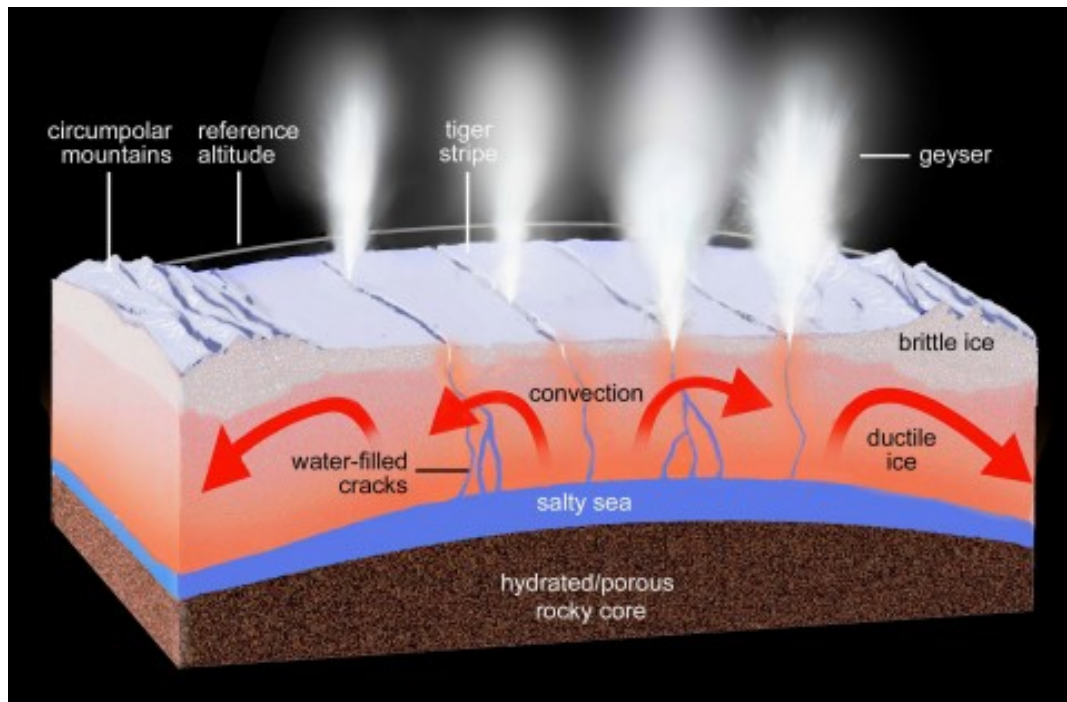
Speculative impression of how Enceladus's geysers function (Credit: NASA/JPL)

Saturn is well-endowed with moons: 35 with names and a whole lot of moonlets. The Saturnian System is astonishing in its diversity, and part of the Cassini probe's mission is to examine in detail as many moons as possible – 20 flown by in the last year. Enceladus is by no means the largest (504 km in diameter), yet it is very odd indeed. One of its singular features is its ability to jet vast amounts of water from warm spots, and the fact that it seems to snow there. The 10 March 2006 issue of *Science* magazine devotes 40 pages to articles on the oddities of Enceladus. To jet water ice and vapour to more than twice its diameter – in fact to drench much of the planetary system and replenish parts of the famed ring system – there must be a powerful heat source. Just what that is has yet to be worked out: it could be bound up with internal radioactive decay or with vast tidal sources from Saturn itself, and maybe something else entirely. Its south pole is curiously its most active part, with sufficient heat energy beneath to create a major positive anomaly in long-wave infrared images. This is where much of Enceladus's resurfacing by snow takes place. Saturn's tidal forces have rucked up the surface to create hilly ridges, perhaps assisted by a kind of icy volcanism. Tidal or internal forces have also opened up great cracks in the surface, which false-colour images that use UV, green and short-wave infrared reveal to be compositionally different from the water-ice bulk of the surface. That may have resulted from hydrocarbon deposits leaking from deeper layers. It is the moon's interior that causes most excitement.

In order for it to spray off watery jets, there must be a deep source of liquid water, either a liquid shell on which an ice 'lithosphere' floats or produced as internal plumes by melting at an interface with a rocky core. That there are hydrocarbons suggests that some of the watery solids include gas-hydrates (ices that incorporate both water and gases).

Getting to the matter of the root (*May 2006*)

As well as by its own low density, continental crust may be prevented from subduction because of the strength and buoyancy of cold, thick mantle that forms a root beneath the oldest cratonic crust. Geophysics shows that such roots are there, and in the case of African cratons they merge with the deeper mantle without the intermediate, more ductile asthenosphere: in a sense Africa is 'nailed' in place and barely moves. Except for xenoliths in some continental volcanic rocks and in kimberlite pipes, samples of the deep continental lithosphere are uncommon. One place where they are abundant at the surface is in the zone of ~400 Ma continent-continent collision in western Norway (Spengler, D. *et al*. 2006. [Deep origin and hot melting of an Archaean orogenic peridotite massif in Norway](#). *Nature*, v. **440**, p.913-917; DOI: 10.1038/nature04644).

These rocks are Archaean (~3.3 Ga) in age, and contain tiny diamonds. Their more common metamorphic minerals indicate that the peridotites stabilised at depths of about 180 to 250 km. Yet they carry trace element and mineralogical evidence that they formed as residues of partial melting from a body of mantle that rose from almost 400 km down. Compositionally, they seem to represent an outcome of high degrees of partial melting, probably to release high-magnesium or komatiitic magmas that are only common in early Archaean greenstone belts. Most likely, this peridotitic root material continued to rise, eventually to underplate Archaean continental crust. Unable to melt any further, being depleted in incompatible elements, the root became a permanent and very rigid fixture once it had formed. Regarding the unending, but probably fruitless quest for crustal materials that predate 4.0 Ga, other than a snuff-pinch of tiny zircons, this well-supported model for cratonisation perhaps offers an explanation. No doubt in the higher heat-producing mantle of Hadean times komatiite magma was the norm for oceanic crust formation, and such depleted, high-pressure peridotite residues formed continually. Unless they rose to adhere to substantial low-density sialic crustal masses, they would be recycled back to deeper levels. Equally, without the support of such rigid underplates, any sialic material at the surface would have been unable to withstand deformation and would become subductible by tectonic mixing with more common, dense, mafic-ultramafic oceanic lithosphere. A great deal of Archaean tectonics suggests that continents then were not fully cratonised – Archaean crustal rocks seem to have been pervasively and repeated deformed, cratons of undeformed old rocks not appearing until the Proterozoic, when modern plate tectonics became established.

Acasta gneiss and another old zircon (*May 2006*)

Readers may by now be satiated with comment on geriatric zircons. Most of them – and they can be counted – are detrital grains that survived around a billion years of sedimentary processes to end up in an otherwise common-or-garden quartz-rich sandstone in Western Australia. Their number has been added to by one more grain, which might be cause for jollification in some quarters, because its host was a piece of deep continental crust of good

provenance (Iizuka, T. *et al*. 2006.

The Acasta Gneiss in northern Canada (Credit NWT Geological Survey)

The Acasta gneisses form the western flank of the Slave craton in northern Canada, and are the world's oldest rocks, having formed at 3.94-4.03 Ga as a series of plutonic rocks of tonalitic to dioritic composition. Archaean geochemists from various Japanese universities, and a lone Briton from Leicester University, understandable wished to confirm and refine the age of the Acasta gneisses as the earliest 'golden spike' in the continental crust , and subjected many zircons extracted from gneiss samples to the latest mass spectrometric dating that uses the U-Pb scheme. Indeed they achieved excellent precision to the nearest few tens of Ma. Using an ion microprobe, they were able to date the zoned interiors of the zircons, revealing progressive crystallisation of the grains, mainly as the igneous precursors of the Acasta complex evolved. In a single grain, however, they came upon zircon in its core that was 200 Ma older. That tiny, trapped granule itself had engulfed even smaller particles of apatite, unlike the bulk of the whole grain.

Ion microprobes are wonderful pieces of kit, as they can give extremely precise and revealing trace element abundances in the mineral into which they burn a hole. In the case of the aged zircon core, such analyses revealed clearly that these few micrograms of zirconium silicate had formed from a magma with broadly granitic composition. Their conclusion: pre-4 Ga granitic crust was more widespread than previously thought. No, not the Acasta gneiss, but whatever material its igneous precursors had picked up while they were magma. In the previous comment in this section, I put forward the view that sial may well have formed before tangible continental material had stabilised as a permanent resident at the Earth's surface. Yet, for reasons that seem to be emerging, such crust would not have resisted subduction and ended up mixed back into the mantle. Since the Acasta gneisses were most certainly not formed before 4.0 Ga, then it is from their mantle source region that their igneous precursors must have picked up this tiny, alien xenocryst. Unless, that is, someone can show me a 2-5 kg lump of gneiss heaving with these blessed grains (preferably with signs of almost as old crustal deformation). There is an obvious prediction

to make. Geochemists are fighting in a heap to acquire ion microprobes and inductively-coupled, laser-ablation, plasma-source mass spectrometers, and why ever not? Now they have something to aim for instead of trawling quartz sandstones for relics of Earth's Hadean past. My prediction is that every single mantle-sourced rock of granitic composition, whatever its age, will contain at least one pre-4.0 Ga zircon granule. Zirconium silicate is sturdy stuff.

Mantle behaviour and the influence of minerals (*May 2006*)

To most geologists minerals are a means to an end. Identifying them and working out their relative proportions in a rock provides a quick means of assessing its rough chemical composition. Textural relations between minerals help work out the sequence of processes that were involved in its evolution, and in the case of metamorphic minerals what pressure and temperatures were involved. In the case of the Earth's mantle, however, mineralogy comprises only one or two abundant minerals – olivine and pyroxene at shallow depths, and the mineral perovskite ($MgSiO_3$) at depths greater than about 670 km – and dominates the mantle's physical properties and bulk behaviour. There are distinct, narrow zones or discontinuities that separate different seismic properties and these have long been considered to represent changes in mineralogy of the more or less uniform bulk composition of the mantle. The most likely phase transition is from olivine + pyroxene to perovskite, in response to increasing pressure, thought to occur at about 670 km down. That transition was confirmed by high-pressure experiments, but whether that simple mineralogy persists down to the outer core has remained a mystery. Using tiny diamond anvils in a laser-heated furnace to create the enormous pressures at depths up to 2700 km is fraught with technical difficulties, but scientists of the Japan Marine Science and Technology Centre have finally achieved them (see: Murakami, M. *et al.* 2004. Post-Perovskite Phase Transition in $MgSiO_3$. *Science*, v. 304, p. 855-858; OI: 10.1126/science.1095932. Cyranoski, D. 2006. Magical mantle tour. *Nature*, v. **440**, p. 1108-1110; DOI: 10.1038/4401108a).

Hirose and Ono discovered that perovskite itself collapses to produce another, more tightly-packed molecular structure – post-perovskite with a sheet-like structure. This phase transition occurred experimentally under conditions that characterise the thin D" layer just above the core-mantle boundary. Seismic tomography has suggested that a number of weird things happen there. For instance, seismic S waves near the CMB have different speeds according to their direction of travel, and even accelerate in some parts. The platy structure of post-perovskite, unlike the more regular perovskite, is likely to create such physical anisotropy, especially if grains are aligned. The mineral, when iron enters its structure, may also help to explain thin (5-40 mm) zones in the D" layer in which seismic wave speeds fall by 5 to 30% compared with expected values (Mao, W.L. *et al.* 2006. Iron-rich post-perovskite and the origin of ultralow-velocity zones. *Science*, v. **312**, p. 564-565; DOI: 10.1126/science.1123442). When first detected by seismic tomography, these zones had been assumed to involve regions in which partial melting occurred. It also seems that the phase transition is temperature- as well as pressure-dependent, so that post-perovskite could form at shallower depths in cooler regions. Being denser than its parent, that could result in sinking: like slab-pull at shallow depths, such a gravitational force would contribute to whole mantle convection by displacing hotter D" material. That in turn would 'flip' through the phase transition in the reverse fashion to become less dense, perhaps encouraging the initiation of rising plumes.

Sure enough, what might seem to be a boring bit of exotic mineralogy promises to exert some control over speculation on what happens at the bottom of the mantle. But it is too early to say how seminal the discovery might be – the errors in the experiments correspond to a depth range of about 350 km. On top of that, other experiments need to be conducted under these extremely difficult conditions, such as finding out if post-perovskite can chemically interact with the iron-rich outer core, and if its electrical properties are in some way different from those of better-understood perovskite.

Has Dune been discovered? (*June 2006*)

Titan, where Kurt Vonnegut's Sirens sang, is, as we all now know, a foggy world shrouded in hydrocarbons. The Huygens probe that sank to its surface revealed a tantalising glimpse of its strangeness, with possible erosion by liquid methane rivers and sediments of icy substances. But Huygens didn't really tell us much, like the probe that lasted a few minutes on equally obscure Venus. To map a foggy world you need orbital radar. The Cassini mission, the mother ship for Huygens, carried a high-resolution radar imaging system, and the results are astonishing; Titan has monster sand dunes (Lorenz, R.D. and 39 others 2006. The sand seas of Titan: Cassini RADAR observations of longitudinal dunes. *Science*, v. **312**, p. 724-727; DOI: 10.1126/science.1123257). They dwarf all but the largest terrestrial dunes in Namibia, rising to 200 m. They are linear dunes, spaced at around 4 km, and trend parallel to Titan's Equator, where there must be a wind belt. So far only a few images have been returned, so the extent of the dune systems is unknown. However, they correlate with optically dark material that is extensive in the equatorial region, so Titan may be dominated by dunes. For dunes to form presupposes an abundant supply of particles small enough to be picked up and transported by winds. The images from different latitudes suggest that transport is equatorwards. What those particles are made of is impossible to tell from radar returns, but most likely they are either organic solids or ice. Notions of Titan being bathed in hydrocarbon oceans now fall flat, as the areas that are not dunes seem to be topographic highs.

Accretion and core formation reviewed (*August 2006*)

Painstaking work on meteorites and their re-evaluation has only a small, non-specialist readership, but now and again developments in the science and its bearing on how the Solar System and its planets formed need a review. The latest of these (Wood, B.J. *et al.* 2006. Accretion of the Earth and segregation of its core. *Nature*, v. **441**, p. 825-833; DOI: 10.1038/nature04763) doesn't deviate much from generally accepted ideas, except in detail. For a long while it has seemed inescapable that gravitational potential energy accumulated from accretion of mass, together with energy released by decaying short-lived isotopes formed by a supernova near the dust cloud that gave birth to the Solar System would have led to hot protoplanets. So core formation by segregation of dense immiscible metal and sulphide melts was likely to have been sooner rather than later – such melts form at lower temperatures than do those made of silicates.

The daughter isotope (^{182}W) of one short-lived isotope (^{182}Hf) is especially revealing in both meteorites and the Earth. Hafnium favours entry into silicates while tungsten has an affinity for metallic iron; they are siderophile. So, when metallic melts form in a silicate body the

Hf/W ratio increases in the silicates. If that segregation occurs before most ^{182}Hf has decayed – within about 45 Ma – then the silicate part will express an excess of ^{182}W while metals have a deficiency. In the case of metallic meteorites, ^{182}W is so low as to indicate segregation of the metal from silicate within less than 5 Ma of the ultimate origin of the Solar System. Inevitably, Earth would have incorporated some of these early-formed metallic parts during its accretion. Tungsten isotopes from terrestrial rocks, however, suggest that core formation lasted about ten times longer, and imply that this early metal re-mixed with silicate in the mantle during accretion, and formation of the core was a secondary product of heating of the growing planet. The mantle has an excess of siderophile elements, which poses a problem. There are three possibilities: core formation was never completed, some of these elements remaining locked in silicate; it took place while overall chemical conditions changed from reducing to oxidizing, so that the most siderophile ended up in the core during the reduced phase then less siderophile elements progressively favoured silicate entry as conditions became oxidising; as the Earth grew the pressure under which segregation of core materials increased. The third scenario invokes a deep 'ocean' of magma through which droplets of metal fell, equilibrating with silicate melt and then forming a pond on the 'ocean' floor, ultimately to descend as large masses.
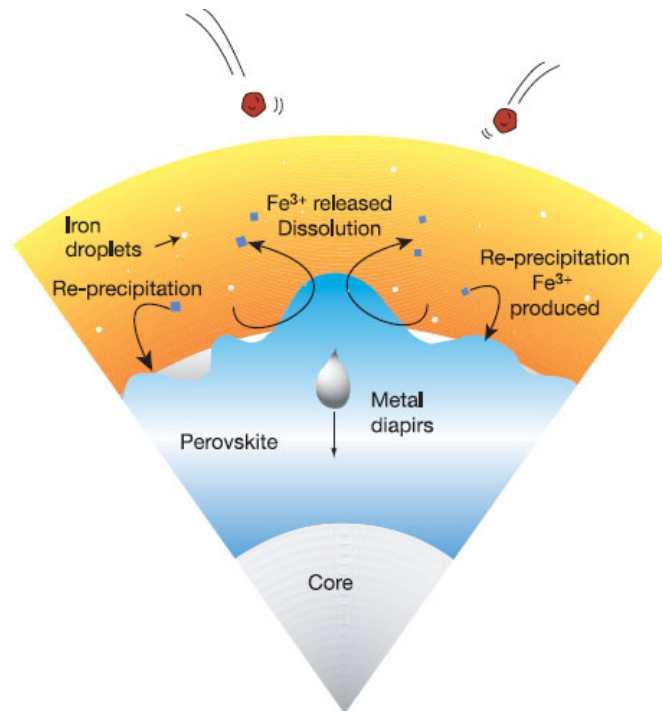
Cartoon of how the mantle may have self-oxidized via perovskite crystallization; note the unusual use of 'diapir' to denote sinking blobs of metal. (Credit: Wood *et al.* 2006; Fig. 5)

Wood *et al.* examine these three scenarios in the light of recent data and planetary modelling, suggesting that the second was the most likely by a process of 'self-oxidation' as its size increased, perhaps linked with the formation of perovskite in the deep mantle once a limiting radius had been achieved. Such a heterogeneous accretion and core segregation would explain the disparity between estimates of the timing of the core from tungsten and lead isotopes (~12 and ~28 Ma respectively)   They also revisit the oddly low density of the liquid outer core – about 8% less than expected of an iron-nickel alloy, ascribing it to a mixture of the low-atomic weight elements, silicon, sulphur, carbon and hydrogen, with an unknown proportion of oxygen.

Is the idea of Hadean continental crust bunkum? (*October 2006*)

As my monthly jottings have noted several times, the geological record of the Hadean (before 4 Ga ago) could easily be lost through an ill-timed sneeze: it consists of a few minute zircon grains extracted from common or garden Archaean meta-sandstones in Western Australia. Milligram for milligram, these have become the heaviest punchers in the world of geochemical debate. They undoubtedly crystallized as long ago as 4.4 Ga. More controversially their detailed chemistry has been suggested to indicate that their crystallization was from granitic magma formed by partial melting of materials that interacted with water at around 700°C; materials that were not primarily of mantle composition (see *Zircons and early continents no longer to be sneezed at* above). If true, that would suggest low-density crust that found difficulty in being recycled into the mantle only a few tens of Ma after the Earth's formation. Either that crust was too thin to resist subduction by some kind of tectonic slicing and has gone forever, or some of it is still out there waiting to be found…by those who become very excited by extremely aged rocks. There is a simple way of putting the early-granite hypothesis to the test — by seeing if zircons in basalts are any different from them (Coogan, L.A. & Hinton, R.W. 2006. [Do the trace element compositions of detrital zircons require Hadean continental crust?](#) *Geology*, v. **34**, p. 633-636; DOI: 10.1130/G22737.1).

Coogan and Hinton, of the University of Waterloo, Canada and Edinburgh University respectively, show that Hadean zircons cannot be distinguished chemically from those found in gabbros that have differentiated from basaltic magmas at modern mid-ocean ridges. As if that were not sufficiently deflating, they also made crystallization-temperature estimates of the gabbro-derived zircons, using a geothermometer that uses the titanium content of zircon in equilibrium with rutile. Despite the fact that the real temperature of gabbro crystallization is well over 1000°C, these estimates came in at between 700 and 800°C. That is, about the same as those proposed as evidence for the crystallization temperature of Hadean zircons from a granitic magma. Coogan and Hinton were not content, and go on to offer an alternative explanation for the zircon's oxygen isotopes, used by others as evidence for the influence of water at shallow depths back to 4.4 Ga. The seemingly water-derived ^{18}O excess in the zircons could well have come from carbonates recycled from surface weathering of basalt, to be assimilated by deep basaltic magma chambers.

So, farewell planet Pluto… (*October 2006*)

One theological mode of discourse is casuistry, best known for disputing the number of angels who can sit on a pinhead. Amongst astronomers, at least those who meet every three years at the General Assembly of the International Astronomical Union (IAU), this form of sophism crops up from time to time. It does too among geologists, and probably more often, as they have a many things to argue about. At 13.32 GMT on the 24th of August the 26th GA of the IAU in Prague upset a great many people by [casting Pluto, formerly known as Planet Pluto, into the indignity of dwarf-planet status](#). NASA may be well-miffed, as their New Horizon probe has been on its way there since mid-January 2006.

The issue of Pluto's status popped up after a larger Sun-orbiting object (2003 UB$_{313}$) was announced in 2005, which, like Pluto is beyond the orbit of Neptune. That new body is the largest known in the dim and distant Kuiper Belt, and Pluto may well be a stray from that

region, having a very odd orbit. IAU decided, somewhat late in its existence, to define 'planet'. Committees were appointed. The primary criterion decided by the final committee to report to IAU was that planets need to orbit the Sun, not another bigger planet. Second, they have to have sufficient mass for their gravitational force to make them nice and round. Sadly, it seems that the committee made quite a gaffe. In order to distinguish trans-Neptunian planets that take more than 200 years to orbit, they suggested the term 'pluton' (oh dear). Whatever, that would give the Solar System 12 planets: trans-Neptunian Pluto, Charon (in binary orbit with Pluto) and 2003 UB$_{313}$; and Ceres, formerly just the largest asteroid known. But the Kuiper Belt might easily have lots of other massive and round objects in it, awaiting discovery. So, has the old Jesuitical mind-expanding exercise been 'larged-up'? Probably not, in a strictly scientific sense, because additional criterion for planetary status, added by the 26th GA of the IAU, is that one should be massive enough either to have 'swept' its orbit clear of minor bodies early on, or to have flung them far away. Since Pluto and Ceres have done neither, they are officially to be considered 'of diminished stature'. Some worry that traumatised children, fond of Pluto, will be driven from an interest in science. Who knows? But if IAU persists in the name 'pluton' as a sop to public opinion, there will be trouble... But more was yet to come in 2017.

Long-term stability of the magnetic poles (*November 2006*)

Back to about 200 Ma ago, charting the motions of plates is relatively simple using the striped patterns of magnetic field strength above the ocean floor, which reflect periodic reversals of polarity of the geomagnetic field. Post-Triassic plate motions can also be assessed in an absolute reference frame with the use of hot spot tracks. Since no ocean floor, other than in obducted ophiolites, is older than 200 Ma, the method cannot be used before then. Instead, the inclination and direction of remanent magnetism in continental rocks, suitably corrected for any tilting by deformation, take on the role of tracking motions. The direction is taken as being towards the magnetic poles at the time a rock formed, whereas the inclination supposedly varies in a simple fashion with latitude as it does today; vertical at the poles and horizontal at the ancient Equator. The post-Triassic break-up of Pangaea allows the palaeomagnetic method to be tested, and for that period it holds up extremely well. The models that chart how continental masses separated from a late-Precambrian supercontinent, drifted and then clanged together in the Devonian to early Permian to form Pangaea use the assumption of a consistently dipolar magnetic field that was lined up with the Earth's axis of rotation: about as uniformitarian as one can get. They are models that delight tectonicians and students alike. There is however, a period in Earth's history, from about 750 to 600 Ma, when palaeomagnetic positioning gives worrying results. Evidence of glaciation occurs at nearly equatorial palaeolatitudes at least three times.

Taken at face value, these results form the basis for the 'Snowball Earth' hypothesis, and the 750 to 600 Ma period has been dubbed the Cryogenian. But there are two other ways of explaining what is about as far from uniformitarian as can be. Maybe there were long periods when the geomagnetic field was neither dipolar nor lined-up with the rotational axis, in which case palaeolatitudes for those periods would be totally meaningless. The other possibility, which is alarmingly odd, is that before about 600 Ma the angle between the Earth's axis of rotation and the plane in which it orbits the Sun was not about 23.5°, but more than 58°. At a high obliquity, Earth's rotation would then ensure that high latitudes

were warmer than low ones, which would neatly explain away much of the evidence for 'Snowball Earth' conditions. It is a worrying idea, simply because some considerable force, i.e. a stupendous impact, would be needed to change the axial tilt from >58° to what it is now and probably has been throughout the Phanerozoic. Settling the matter once and for all seems now to have been achieved by David Evans of Yale University, using a simple yet ingenious approach (Evans, D.A.D 2006. Proterozoic low orbital obliquity and axial-dipolar geomagnetic field from evaporite palaeolatitudes. *Nature*, v. **444**, p. 51-55; DOI: 10.1038/nature05203).

Evans based his study on the uniformitarian assumption that conditions are just right for strong evaporation of shallow, enclosed seas between 15 to 35° of latitude either side of the Equator, which is where evaporite deposits are forming now. If true, and if the geomagnetic field has been much the same as it is now, except during reversals, then all evaporites should give palaeolatitude results with this narrow range. There are lots of them, going back to 2.3 Ga ago, and being quite soft it is easy to drill cores from them. Furthermore they contain wind-blown dust, the magnetic component of which would line up nicely with the geomagnetic field while salts crystallised. The results from 54 world-wide sample are quite a triumph, for no evaporite palaeolatitudes are further than 40° from the Equator, and their means fall within the modern latitude range of an excess of evaporation over precipitation. There are differences between different time periods – before Pangaea existed evaporites formed slightly closer to the Equator than in later times. The fact that they cluster also shows that the dominant component of the geomagnetic field has been consistently been a dipole. However, even though the fundamental assumptions on which palaeomagnetic measurements are based seem sound, there are still problems for the Snowball hypothesis. Are the magnetic measurements up to scratch and do the stratigraphic and radiometric ages of samples refer to the evidence for glaciation?

Bad news for a future lunar base (*November 2006*)

Whether or not the Moon again becomes a target for exploration by astronauts, and for use as a launch pad for Mars, depend on whether there is any water there. There has been considerable optimism that perpetual shadows in some of the deep craters close to the south lunar pole might contain ice that has not been exposed to solar heating. There is a way of telling using radar imaging, and reconnaissance results from orbiting probes had suggested that ice was indeed there, hence the excited men in suits of various kinds. A check using far more revealing radar data produced using the Areceibo radio telescope – it has also produced images of Venus at far greater distances – show that both sunlit and shadowed areas on the Moon can give a signal that is theoretically that from ice (Campbell, D.B. *et al*. 2006. No evidence for thick deposits of ice at the lunar south pole. *Nature*, v. **443**, p. 835-837; DOI: 10.1038/nature05167). Since ice could never survive in full sunlight, the similar results cast great doubt on ice being anywhere else on the Moon. There also seems to be a correlation in degree of belief with degree of involvement with future lunar exploration preparation.