# *Tectonics*

**Archaean tectonics was different (*January 2003*)**

Higher mantle heat production in the past suggests that at some stage in the evolution of plate tectonics oceanic lithosphere would arrive at destructive margins too hot for oceanic basalt to dehydrate and form eclogite. Without excess density over that of the mantle, conferred by subducted eclogite (3300 kg $m^{-3}$), the lithospheric slab would descend at a shallow angle, oceanic crust would probably undergo wet partial melting, and maybe slab pull force would be so low that subduction was a hit or miss affair. The thermal state of the Archaean Earth might not have had plate tectonics as we know it today. However, studies of the oldest probable ocean floor (the ~3800 Ma Akilia Association of West Greenland) looks for all the world as if it formed as an accretionary prism as a result of normal-seeming plate forces. Previous speculation about Archaean tectonics assumed basaltic oceanic crust, much like today's. High heat production also implies that Archaean constructive margins generated a great deal more magma by partial melting of mantle with higher potential temperature; probably more magnesian, picritic primary magma (Foley, S.F *et al*. 2003. Evolution of the Archaean crust by delamination and shallow subduction. *Nature*, v. **421**, p. 249-252; DOI: 10.1038/421230b).

Part of the Akilia association in the Isua area of West Greenland

Instead of the lower oceanic crust being made from gabbroic cumulates, it was then probably dominated by ultramafic products of fractional crystallization. Foley, and colleagues Stephan Buhre and Dorrit Jacob of the Universities of Greifswald and Franfurt in Germany, show from high-pressure experiments that such lower crust would form dense pyroxenites. At destructive margins these might delaminate from the upper oceanic crust to subduct steeply, thereby conferring slab-pull force to drive tectonics. Their eventual partial melting would source basaltic magmas to add to older oceanic crust that failed to subduct during the earliest Hadean times. That would explain the lack of continental materials older than 4000 Ma. . The partial melting of garnet-bearing mafic materials (probably garnet amphibolite) that sourced Archaean continental crust would have had to await the end of such delamination, when the whole oceanic crust could descend, albeit with hot wet basalt in the upper part of the slab. Interesting though the ideas in the paper are, apart from the authors suggestion of a connection with element depletion of the upper mantle progressively affecting an ever deeper zone, they hark back to thoughts on Archaean processes as early as the late 1970s.

## Eskola's mantled gneiss domes revisited (*January 2003*)

The Finnish geologist Pentti Eskola famously recognised in the 1940s that many basement terrains throughout the world, particularly in Scandinavia, have large tracts of gneiss in the form of domal structures separated by synforms (mantles to the domes) of supracrustal rocks. These mantled domes give a curious "egg-box" appearance to the geology of many shield areas, usually picked out by the conventional pink colours used to signify granitic rocks and greens for supracrustal belts. Once it was recognised that interference between upright folds of different ages and with different axial trends could produce "egg-box" structures on the outcrop scale, many structural geologists turned to this as an explanation for the huge features recognised by Eskola, even suggesting that the "mantles" were above profound unconformities. Eskola's view was that these regional features were due to differential uplift of low-density gneisses and more dense supracrustal rocks, and this view lingers with many other geologists. Christain Teyssier and Donna Whitney, of the University of Minnesota, have reviewed the current state of knowledge for the phenomenon (Teyssier, C. & Whitney, D.L. 2002. Gneiss domes and orogeny. *Geology*, v. **30**, p. 1139-1142; DOI: 10.1130/0091-7613(2002)030<1139:GDAO>2.0.CO;2), and conclude something more involved than either hypothesis. Many of the gneiss domes show evidence for the involvement of crustal melting in response to decompression as orogens evolve, almost certainly resulting from removal of the upper crust, either by rapid erosion or extensional tectonics. As well as forming bodies of melt or near-molten migmatites, such a process weakens he crust, allowing masses of low-density crust, including the partially melted bodies, to rise rapidly. This feeds further decompression, the whole process becoming an effective means of advective heat transfer in large orogens.

## Hydrogeology of sea-floor cooling (*February 2003*)

Much of the Earth's internal heat production escapes from the ocean floor, by a combination of direct cooling of new lavas at ridges, hydrothermal pumping of seawater through oceanic crust and conduction. Cooling is responsible for the increase in density with age of oceanic lithosphere that causes the ocean floor to gradually deepen away from spreading axes, thereby adding a gravitational force (ridge-slide force) to help drive plate tectonics. The cooling also ensures that oceanic lithosphere is sufficiently cool at destructive margins for metamorphic processes in subduction zones to further increase its density above that of the mantle, thereby largely driving plate tectonics through slab-pull force. More than 70% of internal heat loss through the oceans is dissipated through crust that is younger than 1 Ma. Some of that emanates from hydrothermal geysers at ridges, about which a great deal has been revealed in recent years.

What of the other 30% that escapes through older crust? The older it is, the more it is literally blanketed by sediments that should act to block circulation of seawater, because they are so fine grained and impermeable. It might seem as if heat lost would have to be by conduction alone. That is not sufficient to explain the shape of the ocean basins. However, some recent work near the Juan de Fuca Ridge in the NE Pacific by a team from the USA, Canada and Germany (Fisher, A.T. and 12 others 2003. Hydrothermal recharge and discharge across 50 km guided by seamounts on a young ride flank. *Nature*, v. **421**, p. 618-621; DOI: 10.1038/nature01352) shows that basic principles of hydrogeology guide seawater to increase heat loss. Outflow is not through the sedimentary cover, but through seamounts, which are outcrops of the underlying igneous part of the crust. Like many springs on land, the water that flows from them can come from far afield. The sedimentary cover acts as an aquiclude, making the crystalline crust a confined aquifer, but for any flow to operate water must infiltrate the ocean floor. Fisher and colleagues have found that some seamounts have higher heat flow than others, and are sites of outflowing warm water. Some have anomalously low heat flow and may well be sites where seawater is infiltrating. Dating outflowing water using $^{14}C$ reveals that it is very young, and must have flowed rapidly, yet in their study area there are no signs of significant recharge through the sediments. One seamount, 50 km from another which discharges water is the only likely source. So, it seems as if the distribution and number of sea mounts on the oceanic part of a plate might bear greatly on the processes that eventually take place when the plate is subducted. "Pimply" plates could have cooled more than smooth plates with an unbroken blanket of inefficiently conductive sediments.

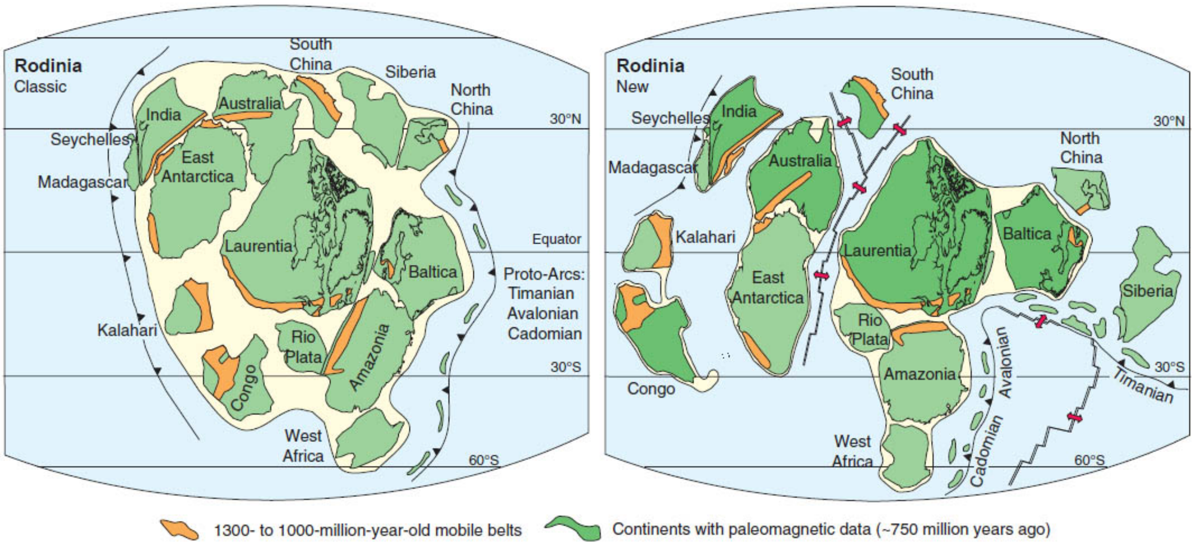
**Plume debates (*May 2003*)**

Jason Morgan's recognised in the early 1970-s that chains of volcanic islands and seamounts, such as the Hawaii-Emperor Chain, which cross sea-floor magnetic stripes, might have resulted from mantle "hot spots" that are fixed relative to motions of lithospheric plates. He went on to suggest that such magmatic anomalies might reflect narrow thermal upwellings within the deep mantle, and applied the term "plumes" to these notional convective zones. Geochemists have since flocked to active and extinct manifestations of within-plate magmatism, and developed a whole sub-culture of classification and hypotheses concerning their origin and inner workings. By the end of the 1990s over 5000 candidates for underlying plumes had been proposed, some still active and others inferred for past events, such as flood basalt provinces. Processing of seismic signals using supercomputers over the last few years has used them to map variations in P- and S-wave speeds at different depths in the mantle. Speeds below those expected are likely to reflect hot mantle relative to high-speed, colder regions. So seismic tomography potentially charts hot rising mantle and cool, descending parts; seemingly ideal for detecting mantle plumes and how deep they extend. Early results centred on proposed plumes were a mixed bag. Some seemed to have very deep origins, perhaps down to the core-mantle boundary, whereas others appeared to be above hardly anomalous mantle. Most exciting was a zone of hot, probably rising mantle with a source at the top of the core beneath the South Atlantic, yet whose upper parts sloped obliquely upwards towards the Red Sea. It seemed that the Afar plume, believed to have been responsible for continental flood volcanism in Kenya and the Ethiopian Plateau, and perhaps the East African Rift and opening of the Red Sea, still existed. Hot-spot activity is a minor aspect of global tectonics today, so it is not an ideal time to ponder on plumes.  If they are real, then periods of massive flood volcanism would have been responses to superplumes, but the last in Ethiopia was 30 Ma ago.

Exciting as seismic tomography is, its resolution is currently too coarse to pick out the most revealing features of the plumes that potentially it could detect.  To have sufficient gravitational potential energy to rise through the entire mantle, a very large volume is required, and that is assigned to the "plume head".  Some hotspots are over large volumes of hot mantle, but they lie just beneath the lithosphere, and could have their origin at any level in the mantle.  The tracks that they followed, if any, and which might continue to be a conduit for uprising material would be much narrower.  Such  predicted "plume tails" are too small for resolution by current tomography.  A compilation and re-classification of hot spots (Courtillot, V. *et al*. 2003. Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters*, v. **205**, p. 295-308; DOI: 10.1016/S0012-821X(02)01048-8) has whittled down candidates for mantle plumes to a mere 50 or so, with less than 10 likely to have risen from core depths.  Two responses have arisen about this hugely popular topic: that Morgan's ideas are still basically valid, but need more work (DePaulo, D.J. & Manga, M. 2003. Deep origin of hotspots – the mantle plume model.  *Science*, v. **300**, p. 920-921; DOI: 10.1126/science.1083623); that hotspots might be linked to plate tectonics, and that mantle plumes are nothing more than a "belief system" (Fouger, G.R. & Natland, J.H. 2003.  Is "hotspot" volcanism a consequence of plate tectonics?  *Science*, v. **300**, p. 921-922).  A sensible aim that might resolve matters is to seek materials from the largest magmatic events – flood basalts – that should contain unambiguous geochemical signs that their parent mantle was at some stage exchanging matter with the core, if they had formed after rise of a superplume.  But, every line of approach to deep-mantle processes relies on proxy evidence, several steps removed from actual events and properties.  That makes David Stephenson's proposal for a mission to the core (see *Potassium in the core* Planetary science 2003) so urgently in need of support!

**Rodinia muddles (*June 2003*)**

In the early 1990s, Ian Dalziel, Eldridge Moores and Paul Hoffman speculated on the former existence of a supercontinent comparable with Pangaea, between about 1100 and 750 Ma.  The name Rodinia, from the Russian for Motherland, seemed appropriate.  They based sketchy reconstructions on the way in which orogens formed almost globally between 1300 and 1000 Ma could be fitted together by shuffling older crustal fragments, along with evidence from sediments in North America, and Antarctica that the supercontinent began to disassemble around 800 Ma.  A great  conundrum of later Neoproterozoic times seemed to be partly resolved by what might have happened when Rodinia broke apart and its fragments drifted across the globe.  This was the event that welded together the southern supercontinent of Gondwana between 800 to 500 Ma ago, forming the web of orogens known colloquially as the Pan African and Brazilide belts of Africa and South America.  Palaeomagnetic pole positions for the 1200-750 Ma period, from the supposed components of Rodinia, were an obvious test of Rodinia's former existence and its gross structure.  As they appeared the palaeomagnetic data seemed to confirm the early ideas that were based on Wegener's method of linking now far-separated orogens to reassemble his Carboniferous Pangaea supercontinent.  A reasonable consensus existed by the early years of the 21st century.  One of the main contributors of palaeopole data for Rodinia reconstruction has been Trond Torsvik of the Geological Survey of Norway, so it is noteworthy that he has cast the first shadows of doubt on what seemed to be an elegant general solution to more than half a billion years of global tectonics (Torsvic, T.H. 2003. The Rodinia jigsaw puzzle. *Science*, v. **300**, p. 1379-1381; DOI: 10.1126/science.1083469).

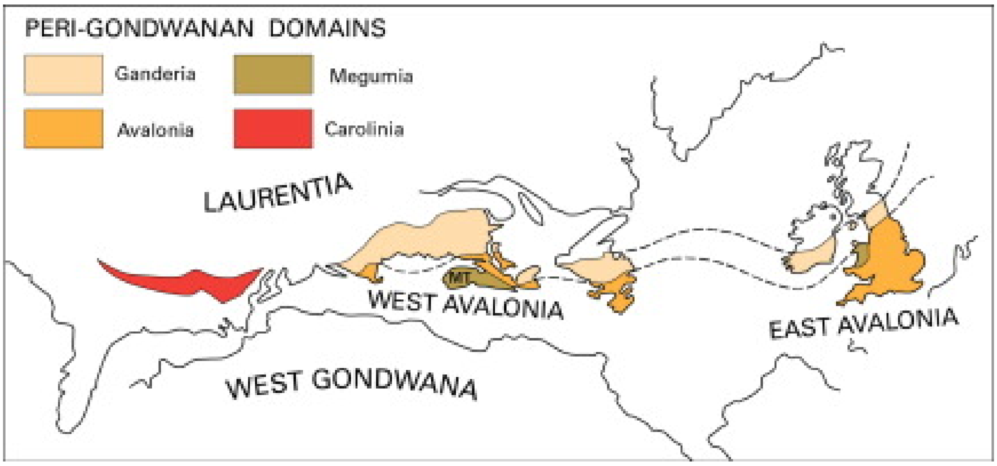



Two reconstructions of Rodinia at 750 Ma: previously accepted (left); that based on the latest Paleomagnetic pole positions for its components (right). Credit: Torsvik 2003)

The problem that Torsvik recognises is that superficially convincing geological jigsaw fits are coming into increasing conflict with better evidence for the palaeolatitudes of different segments. This is compounded by a lack of palaeomagnetic data for some of the 13 major continental segments that had formed earlier in Precambrian times. The central element in the original Rodinia model was the way that India, Antarctica and Australia's 1300-1000 Ma orogens fitted in what appeared to be a rational reconstruction of East Gondwana. The first fly in the ointment is that revision of Australia's palaeolatitude seems to make its fit with India impossible. Likewise the position of the geologically fitted Congo and Kalahari cratons, that now make up West Africa, is less certain. Amazonia is also not "behaving" as expected, and Baltica may have been rotated by 180 degrees relative to its former orientation in the old Rodinia model. As well as varying quality of palaeomagnetic data, and its lack from crucial components such as Siberia and North China, their dates vary so much that it is impossible to allow for large-scale readjustments through the lifetime of the putative supercontinent. Torsvik figures a "worst case" scenario, in which the whole Rodinia concept becomes merely continents that were near one another and separated by a variety of active rifts; something of a dog's breakfast that should spur more dating, palaeomagnetism and tectonic research on the orogens that first suggested a grand unification. That is, if the main proponents do not become so profoundly depressed that they simply give up!

**Zircons that wander (*July 2003*)**

The crust beneath the British Isles is made up of several once widely separated terranes, parts of Laurentia, an arc segment called Avalonia that split from Gondwana around 500 Ma ago, and a similar terrane (Armorica) that followed Avalonia across the Iapetus Ocean to accrete to Laurentia at the end of the Palaeozoic Era. Because of its maritime position, modern Britain is cloaked in vegetation so that rock occurrences are few and far between by comparison with less humid areas. Conditions for geological investigations are made yet worse by a mantle of glacial sediments plastered on top of bedrock. So, although having been studied for longer than almost every other piece of continental crust, the evolution of that beneath the British Isles is a subject of continual controversy and surprises. Sitting at the interface between the Laurentian and Avalonian terranes, roughly where the Iapetus suture is thought to have consumed at least half of the eponymous ocean, sit the Lower Palaeozoic rocks of the Southern Uplands of Scotland. They are widely thought to have formed as an accretionary prism on the edge of the plate underidden by subducted Iapetus oceanic lithosphere until Avalonia collided with the north-British terranes at the close of the Silurian. Some of the Ordovician sediments in the pile contain clasts of volcanic rocks, which were long thought to be contemporary and giving evidence of the expected arc volcanism behind the prism. However, they turn out to be much older, now that zircons from the sediments have been dated using high-precision methods (Phiilips, E.R. and 7 others 2003. Detrital Avalonian zircons in the Laurentian Southern Uplands terrane, Scotland. *Geology*, v. **31**, p. 625-628; DOI: 10.1130/0091-7613(2003)031<0625:DAZITL>2.0.CO;2).




Microcontinental terranes accreted to Laurentia durin the Lower Palaeozoic.

The zircons yielded Neoproterozoic ages (557 to 613 Ma), with evidence that some had been assimilated from older crust (1043 Ma) during volcanism. Taken at face value, the Neoproterozoic ages are similar to those of volcanic rocks in England and Wales, which formed off Gondwana in an arc setting, when the terranes were widely separated. The problem is one of getting the material across the subduction zone that separates the accreted terranes, but that is the issue proposed by the authors (all from the Natural Environment Research Council. However, such a conclusion might stem from the authors' narrow context; that of British geology. Immediately to the north of the Southern Uplands terrane is another, poorly exposed crustal block that underlies the Scottish Midland Valley. It was directly involved in the Ordovician Grampian orogeny that formed the highly deformed Precambrian rocks of the Scottish Highlands. With a narrow view, that terrane is also a mystery, yet it has a counterpart in the Taconia terrane that is familiar to North American geologists, which was involved in orogenic events contemporary with the Grampian orogeny in Scotland. Taconia has late Neoproterozoic to Ordovician arc volcanics.

**Setting up subduction (*August 2003*)**

Although they have roughly the same size and overall density, and probably very similar bulk compositions, Earth and Venus behave in very different ways. The Earth has plate tectonics, whereas radar images how that Venus has no such phenomenon. For the most part, Earth loses its internal heat production steadily and plate movements are intimately bound up with that generalised convective heat transfer. The surface of Venus has seen no significant deformation in half a billion years. In fact, that surface was probably formed by a massive blurt of magma around late Cambrian times. In some respects that is similar to the roughly 30 Ma appearance of flood-basalt volcanism on Earth, but on a scale that dwarfs large igneous provinces such as the Deccan and Siberian Traps. Quite probably, Venus builds up thermal energy in its mantle, until its release by massive partial melting. The key to Earth's behaviour seems to be the fact that its oceanic lithosphere is able to break and descend into the mantle. The gravitational force down a subduction zone is sufficient to keep plate tectonics going. But why does it start? Oceanic lithosphere is as strong as that beneath continents, and the other main force involved in plate tectonics, due to the gravitational effect of deepening sea floor as it cools away from constructive margins, is so low that it is unlikely to result in lithospheric failure. This vital, but often overlooked topic is nicely reviewed by Stephen Battersby, a consultant to *New Scientist* (Battersby, S. 2003. Eat your crusts. *New Scientist*, 30 August 2003, p. 30-33).

A possible explanation lies in the way in which the strength of the main mantle mineral, olivine, varies with the presence of water. Even minute amounts of water allow hydrogen ions to enter the olivine molecular lattice, thereby creating defects that can migrate and result in softening of the mineral. Experimental deformation under mantle conditions, carried out at the University of Minnesota, show ten-fold decrease in olivine's strength with as little as 20 parts per million of available water. Subduction at continental margins might therefore be set in motion by the weight of sediments accumulating on the ocean floor, and with time that weight increases as the continents are eroded. The other factor, perhaps bearing on the start of intra-oceanic subduction that forms island arcs, is the effect of transform faults and fracture zones that separate segments of different age and therefore density. Maybe that sets up forces that stress the oceanic lithosphere. The big problem is that the bulk of the oceanic lithosphere is mantle rock, and when it has been left as a residue by the basalt melting at constructive margins, it is well-nigh anhydrous. To soften it demands a source of water that permeates the peridotite. An obvious source is seawater penetration, but at the depths involved any pathways seal up tightly. Possibly there are wet masses in the deeper mantle, either as a result of earlier subduction or dating back to Earth's origin. Slow convection in the deep mantle could bring these into contact with the base of the oceanic lithosphere, where their water could permeate and weaken it to the point of failure. Just an idea, maybe. However, seismic tomography, so effective at charting the distribution of hot and cold (low- and high-velocity) mantle rocks, is also able to suggest places where damp, weak rock occurs in the deep mantle. One such low-velocity blob occurs beneath the eastern seaboard of North America (maybe a relic of the Palaeozoic Iapetus subduction zone that runs parallel to the present margin), where there is, as yet, no sign of subduction. But there is little sign that the blob is abnormally hot, and in all probability it is damp. The history of tectonics suggests that no ocean remains with passive margins forever, and inevitably subduction ends up devouring it, in 200 Ma at most (the greatest age of today's ocean floor). Given time the eastern USA may rank with the Andes!

So why does Venus behave so differently? Although we cannot yet analyse any Venus rock (there are no accredited Venusian meteorites!) there is a plausible scenario. Venus is the greenhouse planet. It is highly unlikely that it ever harboured life, particularly of a photosynthetic kind which could have produced free oxygen. In the Earth's atmosphere, it is the presence of ozone in the stratosphere that gives the atmosphere its peculiar thermal structure, especially the tropopause. That marks a sudden cooling that limits the height to which water vapour can rise before freezing out. In the stratosphere temperature warms up with height, due to the minor "greenhouse" effect of ozone. Venus probably never has a tropopause, so that clouds of water vapour could rise to the outer limits of the atmosphere warmed by high $CO_2$ levels. In contact with ultraviolet light, water dissociates to hydrogen and oxygen, and at high levels the hydrogen leaks away to space. Any oxygen is quickly drawn down by oxidation of iron at its surface. So Venus has progressively lost all its water and as a result is a tough nut to crack, as regards forces in its interior. Earth on the other hand is a bit like a fondant chocolate…

**Wandering hot spots (*August 2003*)**

It was once an axiom of plate tectonics that volcanic-island and seamount chains provided robust evidence for sea-floor spreading. Jason Morgan in 1971 developed the notion, based on a pre-plate tectonic idea by John Tuzo Wilson, that within-plate oceanic volcanic islands derived their magma from upward moving plumes in the mantle below the lithosphere. Many of them in the Pacific have extinct volcanic islands and seamounts arranged in straight chains that parallel the direction of sea-floor spreading shown by magnetic stripes. He likened their formation to the burn mark on a sheet of paper passed slowly over a candle flame. The Hawaii-Emperor chain bucks this hypothesis, by being profoundly bent from a WNW trend in its youngest part to north for ages greater than about 50 Ma. The problem is that neither leg is at right angles to the magnetic stripes, which does rather suggest that hot spots move. Hot spots have long been used as a frame of reference for absolute plate motions, but if one has moved then so might all the rest, and how they have moved would probably be independently of one another. Absolute motions then are hard to judge. The key to checking on the suspected hot-spot drift is to look at the palaeolatitude of differently aged volcanic rock samples along a chain. This has been achieved using palaeomagnetic measurements from the S-N Emperor chain (Tarduno, J.A. *et al*. 2003. The Emperor seamounts: southward motion of the Hawaiian hotspot plume in Earth's mantle. *Science*, v. **301**, p. 1064-1069; DOI: 10.1126/science.1086442). The test proved positive; the hotspot itself moved southwards between 81 to 47 Ma, while the Pacific plate was itself moving. Other tests suggest that hotspots in the Indian and Atlantic Oceans were indeed fixed for long periods, but the Pacific ones seem to have had a tendency to wander. Why that has happened is possibly connected to deep mantle flow, which might bend the plumes to which the hot spots owe their magmatic activity. Maybe their source region in the mantle shifts for entirely different reasons. Seismic tomography of the mantle has had some success in tracking the shapes of plumes, but not for relatively small ones because of its present poor resolution. One large plume that has an enormous tilt in the vertical dimension starts near the core-mantle boundary beneath the South Atlantic and hits the lithosphere in the Red Sea. No-one knows why, but its magmatic expression in the volcanic rocks of east Africa suggest that it too has moved from beneath Kenya about 50 Ma ago, across Ethiopia to its present position that fuels active volcanoes in the Afar Depression of NE Ethiopia, Djibouti and Eritrea.

**See also:** Stock, J. 2003. Hotspots come unstuck. *Science*, v. **301**, p. 1059-1060; DOI: 10.1126/science.1089049.

**Wetting oceanic lithosphere (*September 2003*)**

Loss of watery fluids from downgoing subduction zones and their rise into the over-riding mantle wedge is the main reason why arc magmas form there by partial melting under high $pH_2O$ conditions. It is usually assumed that all oceanic crust becomes thoroughly hydrated by circulation of seawater shortly after it forms at constructive plate margins. However, many oceanic basalts from ophiolites or dredged from the ocean floor are very fresh. It also seems that to explain the depth of fluid-influenced melting in some volcanic arcs, large amounts of water must be coming from the mantle part of the subducted slab. That is more difficult to hydrate by sea-floor hydrothermal processes. German and US geophysicists have found abundant evidence for faults oceanwards of where the Cocos Plate bends to descend below the Middle America Trench (Ranero, C.R. *et al*. 2003. Bending-related faulting and mantle serpentinization at the Middle America Trench. *Nature*, v. **425**, p. 367-373; DOI: 10.1038/nature01961). The faults show up clearly on detailed bathymetric images as wrinkles on the ocean floor off Nicaragua, and high-resolution seismic reflection profiles show that they penetrate deep into the mantle part of the Cocos Plate. Water can easily make its way down to form serpentinite from mantle peridotites just before the slab plunges down the subduction zone.

**How mountains grow (*November 2003*)**

In the Lake District of Cumbria, asking older local farmers how the fells grew will often get the response that they started out as pebbles. The justification of this seemingly implausible hypothesis is that once a field is cleared of boulders, about 20 to 30 years later new ones have appeared and the clearing has to start again. Geologists have their own ideas.

Compressive deformation of continental crust will thicken it, and gravity acting on this low-density material will ensure that its surface rises. Counter-intuitively, the action of erosion can cause mountains to rise as well. Debris flushed from deep valleys lessens the load on the underlying crust, so that it continually rises to drive up the elevations of the remaining ridges and peaks. The compressional origin of the Himalaya is hard to dispute, yet they bounced up quite quickly, long after they began to form. Current ideas, backed up by a variety of evidence, suggest that a lump of the dense lithosphere beneath the India-Asia collision zone fell off (delaminated) and sank into the mantle. That reduced the mass of the lithosphere beneath and the gravitational field, so that the surface rose. The second highest mountain range, the Andes, offer no such mechanism, for they are not products of compression associated with collision. Dense Pacific Ocean lithosphere subducts beneath them, yet the forces involved are insufficient to raise the Andes to even half their present elevation. Simon Lamb of the University of Oxford and Paul Davies of the University of California, Los Angeles have attempted an explanation for the anomalously high Central Andes (Lamb, S. & Davies P. 2003. Cenozoic climate change as a possible cause for the rise of the Andes. *Nature*, v. **425**, p. 792-797; DOI: 10.1038/nature02049).

Their idea is that sediments that pour into subduction-related trenches from rising arcs, to form part of the accretionary prism where lithosphere starts to go down, lubricate subduction because of the pore water in them. If there is little sediment supply from the rising crust, then frictional forces build up along the line of the subduction zone. That focuses the plate boundary stresses over a narrow zone, thereby giving sufficient force to drive the crust higher and higher. Today the cold northward ocean current along western South America provides little rainfall to the Central Andes, so erosion is much slowed. Episodic global cooling since the Mid-Eocene probably reduced erosion there several times during the Cenozoic. So for long periods the worlds largest subduction zone would have been starved of lubricants, thereby driving up the Andes. The mountains themselves, by forcing maritime air upwards, would also starve the rising peaks and the great Altiplano plateau of rainfall, further influencing sediment supply to the trench system. Lamb and Davies reckon that the Andes are fortuitous results of a N-S subduction zone at a continental margin, combined with its development during a period of global cooling and tropical drying.

**Geoscience consensus challenged (*December 2003*)**

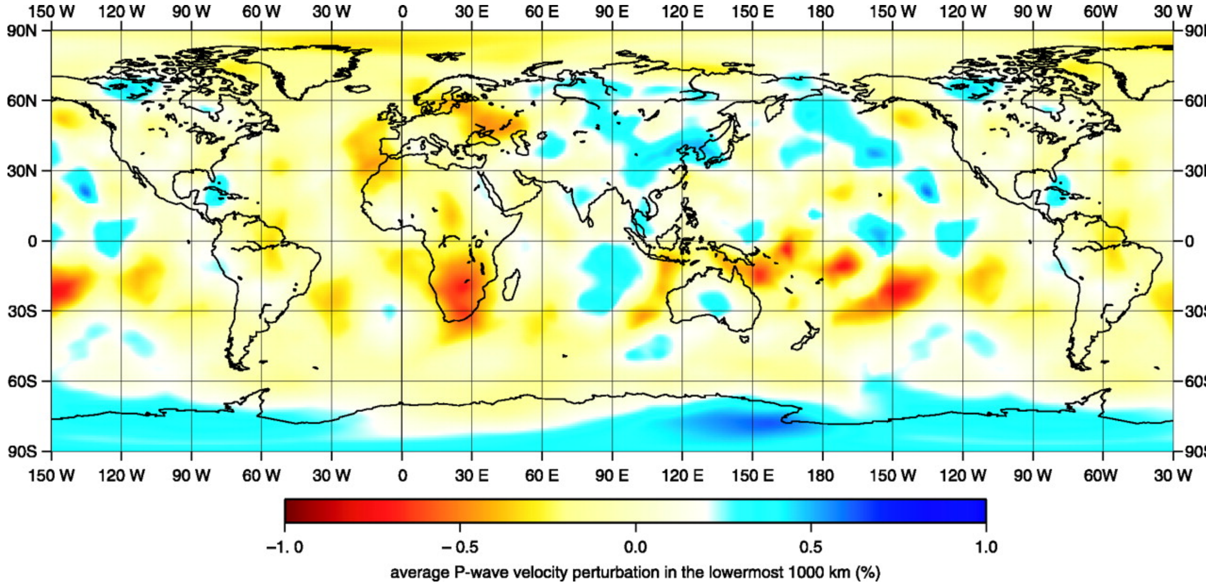
The history of science shows that what is widely agreed is often generally wrong. Yet, there is more than the temptation of cosiness, and the ease of publication that goes with it, which induces even the most imaginative scientists rarely to stick their necks out. In their overthrow of the geocentric view of the cosmos, Copernicus, Galileo and Kepler felt ideological pressures that we can only guess at. Colleagues of Copernicus had been burnt at the stake, so he hid himself for the last 40 years of his life and only dared publish his ideas so late that the galleys arrived at his deathbed. Galileo was hauled up before The Roman Inquisition in 1615. Kepler, a Protestant in the Holy Roman Empire, kept one step ahead of trouble only by networking that would have done many a modern scientist proud, and a sort of Bowdlerisation of his ideas so that they merged almost seamlessly with the prevailing ideology of both sides of European Christianity. Even the bravest, most honest and gifted scientists generally agree with their peers, simply because they rarely know any better. If they do know better, they either keep or are kept quiet. There is very little, if any objectivity in the science of any age… because it is human scientists who do it! Kepler cuddled up to Tycho de Brahe, he of the gold and silver nose (fitted after its loss through student duelling), in order to gain access to Tycho's observational data when the old feller died. He got them alright, and began to turn the universe back on its feet, thereby opening an avenue for Newton. Neither Kepler, an unstable hypochondiac who was good at geometry, but not much else, nor Tycho, an anal retentive maker of revolutionising instruments and the founder of empirical science, but devoid of ideas, would have been celebrated for four centuries if the one had not worked with the other. The evolution of science has been marked by the influence of non-conformists, but few worked in isolation against the mainstream.

One modern geoscientist who seems rarely to conform is Warren Hamilton of the Colorado School of Mines, and now he has gone for it big time (Hamilton, W.B. 2003. An alternative Earth. *GSA Today*, v. **13**(11), p. 4-12). His starting point is to challenge the consensus among geophysicists and geochemists that the mantle has a still-unfractionated lower part beneath depleted upper mantle which has sourced oceanic and continental lithosphere progressively over time. Linked to that is the notion of easy circulation of material from top to bottom through descending, subducted slabs and plumes rising from the core-mantle boundary. Hamilton says that neither exists, and that upper and lower mantle are decoupled. His challenge stems from the certainty that the Earth accreted "hot, fast and violently", and the strong likelihood that its Moon originated after a titanic collision of Earth with a Mars-sized planet less than 100 Ma after accretion.  Chances are it became wholly molten and suffered massive loss of volatiles.  Such a body would have fractionated rapidly, to produce a lower mantle very unlike that imagined by most geochemists and geophysicists.  Moreover, it would have remained so, partly due to its likely perovskite mineralogy, highly fractionated nature and phase-change barriers to transfer of matter – the 630, 1000 and 2000 km discontinuities.  Such an early scenario would have transferred most potassium, uranium and thorium into the outermost Earth, where the generation of radiogenic heat would have concentrated.  This is very similar to models proposed in the 1960s and early 70's by J.V. Smith and others, when lunar geochemistry, particularly that of the anorthositic highlands, set in motion ideas about a planet-wide magma ocean and global fractionation as it cooled.  Like Smith and others, Hamilton considers continental crust to have formed rapidly, sequestering a large proportion of the elements that make mantle rocks "fertile".  But only traces remain in the form of a small pinch of pre-4 Ga zircons, that could easily be lost in a single sneeze.  Much of this early sial returned swiftly to the upper mantle to make it increasingly heterogeneous – fertile parts and some not so petrogenetically prone.

The current consensus has its roots, according to Hamilton, in much older ideas about the early phases of Earth's evolution.  Harold Urey and others in the 1950s and early 60s considered the planet to have formed by slow, cold accretion of the most primitive meteoritic materials, chondrites, particularly those containing carbonaceous materials. They are petrogenetically highly fertile, and the radioactive heating of a chondritic Earth, plus that from core formation, would involve a continual, slow fractionation of the mantle that would probably still be going on today.  That this fundamental set of assumptions still dominates, though is rarely mentioned, is down to the rapidly increasing number of mantle profiles based on seismic tomography, that are claimed to have imaged seismic-speed anomalies that could be explained by both slabs and plumes extending to the core-mantle boundary.  Hamilton makes the reasonable point that the very irregular distribution of earthquakes in the top 600 km of the Earth leaves large volumes of the mantle in blind spots, and that the majority that are used are subduction related.  That, he suggests, predestines tomograph images to create artefacts that just "look" like deep penetration of descending slabs.  Moreover, stunning as they look in publications, there is much graphic sleight of hand that assigns primary colours to lower mantle anomalies that have an order of magnitude lower amplitude than those at shallower depths, as well as filling unimaged areas with average or interpolated values, placement of sections to look most plausible, and a great deal of data filtering.  There is a "fudge factor" that hypes the hoped-for, and avoids alternative data analysis – you can't do this kind of thing on a PC.  The plume hypothesis is falsified exactly where it ought not to be – in the Emperor-Hawaiian seamount chain (see *Wandering hot spots* above).  There the great bend dated at 45 Ma is not matched by any known change in the direction of Pacific sea-floor spreading.  The magma source for the chain might well be a restricted volume of mantle, but it didn't stay still as a plume must. Seismic tomography, at the time Hamilton's essay went to press, had not verified a single plume sourced in the lower mantle – there are many cases of volcanic hotspots without any plume, and tomographically inferred hot mantle doesn't always have a volcanic expression.

Hamilton's essay is worth reading in its entirety, as it reviews the whole of Earth's tectonic and magmatic evolution.  I have just tried to pick out the critical aspects here.

**More, or less plumes (*December 2003*)**




Deviation from the average P-wave speed in the lowermost 1000 km of the mantle. The negative values suggest the sites of hot, rising plumes. (Credit: Montelli *et al*. 2004; Fig. 1)

In view of Warren Hamilton's questioning the existence of mantle plumes (see *Geoscience consensus challenged* above), in the same month as his essay appeared a team of seismologists from the universities of Princeton, California, Colorado and the National Taiwan University used a new approach to seismic tomography to seek evidence for plumes (Montelli, R. *et al*, 2004. Finite-frequency tomography reveals a variety of plumes in the mantle. *Science*, v. **303**, p. 338-343; DOI: 10.1126/science.1092485). They present evidence for 32 suspected plumes. Some have a seismic expression at shallower depths than 650 km in the mantle, such as beneath Iceland and the Galapagos. Others seem to reach as deep as the core-mantle boundary, as beneath Hawaii and the Kerguelen Plateau. In fact most of the classic volcanic hotspots that have associated chains appear to have plumes beneath them, with the exception of Yellowstone. An apparent duality of shallow and deep plumes suggests to the authors a two-tier division in vertically moving mantle, above and below the 660 km discontinuity. The long-suspected major plumes beneath Africa and the Pacific also appear to spawn lesser plumes that in turn sometimes split