

Planetary science and meteoritics

Pushing back the “vestige of a beginning” (January 2001)

About 4.5 billion years ago the Moon formed, probably as a result of a stupendous collision between the original Earth and a body about the size of Mars. That would have left Earth with its outer parts molten in a global magma ocean, and without any atmosphere. Such a dreadful condition formed the point of departure for all subsequent evolution of our home world; the beginning of geological history. No matter how many terrestrial rocks geochronologists analyse, it seems pretty clear that they are never going to push back their erstwhile grail of the oldest one beyond 4 billion years. Among the oldest rocks, those from Akilia in west Greenland contain sedimentary evidence for flowing water and the isotopic signature of established life. The date 4 billion years before the present seems to be the maximum for every aspect of geological research that might support theory with concrete evidence, which is sad, because both continents and oceans existed, the planet was inhabited, some form of tectonics operated and water moved matter around. Studying the emergence of such broadly familiar processes is a lost cause, at least on this planet, for a half billion years has simply vanished.

The enduring outer skin of the Earth, continental crust, is made mainly of two minerals, quartz and feldspar. Feldspar can be dated, but it breaks down to clay and soluble compounds, so the weather removes it as a source of information. Quartz offers not a single clue to when it formed, even though its hardness and stable molecule mean that it is durable. Its abundance of silicon demands several stages of evolution from the silicon-poor mantle. Quartz is quintessentially continent stuff. Probably among those quartz grains found on a beach or in a sandstone some date back to the emergence of the first crust, but you would never know. Even more durable is zirconium silicate, or zircon, tiny amounts of which settle from many sands because it is denser than quartz. Zircon's structure is hospitable to several elements rarer still, including radioactive uranium and thorium. Build up of radiogenic lead isotopes inside zircon crystals means that grains carry their own history. Zirconium finds no easy resting place in minerals that form the bulk of the mantle. So it tends selectively to enter magma formed there. Nor are the minerals of oceanic crust particularly accommodating. Naturally, zirconium becomes concentrated in materials that end up as continental crust, so to form zircons. A handful of zircons from beach sands continually sorted according to density at Cape Comorin in South India contains the entire history of the formation of the Indian continent - they are sold in bottles by urchins at tourist resorts as one of Lord Krishna's five varieties of “rice”.

The Mount Narryer Quartzite of Western Australia is a similarly well sorted, though 3 billion-year old sedimentary repository. Fourteen years ago, Bill Compston and Bob Pidgeon managed to extract 17 tiny zircons from it that extinguished at a stroke the ambitions of other geochronologists to date the oldest rock in the world. Their ages, obtained by methods based on the build up of lead isotopes from decayed uranium and thorium reached back to 4.27 billion years. They had discovered the oldest continent, but one sneeze and they would have lost the lot. Mount Narryer made the front pages early in January by providing even older zircons that post-date “Year Zero” by a mere hundred million years. Some continental material was around 4.4 billion years ago (Wilde, S.A. *et al.* 2001).

[Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago](#). *Nature*, v. **409**, p. 175-178; doi: 10.1038/35051550). Oxygen isotopes in these tiny, aged grains offer another insight. They have contents of ^{18}O that are too high to have formed other than in an environment that involved liquid water reacting with the source of the zircon-forming magma (Wilde *et al.*, 2001; Mojzsis, S.J *et al.* 2001. [Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago](#). *Nature*, v. **409**, p. 178-181; doi: 10.1038/35051557).



Mount Narryer, Western Australia. (Credit: [Jonathan Duhamel](#))

Evidence for such old liquid water drew attention from many planetary scientists. Life is impossible without it. The conclusion drawn is that it *could* have been around so close to “Year Zero” . But evidence for early water is no surprise. Earth’s high content of volatiles ensures that water in one phase or another must always play a role in its internal processes. Hot as it must have been immediately following Moon formation, convection in its “magma ocean” and radiation from its surface (proportional to the fourth power of surface temperature) would have been so efficient that cooling to permit liquid water at the surface may have taken less than 100 million years. The maximum temperature of the liquid water that interacted with the zircon-forming magma depended on the pressure of the environment where that happened. That was not necessarily an ocean or even “some warm little pond”. Water is liquid, if the pressure is high enough, at temperatures up to 274°C, which is too high for most of life’s molecules.

See also: Halliday, A.N. 2001. In the beginning... *Nature*, v. **409**, p. 144-145; doi: 10.1038/35051685.

Loss of the Martian atmosphere (*February 2001*)

Mars seem quite massive enough to have held a substantial atmosphere, as have Earth and Venus. That it has barely any is a major puzzle. One possible reason is that Mars has a tiny magnetic field. A strong magnetic field on Earth serves to deflect the solar wind, a stream of

charged particles emitted by the outer part of the Sun. Undelected in this way, the solar wind would gradually strip off an atmosphere. Currently, Mars has so little atmosphere that photosynthetic life that combines water and carbon dioxide to build carbohydrate is probably impossible there, despite the fact that most of what little air there is comprises CO₂.

In the great chattering about prospects for Martian life at some time in the planet's past, a central issue is the timing of atmospheric loss. It is inconceivable that Mars never had an atmosphere, because it possesses the largest volcanoes in the Solar System which must have vented mantle gases. If its magnetic field slowly dwindled, that gives ample time for life to have emerged.

Unsurprisingly, one of the tasks of NASA's Mars Global Surveyor Mission has, for the last two years, been a global survey of the Martian ionosphere. That is a proxy for regional variation in magnetic field strength. A recent meeting of the Mars Global Surveyor team revealed the maps and their implications to the public. The oldest terrains - those showing the greatest density of impact structures, as in the Lunar Highlands - show evidence of remanent magnetism. Those affected by the youngest major impacts - analogous to the 4 billion-year old lunar *maria* - do not. This suggests that Mars lost its magnetic field some time in its first half billion years, and thereby any substantial atmosphere. One possible reason for this loss is that Mars has long been a geologically sluggish planet. It is turbulent motion in the Earth's liquid outer core that generates a magnetic field. That turbulence is probably kept in motion by convective heat transfer in the mantle - it is a companion of terrestrial plate tectonics or any kind of regular mantle overturn. Mars' mantle does not do that, either by tectonics or through plume activity (unlike Venus), so its core may well be devoid of motion.

Exactly when magnetism stopped, with the attendant effect of the solar wind on any atmosphere, is crucial for estimates of how long life might have had to appear and begin evolving. The results certainly rule out evolution beyond the most primitive life forms. However, establishing that date must await future Mars landers, either staffed or robotic, on which the most important experiments will aim at detecting signs of former or extant life. The magnetic data are not encouraging for exobiologists.

(Source: Samuel, E. 2001. The day the dynamo died. *New Scientist*, v. 16 (2277), p. 4)

And now, Martian glaciers (*February 2001*)

Readers will have seen scornful comments in [*First signs of liquid water on Mars?* \(June 2000\)](#), regarding the desperate search for evidence of liquid water on modern Mars. That water once was there seemed cut and dried from the giant valleys scoured across the Red Planet's surface. It was said that vast volumes of deep-seated ice catastrophically melted to flood from large impact sites. Like the supposed evidence for active watery emissions in recent time, that for past flooding which cut the large valley systems rested on interpretation of the landforms themselves. Re-examination of the valleys shows that they almost exactly mimic features revealed by sonar sounding on the sea floor surrounding the Antarctic ice sheet. The Antarctic features probably formed during increased flow regimes when sea level stood at its lowest during glacial maxima. Such surges can flow uphill, and sure enough the valley systems on Mars do have uphill tracts.

Baerbel Luchita of the US Geological Survey applied work on structure beneath the Ross Ice Shelf to Mars, suggesting that impact-melted water froze on emergence at the surface to flow in a more or less glacial fashion. Undoubtedly, ice flow is far more capable of large-scale excavation than an equal volume of water, but to form the 1000 km long systems on Mars implies a considerable head. Also its branching nature forces the assumption of many coalescing glaciers over a very large area. That meets problems in imagining a widely distributed source of energy that caused the melting. Impacts are at points, so perhaps yet another mechanism, such as seismicity, will need to be invoked.

(Source: Hecht, J. Sliced by ice. *New Scientist*, 27 January 2001 issue)

Ganymede's water volcanism (March 2001)

Jupiter's giant moon Ganymede is an icy world, as are many satellites of the Outer Planets. But is also one of the few showing signs of some kind of tectonics. Its surface is made up of dark, cratered material, presumably an ancient mixture of rocky debris and ice, riven by swaths of lighter surface. The latter, which covers two-thirds, has little cratering and is a later feature of the moon's surface. Somehow, Ganymede underwent a resurfacing, perhaps in a similar manner to neighbouring Europa - a simple ice ball - but not so all-consuming.

The event probably stemmed from the coming together of Jupiter's largest moons into orbital resonance that generated sufficient gravitational energy to cause internal melting. Precisely how this achieved the intricacies of Ganymede's surface is something of a mystery.

Images from Voyager and Galileo missions form stereoscopic pairs from which the moon's topography can be derived with useful precision (Schenk, P.M. *et al.* 2001. Flooding of Ganymede's bright terrains by low-viscosity water-ice lavas. *Nature*, v. **410**, p.57-60; doi: 10.1038/35065027). Using digital elevation data with high-resolution Galileo images, Schenk *et al.* have been able to subdivide the light swaths into three kinds of surface, reticulate, grooved and smooth at different elevations from highest to lowest. Large elevation differences of the order of 2 km are involved. That in itself is evidence that ice at the prevailing temperature behaves more like rock than glacial ice.

The greater surprise is that the lowest, smooth unit shows evidence of having formed by processes akin to volcanism, with calderas and features that engulf earlier structures. However, even the fine resolution of the latest images does not reveal "lava" flows. Some rifting mechanism seems to have encouraged emergence of water-ice "magma" to form the low smooth terrains. All very counter-intuitive for terrestrial volcanologists, because water "magma" must be more dense than the solidified flows forming from it, unlike silicate liquids or those rich in sulphur on Io. That makes the formation of high volcanoes impossible.

Presumably, the much higher grooved and reticulate terrains started in the same manner, as linear troughs, then to be deformed and thickened by "water tectonics".

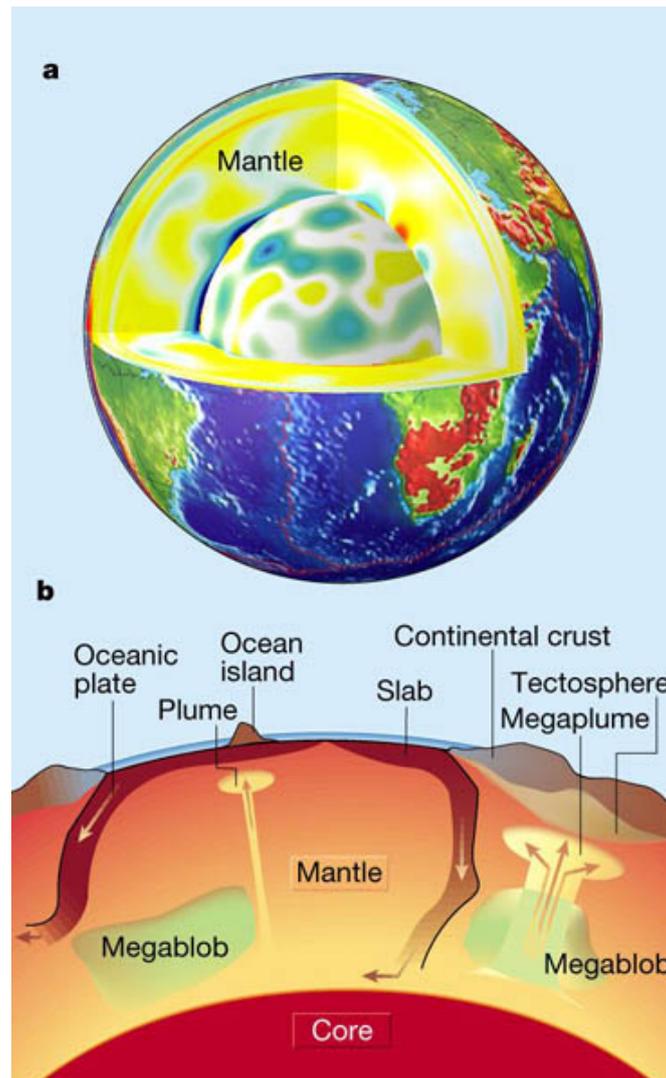
How the Earth works: "mega-blobs" in the mantle (April 2001)

Seismic waves generated by large earthquakes arrive at different times at seismographs arranged in a world-wide network. When they arrive depends on the relative positions of

epicentres and receivers, but most importantly on variations in physical properties within the Earth that affect the speed at which they travel. Given enough high-quality seismic records and powerful computing, such data allow geophysicists to map how wave speeds change with depth in the mantle and produce 3-D models. In other words, seismic energy can produce geophysical homologues of medical CAT scans. The second important means of visualizing the unseeable comes from the geochemistry of basaltic lavas formed by partial melting of the mantle in different tectonic settings. Results from such studies reveal that the composition of the mantle is not homogeneous. Combining information from both sources, in the light of motions of the lithosphere, provides a powerful input to modelling how the Earth behaves as a whole (see [Plate tectonics and seismic tomography](#) *Tectonics* July 2000).

Seismic tomography's most important derivative stems from the manner in which wave speed depends on variations in the mechanical properties of the mantle. For P-waves, speed varies with the mantle's differing resistance to compression, and S-wave speed is directly proportional to the rigidity of the mantle. Unusually high mantle temperatures cause decreases in compression resistance and rigidity, and therefore drops in the speeds of both kinds of body wave. The cooler the temperature, the higher both speeds. So, velocity variations in seismic tomographs are proxies for changing mantle temperature, and in turn for regions of different density - the hotter a material is, the lower is its density. The implications are quite simple; high-speed anomalies signify cool, potentially sinking regions in the mantle, whereas low speeds suggest that matter is able to rise. In practice, modelling the fundamental dynamics of the Earth's mantle using seismic tomography is computationally difficult, often ambiguous and blurred because of the lack of suitable data.

Seismic tomography gave the first clues to the idea that subducted slabs penetrate all the way down to the core mantle boundary, and that at least some of the plumes suspected to underpin hot spots have their source at such depths. Together, these findings support whole-mantle convection. As well as improving the amount of high-quality seismic data and the software to analyse them, combining physical parameters with sketchy knowledge of variations in mantle chemistry and mineralogy is the next step in "sharpening" the focus of mantle models. That seems to have been taken by Alessandro Forte and Jerry Mitrovica of the Universities of Western Ontario and Toronto (Forte, A.M. and Mitrovica, J.X. 2001. [Deep-mantle high-viscosity flow and thermochemical structure inferred from seismic and geodynamic data](#). *Nature*, v. **410**, p. 1049-1056; doi: 10.1038/35074000). Their work confirms the concept of whole-mantle convection resulting from thermal anomalies, but has an added bite. They show evidence for very large variations in deep-mantle composition - to megaplumes they have added "mega-blobs".



Cutaway and schematic cross section of the Earth showing temperature, compositional and tectonic variations in the mantle. (Credit: Forte and Mitrovia 2001)

Although the results of their analyses are limited by data availability and reliability, and by simplifying assumptions, they imply that such blobs can respond to temperature changes by rising and sinking periodically. That is, the mantle may move as vast domes and downwellings as well as in the more tightly constrained plumes and sinking slabs. One intriguing possibility is that such blobs may be primitive and retain high concentrations of elements that evolution of other parts of the mantle has transferred to the continental crust. Such primitive signatures are passed on to the geochemistry of basalts forming from plumes beneath ocean islands. However, there is a long way to go before a blob-plume-ocean island connection can be made. If it proves to be plausible, then such ancient blobs would have to be very viscous to have resisted mixing over time with more evolved mantle. Another possibility is that the blobs are themselves highly evolved, through the progressive accumulation of subducted slab material.

(See also: Manga, M. 2001. Shaken, not stirred. *Nature*, v. **410**, p. 1041-1042; doi: 10.1038/35074235)

Erosion on Mars (May 2001)

Mars is the only planet in the Solar System that has landscapes that bear any resemblance to those we see on Earth. The one factor common to both planets is that surfaces have been shaped by flowing water. On Mars, that was a one-off event early in its history, and thereafter shaping the planet has been through continual movement of dust in its thin, but energetic atmosphere, the formation of impact craters and volcanism. Evidence for fluvial processes occurs in the highland regions, which were built mainly by volcanic activity., and stems from careful examination of high-resolution photography from orbiting probes. Whether the various kinds of valleys formed by catastrophic, short-lived floods of melt water released by impacts into deep frozen ground, through steady release of groundwater or actually by precipitation are the ground for speculation and controversy. A means of assessing the possibilities is using accurate data on topographic elevation. Digital elevation models for the Earth, even at coarse resolution (GTOPO30 data at 1 km resolution), map out the intricacy of surface drainage of the continents. A DEM produced by the laser altimeter aboard Mars Orbiter allows not only the various models to be assessed, but enables quantitative work on the amount and rate of water erosion and deposition of sediment when combined with evidence for the age and duration of Mars' fluvial event (Hynek, B.M. and Phillips, R.J. 2001. [Evidence for extensive denudation of the Martian highlands.](#) *Geology*, v. **29**, p. 407-410; DOI: [10.1130/0091-7613\(2001\)029<0407:EFEDOT>2.0.CO;2](#)).

Hynek and Phillips show that the event was long lived, lasting 350 to 500 Ma around 4 billion years ago. Their study was of an area the size of Europe. Scaled up, their findings suggest that of the order of 5 million cubic kilometres of sediment was transported, equivalent to deposition of a 120 metre thick sediment layer in the flat plains of Mars' northern hemisphere. The average rate of erosion during the event compares closely with that typical of temperate maritime areas of mountains on Earth. It is difficult to see how such prolonged erosion could have taken place without runoff fed by precipitation on the surface, and that implies a much warmer climate and thicker atmosphere than on modern Mars, albeit only for a very early episode in its evolution.