

Tectonics

The timing of ups and downs of metamorphism (*January 2011*)

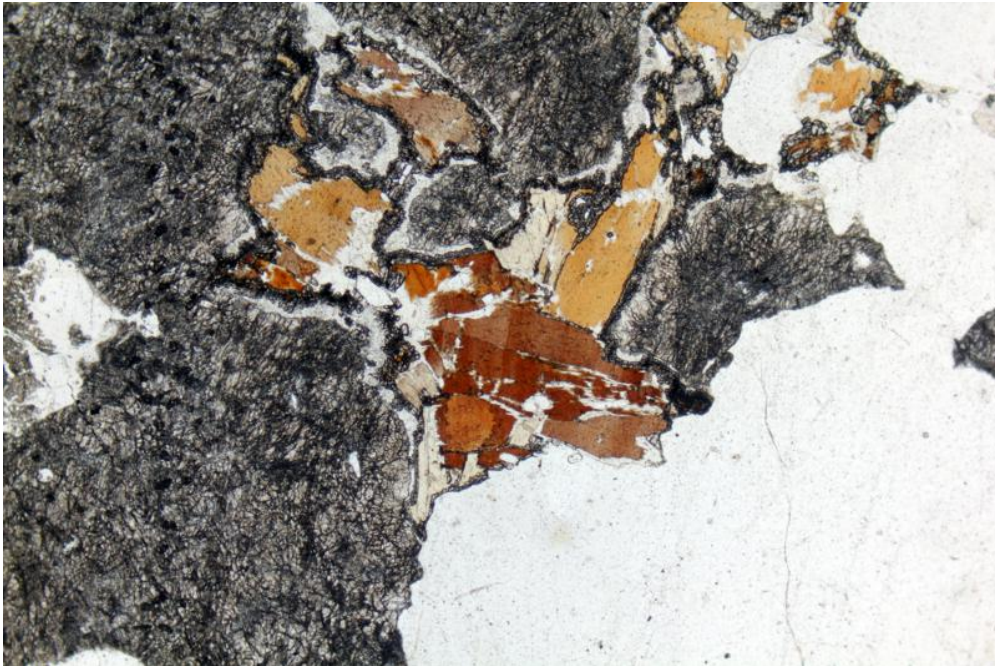
As the temperature and pressure affecting crustal rocks go up and down. For example, in the thickening of crust when two continents collide and then erosion strips off the cover so that the rocks slowly rise, the rocks undergo progressive changes in their mineral content; in both cases they are metamorphosed. Rising intensity of conditions gives rise to a prograde metamorphic sequence, and when they wane [retrograde metamorphism](#) takes place as the elements that combine in minerals react to adjust to new conditions. In some cases it is possible to use the mineral assemblages, specifically the proportions of different elements that are shared between two or more minerals, to chart the changes in temperature and pressure. That reveals the path taken by the rock through temperature- and pressure space, which is effectively a measure of the crustal processes involved and the geothermal conditions under which they acted: a P-T path. Adding the timing to give a sort of movie to all the changes has been hit-or-miss up to now, and based on radiometric ages from igneous rocks formed and emplaced during the metamorphic evolution.

Thanks to the finely targeted mass spectrometry that an ion microprobe can achieve, adding the 't' dimension is now possible from the metamorphic rocks themselves (Sajeev, K. *et al.* 2010. Sensitive high-resolution ion microprobe U-Pb dating of prograde and retrograde ultrahigh-temperature metamorphism exemplified by Sri Lankan granulites. *Geology*, v. **38**, p. 971-974; DOI: 10.1130/G31251.1). Minerals based on the element zirconium (Zr), such as zircon and monazite are extremely resistant to the effects of temperature as regards the radioactive and radiogenic elements that they contain, specifically uranium (U) and thorium (Th) and the lead (Pb) isotopes that form when ^{235}U , ^{238}U and ^{232}Th decay. Both these minerals become zoned as successive layers grow during metamorphism, and the ion microprobe can measure the isotopic composition on a later-by-layer and therefore event-by-event basis. The famous granulites (charnockites) of the island of Sri Lanka (Ceylon) reached the peak of their metamorphism (1050°C and 0.9 GPa) at ~570 Ma and began to retrogress about 20 Ma later around the start of the Cambrian. Previously it was not possible to separate metamorphic ages from those when the original rocks formed in the Archaean and early Neoproterozoic. Such high temperatures are very difficult to attain in the crust under normal geothermal conditions unless extra heat is added by large volumes of basaltic magma ponding at the base of the crust during crustal thickening.

Bouncing back from the deep (*May 2011*)

Because the average density of the rocks making up the continental crust is about 2.7 t m^{-3} while that of the mantle is greater than 3.0 t m^{-3} it might seem as though continents cannot be subducted. Indeed, that was one of the first principles of plate tectonics, which would account for continental crust dating back to 4000 Ma, whereas there is no oceanic crust older than about 150 Ma. Yet in the southern foothills of the Alps in Piemonte, Italy is a site which refutes the hypothesis in a stunning fashion. The minor ski resort of Monte Mucrone is backed by cliffs in what to all appearances is a common-or-garden granite: it even seems to contain phenocrysts of plagioclase feldspar. Microscopic examination of the megacrysts

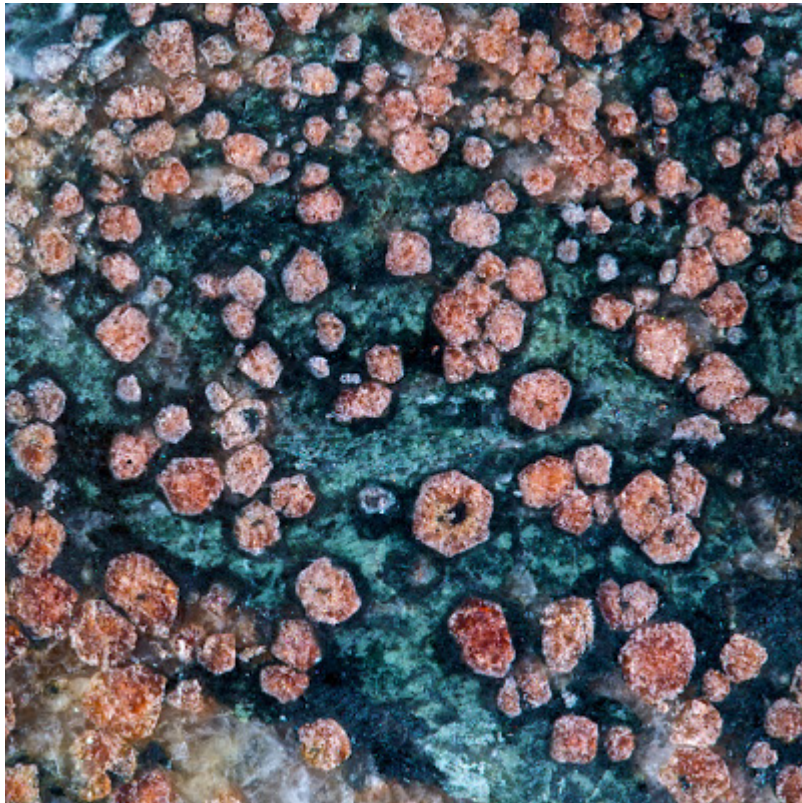
reveals them to be made up of a complex intergrowth between jadeite, a high-pressure sodic pyroxene, and quartz. This is exactly what should form if albite, the sodium-rich kind of plagioclase feldspar, descended to over 70 km below the surface, i.e. to mantle depths. Monte Mucrone proves that continental materials can be subducted, but also reveals that these granites popped back up again when the forces of subduction were relieved at the end of the Alpine orogeny. Other examples have since turned up, but few so spectacular as continental rocks from Switzerland (Herwartz, D. *et al.* 2011. [Tracing two orogenic cycles in one eclogite sample by Lu-Hf garnet chronometry](#). *Nature Geoscience*, v. 4, p. 178-183; DOI: 10.1038/ngeo1060).



Grey, high-relief jadeite pseudomorphs of albite in the Monte Mucrone granite

The Adula nappe of the Swiss Lepontine Alps consists of granitoid gneisses and metasediments of continental affinities, associated with mafic and ultramafic metamorphic rocks. The mafic rocks include eclogites formed by the high-pressure, low-temperature metamorphism characteristic of subduction. Their minerals record formation temperatures around 680°C at a depth of more than more than 80 km. Eclogites are beautiful green and red rocks containing high-pressure omphacite pyroxene and pyrope garnet. Garnets generally contain abundant rare-earth elements especially those with the highest atomic numbers. One of these is lutetium (Lu) that has a radioactive isotope ^{176}Lu with a half-life of 3.78×10^{10} years to yield a daughter isotope of hafnium ^{176}Hf ; garnets can be dated using this method. Garnets are frequently zoned, and the Adula eclogites clearly show several generations of zonation. Zoning can form as metamorphic conditions change, so in itself is not unusual, but dating different generations is. The German team from the Universities of Bonn, Cologne and Münster found that the garnets defined two distinct isochrons, one of Variscan age of just over 330 Ma, the other Alpine around 38 Ma. Clearly the pre-Variscan crust (probably once part of the African continent) had been subducted twice but had wrested itself clear of the mantle's clutches on both occasions, each time remaining more or less intact. One idea that stems from this coincidence is that the Variscan mountain belt that formed at the earlier subduction zone subsequently split at its high P – low T core, so that

the eclogites lay at a new continental margin and could suffer the same extreme compression when new subduction began there.



Typical eclogite from the Czech Republic (Credit: Ian Stimpson)

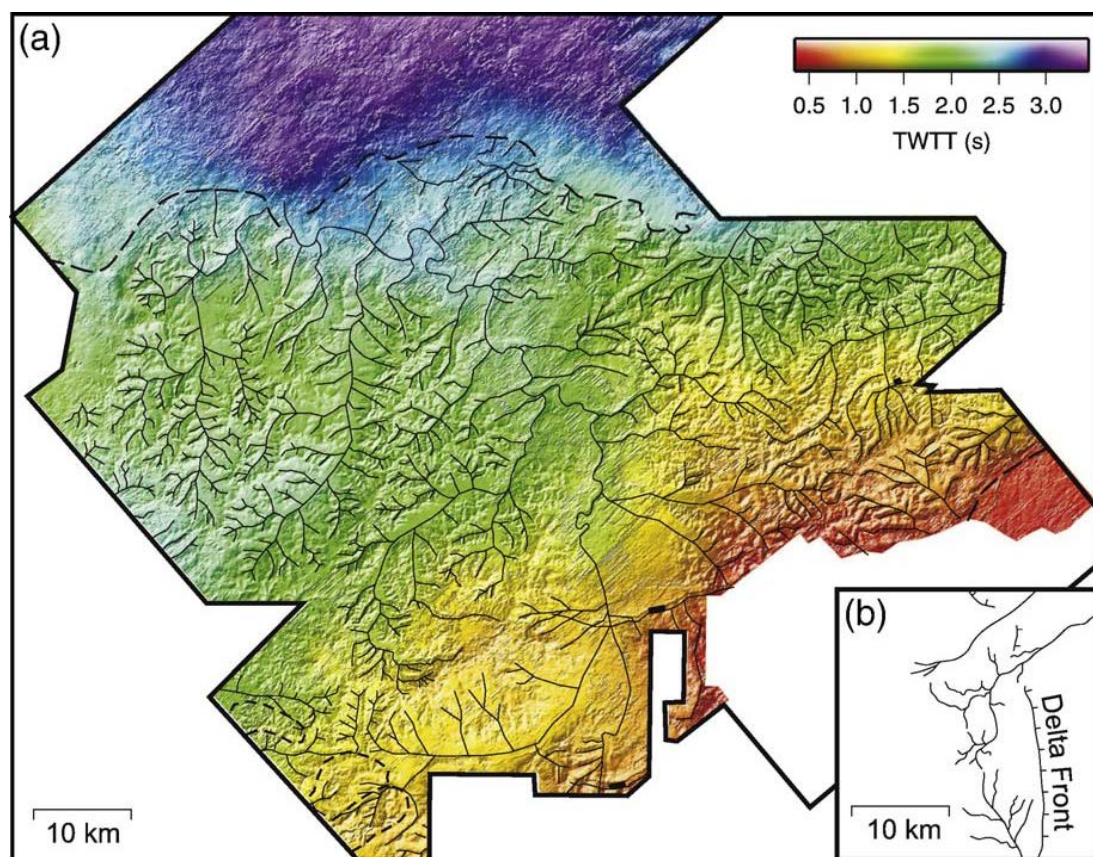
It also turns out that the region in which Monte Mucrone lies, the Sesia zone of the Western Alps, also records a double whammy of continental subduction, but a repetition that occurred during the early events of the Alpine orogeny (Rubatto, D. *et al.* 2011. [Yo-yo subduction recorded by accessory minerals in the Italian Western Alps](#). *Nature Geoscience*, v. **4**, p. 338-342; DOI: 10.1038/NCEO1124). The team of Australian, Swiss and Italian geologists focused on the P-T record preserved in zoned garnets, allanites and zircons and evidence for two generation of white micas in eclogites and blueschists. Backed by U-Pb dating of zircon and allanite zones, the authors uncovered two episodes of deep subduction separated by period of rapid exhumation over the period between 79 to 65 Ma ago. The double subduction took place while the African plate converged obliquely with Eurasia; a strike-slip configuration that probably resulted in large-scale switches from compression to extension.

See also: Bruekner, H.K. 2011. Double-dunk tectonics. *Nature Geoscience*, v. **4**, p. 136-138; DOI: 10.1038/ngeo1063

Bulges that move (May 2011)

In 2008 a team of geophysicists from Cambridge University, UK published an astonishingly detailed picture of about 500 km² of a land surface complete with drainage systems (see image below from Rudge, J.F. *et al.* 2008. A plume model of transient diachronous uplift at the Earth's surface. *Earth and Planetary Science Letters*, v. **267**, p. 146-160; DOI: 10.1016/j.epsl.2007.11.040). The surprise was not its Palaeogene age (~55 Ma), but that it

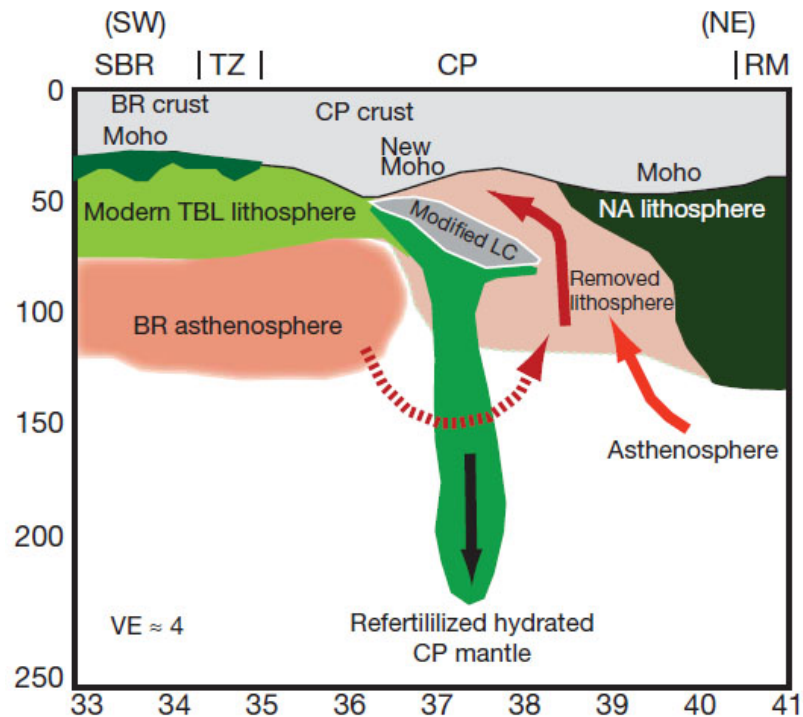
is buried beneath the Atlantic continental shelf about 200 km west of the Shetland Isles and had been revealed by detailed, 3-D seismic reflection surveys during oil exploration. Technically it is buried landscape unconformity that resulted from uplift (by almost 500 m) and erosion (for ~1.3 Ma) that interrupted Palaeocene to Eocene marine sedimentation. It was suddenly buried to preserve the details of river channels: uplift rapidly gave way to subsidence and conditions returned to marine about 0.6 Ma later. The timing and the location of such a transient crustal bulge, during the early part of opening of the North Atlantic, suggests that it stemmed from a thermal source, probably the Iceland hot spot straddled by the mid-Atlantic Ridge. The model favoured by the authors is radially horizontal spreading of a pulse of especially hot mantle outwards from the plume beneath the Iceland hot spot; a 'plume head'. Volumetric expansion of the lithosphere causes the uplift, and movement away from the plume of the hot mantle results in an annular, outward moving ripple. Cooling once the thermal source has passed produces subsidence.



Topography of a buried Palaeogene surface in the Faeroe-Shetland Basin – elevation given in seismic two-way time. (Credit: Rudge *et al.* 2008; Fig. 3)

The idea clearly has 'legs' for a whole number of reasons, not the least being the sheer number of long-lived hot spots above mantle plumes that affect the ocean basins and parts of the continents, Africa and North America especially. Now it has been publicised more widely than in a specialised journal (Williams, C. 2011. [Pulsating planet: superhot rocks make the Earth roll](#). *New Scientist*, v. **209** (12 March 2011), p. 41-43). One of the original authors is reported to have suggested that the ~55 Ma thermal ripple beneath the nascent North Atlantic may have destabilised gas hydrates in the sediments causing methane to belch out in its wake. That is a possible mechanism for the Palaeocene-Eocene thermal

maximum and its huge associated carbon isotope ‘spike’ likely stemming from boosted atmospheric methane.



Drip of lithosphere beneath the Colorado Plateau, inferred from USArray seismograph data.
(Credit: levander *et al.* 2011; Fig. 4c)

Probably the most famous bulge of the Earth’s surface is the one through which the Colorado River has carved the USA’s 1.8 km deep Grand Canyon: the Colorado Plateau. Long believed to have formed above hot, low-density lithosphere too, this uplift is the subject of completely new ideas that have also stemmed in part from seismic data, though not produced by artificial reflectance methods. Geophysicists in the US have developed a system that uses hundreds of transportable seismometers that are being ‘marched’ from west to east as an array that uses seismographs from natural earthquakes world-wide to perform seismic tomography –3-D mapping of varying seismic velocities and thereby rigidity and density in the mantle – with improved resolution because of the close spacing of the recording stations. Publications from the Earthscope USArray are beginning to appear from the western USA, one of which concerns the Colorado Plateau (Levander, A.*et al.*, 2011. [Continuing Colorado plateau uplift by delamination-style convective lithospheric downwelling](#). *Nature*, v. **472**, p. 461-465; DOI: 10.1038/nature10001). The western part of the plateau is associated with a high-velocity anomaly that extends to around 90m km beneath, which the authors ascribe to a large blob of rigid mantle that has detached from the lithosphere and is slowly sinking. This ‘drip’ is an example of delamination where mantle that becomes detached from the lithosphere causes it to thin and reduces its overall density. The overlying crust rises in response. There is a thermal effect, as warmer, less rigid asthenosphere convects upwards to fill the gap left by the drip, but it is an effect rather than a cause of the uplift.

See also: Zandt, G. & Reiners, P. 2011. Lithosphere today... *Nature*, v. **472**, p. 420-421; DOI: 10.1038/472420a.

Tectonic risk analysis: Atlantic subduction due any time soon! (July 2011)

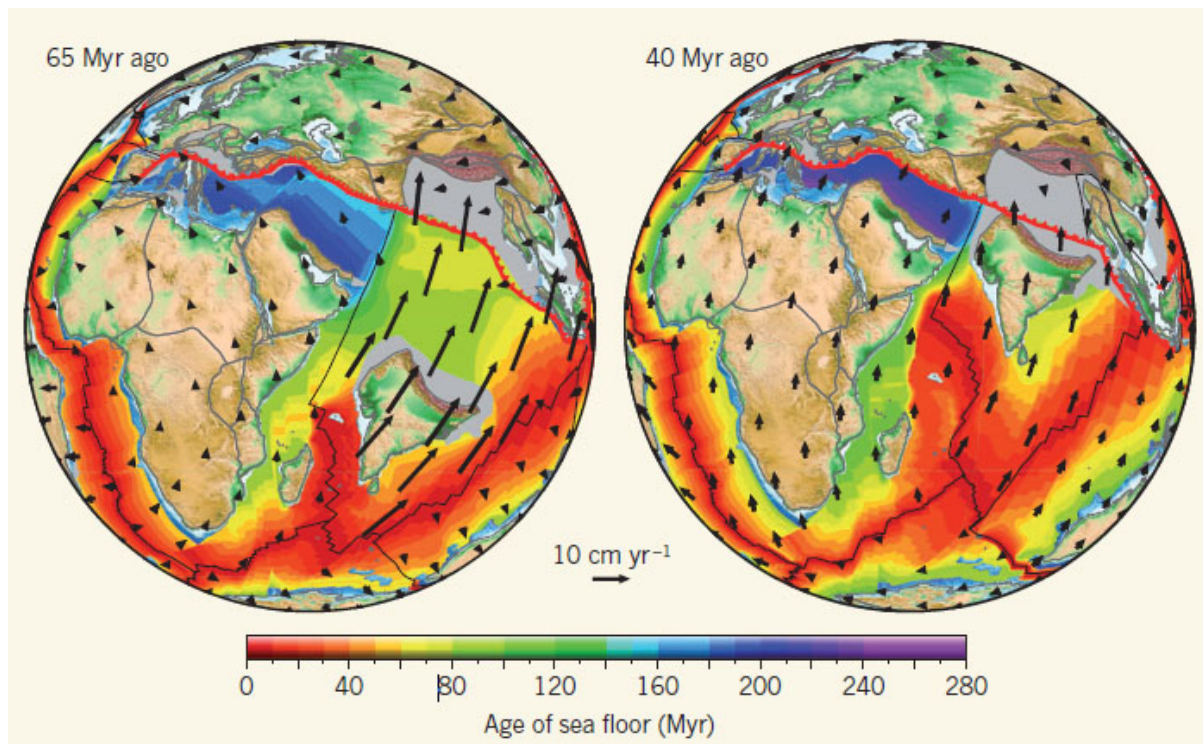
Earthquake prediction has not had a good record, but it seems that vastly larger tectonic processes are now becoming the subject of risk analysis (Nikolaeva, K. *et al.* 2011. [Numerical analysis of subduction initiation risk along the Atlantic American passive margins](#). *Geology*, v. **39**, p. 463-466; DOI: 10.1130/G31972.1). The Swiss, Russian and Portuguese authors focus on the old (Jurassic ~170 Ma) and presumably cold oceanic lithosphere on the western flank of the Atlantic, against both the North and South American continents. Increased density with ageing imparts a potential downwards force, but that has to overcome resistance to plate failure at passive margins. The dominance of upper continental lithosphere by rheologically weak quartz tends to make it more likely to fail than more or less quartz-free oceanic lithosphere. So, if subduction at a passive continental margin is to take place, then where and when it begins depends on the nature of the abutting continental lithosphere. That on the Atlantic's western flank varies a lot, and ranges from 75-150 km thick. Consequently the temperature at the Moho, the junction between continental lithosphere and weaker asthenosphere, varies too. The loading by marginal sedimentation also plays a role, as do continent-wide forces associated with far-distant mountain ranges, such as the Western Cordillera and Andes, and the forces from opposed sea-floor spreading from the Juan de Fuca and East Pacific systems that affect the whole of western South America, most of Central America and the far NW of North America.

Analysing all pertinent forces acting along 9 lines of section through both North and South America, the authors' focus fell on the relatively thin continental lithosphere of the Atlantic margin of South America. It is at its thinnest along the southernmost part of the margin adjacent to Brazil, where the Moho temperature reaches as high as 735°C. This is the weakest link in the American continental lithosphere, where there is seismicity and indications of igneous activity. The modelling suggests that incipient deformation may begin off southern Brazil within 4 Ma to form a zone of overthrusting, eventually evolving towards failure of the ocean-continent interface and the start of proper subduction in the succeeding 20 Ma. Other stretches of the eastern Americas are deemed safe from subduction for considerably longer by virtue of their greater thickness, lower Moho temperatures and thus higher strength. It is an interesting situation because, insofar as I understand plate tectonics, extensional or compressional failure needed to generate plate boundaries must also propagate from the weak spots that first fail; plate boundaries are lines not points. If that does not happen, then the very strength of the overwhelming longer continent-ocean interface will surely prevent subduction at a single, albeit weak link.

A plume drive for tectonics? (September 2011)

The theory of plate tectonics resolved Alfred Wegener's search for a force to drive continental drift around half a century after his discovery faced near-universal rejection for not having one that was large enough or plausible. Plate theory recognises many forces, both driving and in opposition to tectonic movement. By far the largest is the gravitational pull exerted by subducting slabs of dense oceanic lithosphere, followed in distant second place by ridge-push, another gravity-driven force that arises from the slope on the ocean floors away from sea-floor spreading centres as the oceanic lithosphere cools and shrinks as it ages. Until very recently, no place was assigned in the theory to forces associated with the

apparently non-tectonic plumes that rise through the mantle from far beneath the lithosphere from which plates are made, quite possibly because it seems logical to expect a vertically upwards force, if any, from hot plumes whereas plate tectonics is mainly concerned with horizontal movements. Looking around the present state of sea-floor spreading, the maximum pace at which plates move is just over 100 mm a^{-1} (100 km Ma^{-1}) in the case of the Pacific Plate. Yet, after India had been wrenched from the Gondwana supercontinent during the Late Cretaceous eventually to collide with Eurasia in the Early Palaeogene, the subcontinent experienced an extraordinary episode after 68 Ma when its pace increased to as high as 180 km Ma^{-1} .



Rapid motion of India from 65 to 40 Ma (Credit: Müller 2011; Fig. 1)

This accelerated motion continued over some 15 Ma and then equally abruptly slowed to less than 40 km Ma^{-1} around the start of the Eocene (Cande, S.C. & Stegman, D.R. 2011. [Indian and African plate motions driven by the push force of the Réunion plume head](#). *Nature*, v. **475**, p. 47-52; DOI: 10.1038/nature10174). The acceleration coincided with the start of continental flood-basalt volcanism that blanketed much of western India with the Deccan Traps across the K-P boundary when the subcontinent lay over the site of the Réunion hot spot. Coincidentally, the Réunion plume head formed at that time; i.e. the Indian continental lithosphere did not drift over an active plume, but was hit from below by one that happened to be rising to the surface. Curiously, while the Indian plate was accelerated, nearby Africa was slowed, explained by a push in the same direction of India's travel towards a subduction zone beneath Asia and one applied to Africa that opposed its motion. Africa too resumed its usual tectonic progress at the start of the Eocene. But how did a mantle plume exert such a force: was it because it caused a local bulge from which the plates slid, or did mantle motion associated with the mushroom-like structure of the horizontally growing plume head exert viscous drag on the overlying plates? Such shifts in motion of major plates inevitably have an effect on the whole plate tectonic carapace, and the authors list a number of contemporary, distant consequences, speculating that the

famous bend in the Hawaii-Emperor island and sea-mount chain in the Early Eocene (~50 Ma) resulted from the final waning of the Réunion plume head's influence and major readjustment of tectonics (see [The Great Bend of the Pacific ocean floor](#) May 2009)

See also: Müller, R.D. 2011. [Plate motion and mantle plumes](#). *Nature*, v. **475**, p. 40-41; DOI: 10.1038/475040a.

Pristine mantle and basalt floods (September 2011)

Plot the ages of major extinctions against those of flood basalt events and you will get a straight line graph for six co-occurrences since 250 Ma, with very little error. Although the exact mechanism for mass death of species and families is argued over interminably, for those six, flood basalt events have to be deeply implicated. There again, every geologist and their aunties dispute the mechanisms behind monster basalt effusions that re-pave whole landscapes beneath flow after flow and create very distinctive landforms. When they are eroded they form regularly stepped mountain sides, hence their formerly popular name trap basalts, after the Swedish word *trappa* meaning staircase. There is a hint of cyclicity in their age distribution. But most important of all, no-one has witnessed these vast, pulsating events, the last having mantled the surroundings of the Columbia and Snake River catchments in the US states of Oregon and Washington between 14-17 Ma ago in the Middle Miocene. Some mark episodes of continental break-up, such as those flanking the Central Atlantic at the time of the end-Triassic (~200 Ma) mass extinction, while others are associated with hot spots, such as the Deccan Traps of western India erupted between 60-68 Ma as India drifted over the Reunion hot-spot and those of the Ethiopian highlands (30 Ma) associated with the Afar hot spot.



Columbia River flood basalts, Washington State US (Credit: Anja Schmidt)

A common geochemical feature is beginning to emerge concerning the mantle from which the basalts were partially melted. Six sets of flood basalts exhibit the same trace-element and isotopic (Nd, Pb, Hf and He) characteristics, which suggest that their source had been little effected by previous extraction of crust-forming magmas; it is primitive and may be a relic of the original mantle formed shortly after the catastrophic collision between the early Earth and a wandering Mars-sized planet that flung off the Moon (Jackson, M.G. & Carlson, R.W. 2011. [An ancient recipe for flood basalt genesis](#). *Nature*, v. **476**, p. 316-319; DOI: 10.1038/nature10326). Although undepleted, the chemistry of the mantle source, worked out by back-calculation from that of the flood basalts, is not the same as the once-postulated original accretion of carbonaceous chondrite meteorites, conceivably a result of the chemical reworking when the Moon formed and the remaining Earth was probably molten from top to centre. The important feature is that the recast chemistry is rich in heat-producing elements compared with the source of 'common-or-garden' basalts that continually contribute to the ocean floors and island arcs. Wherever the relic mantle is, it is capable of heating itself, over and above the heating from the core and surrounding mantle, and thus likely to generate thermal and material plumes rising through the mantle.

Preceding the work of Jackson and Carlson, another group discovered that when flood basalt events since the Carboniferous are restored to their former geographic positions at the time they were erupted, they cluster above what are now two patches of more ductile mantle close to the core-mantle boundary (Torsvik, T.H. *et al.* 2010. Diamonds sampled by plumes from the core–mantle boundary. *Nature*, v. **466**, p. 352–355; DOI: 10.1038/nature09216). If that is the source of basalt flood-forming plumes, then it is still there and, aside from giant impacts with extra-terrestrial projectiles, the most catastrophic upheavals of the Earth system inevitably will continue, perhaps in the next few million years.

Plate tectonics monitored by diamonds (September 2011)

For more than 30 years a debate has raged about the antiquity of plate tectonics: some claim it has always operated since the Earth first acquired a rigid carapace not long after a molten state following formation of the Moon; others look to the earliest occurrences of island-arc volcanism, oceanic crust thrust as ophiolite complexes onto continents, and to high-pressure, low-temperature metamorphic rocks. The earliest evidence of this kind has been claimed from as far apart in time as the oldest Archaean rocks of Greenland (3.9 Ga) and the Neoproterozoic (1 Ga to 542 Ma).

A key feature of plate interactions that can be preserved are high-P, low-T rocks formed where old, cool oceanic lithosphere is pulled by its own increasing density into the mantle at subduction zones to form eclogites and blueschists. In the accessible crust, both rock types are unstable as well as rare and can be retrogressed to different metamorphic mineral assemblages by high-temperature events at lower pressures than those at which they formed. Relics dating back to the earliest subduction may be in the mantle, but that is physically inaccessible. Yet, from time to time explosive magmatism from very deep sources brings mantle-depth materials to the surface in kimberlite pipes that are most commonly found in stabilised blocks of ancient continental crust or cratons. Again there is the problem of mineral stability when solids enter different physical conditions, but there is one mineral that doggedly preserves characteristics of its deep origins – diamond. Steven Shirer and Stephen Richardson of the Carnegie Institution of Washington and the University of Cape

Town have shed light on early subduction by exploiting the relative ease of dating diamonds and their capacity for preserving other minerals captured within them (Shirey, S.B. & Richardson, S.H. 2011. [Start of the Wilson cycle at 3 Ga shown by diamonds from the subcontinental mantle](#). *Science*, v. **333**, p. 434-436; DOI: 10.1126/science.1206275).

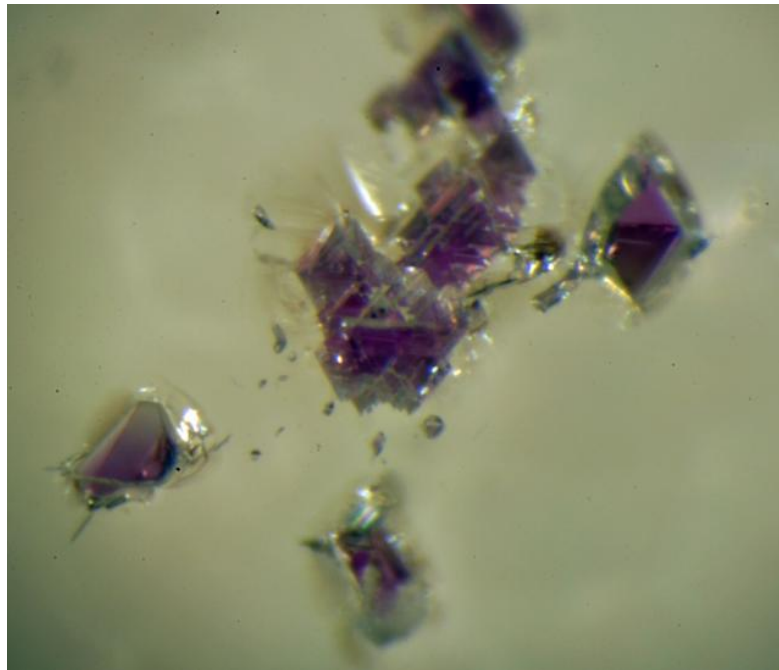
Their study used data from over four thousand silicate inclusions in previously dated large diamonds, made almost worthless as gemstones by their contaminants. It is these inclusions that are amenable to dating, principally by the Sm-Nd method. Adrift in the mantle high temperature would result in daughter isotopes diffusing from the minerals. Once locked within diamond that isotopic loss would be stopped by the strength of the diamond structure, so building up with time to yield an age of entrapment when sampled. The collection spans five cratons in Australia, Africa, Asia and North America, and has an age spectrum from 1.0 to 3.5 Ga. Note that diamonds are not formed by subduction but grow as a result of reduction of carbonates or oxidation of methane in the mantle at depths between 125 to 175 km. In growing they may envelop fragments of their surroundings that formed by other processes.

A notable feature of the inclusions is that before 3.2 Ga only mantle peridotites (olivine and pyroxene) are trapped, whereas in diamonds younger than 3.0 Ga the inclusions are dominated by eclogite minerals (garnet and Na-, Al-rich omphacite pyroxenes). This dichotomy is paralleled by the rhenium and osmium isotope composition of sulfide mineral inclusions. To the authors these consistent features point to an absence of steep-angled subduction, characteristic of modern plate tectonics, from the Earth system before 3 Ga. But does that rule out plate tectonics in earlier times and cast doubt on structural and other evidence for it? Not entirely, because consumption of spreading oceanic lithosphere by the mantle can take place if basaltic rock is not converted to eclogite by high-P, low-T metamorphism when the consumed lithosphere is warmer than it generally is nowadays – this happens beneath a large stretch of the Central Andes where subduction is at a shallow angle. What Shirey and Richardson have conveyed is a sense that the dominant force of modern plate tectonics – slab-pull that is driven by increased density of eclogitised basalt – did not operate in the first 1.5 Ga of Earth history. Eclogite can also form, under the right physical conditions, when chunks of basaltic material (perhaps underplated magmatically to the base of continents) founder and fall into the mantle. The absence of eclogite inclusions seems also to rule out such delamination from the early Earth system. So whatever tectonic activity and mantle convection did take place upon and within the pre-3 Ga Earth it was probably simpler than modern geodynamics. The other matter is that the shift to dominant eclogite inclusions appears quite abrupt from the data, perhaps suggesting major upheavals around 3 Ga. The Archaean cratons do provide some evidence for a major transformation in the rate of growth of continental crust around 3 Ga; about 30-40 percent of modern continental material was generated in the following 500 Ma to reach a total of 60% of the current amount, the remaining 40% taking 2.5 Ga to form through modern plate tectonics.

The ultra-deep carbon cycle

The presence of diamonds in the strange, potassium-rich, mafic to ultramafic igneous rocks known as kimberlites clearly demonstrates that there is carbon in the mantle. But it could have come from either biogenic carbon having moved down subduction zones or the original meteoritic matter that accreted to form the Earth. Both are distinct possibilities for

which evidence can only be found within diamonds themselves as inclusions. There is a steady flow of publications focussed on diamond inclusions subsidised to some extent by companies that mine them (see *Plate tectonics monitored by diamonds* above). The latest centres on the original source rocks of kimberlites and the depths that they reached (Walter, M.J. and 8 others 2011. [Deep mantle cycling of oceanic crust: evidence from diamonds and their mineral inclusions](#). *Science*, v. **334**, p. 54-57; DOI: 10.1126/science.1209300). The British, Brazilian and US team analysed inclusions in diamonds from Brazil, finding assemblages that are consistent with original minerals having formed below the 660 km upper- to lower-mantle seismic boundary and then adjusting to decreasing pressure as the kimberlite's precursor rose to melt at shallower levels. The minerals – various forms of perovskite stable at deep-mantle pressures – from which the intricate composites of several lower-pressure phases exsolved suggest the diamonds originated around 1000 km below the surface; far deeper than did more common diamonds. Moreover, their geochemistry suggests that the inclusions formed from deeply subducted basalts of former oceanic crust.



Majoritic garnet inclusions in diamond, from 300-700 km. (Credit: deepcarbon.net)

Previous work on the carbon isotopes in ‘super-deep’ diamonds seemed to rule out a biogenic origin for the carbon, suggesting that surface carbon does not survive subduction into the lower mantle. In this case, however, the diamonds are made of carbon strongly enriched in light ^{12}C relative to ^{13}C , with $\delta^{13}\text{C}$ values of around -20 ‰, which is far lower than that found in mantle peridotite and may have been subducted organic carbon. If that proves to be the case it extends the global carbon cycle far deeper than had been imagined, even by the most enthusiastic supporters of the Gaia hypothesis.

Pan African review (November 2011)

Undoubtedly the best exposed and one of the biggest examples, the accretionary orogen of the [Arabian-Nubian Shield](#) (ANS) is a witness to the creation of a supercontinent from the remnants of an earlier one. At about 1 Ga, most of the Earth's continental material was

clumped together in the [Rodinia](#) supercontinent that existed for a quarter of a billion years. At a time of massive mantle upheaval that left most crust of that age affected by basaltic magmatism, in the form of lava flows and dyke swarms, Rodinia began to break up at 800 Ma to scatter continental fragments. Subduction zone accommodated this continental drift to form many ocean and continental-margin volcanic arcs. The ANS is a repository for many of these arcs which episodically accreted between earlier cratons to the west in Africa and those comprising Somalia and the present Indian subcontinent. Primarily the terranes are oceanic in origin and formed in the aftermath of the dismemberment of Rodinia, although a few slivers of older, reworked crust occur in Saudi Arabia and Yemen. Among the various components are ophiolites marking sutures and other major tectonic features of the orogen. The shape of the Shield is unlike that of any other major orogen of later times, for it shrinks from a width estimated at ~2000 km in Arabia to the north to vanish just south of the Equator in southern Kenya. This 'pinched' structure has suggested to some that the bulk of the new crust was forced laterally northwards when the African and Indian cratons collided, in the manner of toothpaste from a trodden-on tube.



A terrane boundary close to the Nile in the Sudan, detected by radar from the Space Shuttle: the Keraf Suture. (Credit: NASA)

Today the ANS is a harsh place, some off-limits to geologists either for political reasons or the sheer hostility and remoteness of the environment. Yet a picture has emerged, bit by bit, over the last 30 years. So a detailed review of the most extensive and varied part from 7° to 32°N and 26° to 50°E – in Egypt, Saudi Arabia, eastern Sudan, Eritrea, Yemen and northern Ethiopia is especially welcome (Johnson, P.R. *et al.* 2011. [Late Cryogenian–Ediacaran history of the Arabian–Nubian Shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen](#). *Journal of African Earth Sciences*, v. **61**, p. 167-232; DOI: 10.1016/j.jafrearsci.2011.07.003).

Peter Johnson himself compiled a vast amount of information during his career with the US Geological Survey Mission in Saudi Arabia and has blended the inevitably diverse ideas of his 7 co-workers – but by no means all the ideas that are in the literature. The result is a readable and well illustrated account of how the ANS assembled tectonically during times when a near-global glaciation took place, and the first macroscopic animals appear in the fossil record. Tillites and other glaciogenic rocks from the Marinoan ‘SnowBall’ occur from place to place in the ANS, as do banded iron formations that made a surprise return after a billion-year or longer absence in the [Cryogenian Period](#) . Coincidentally, glacial conditions returned to the region twice in Ordovician and Carboniferous to Permian times, forming distinctive, tectonically undisturbed sediments in the Phanerozoic cover that unconformably overlies the Neoproterozoic orogen.

Except in a few areas only recently explored, geologists have assiduously dated events in the ANS, showing nicely that all the basement rock formed after 800 Ma, and that orogenic events culminated before the start of the Cambrian period, although one or two unusual granites intruded as late as the Ordovician. The deformation is immense in places, with huge nappes, often strike-slip shear zones and exposure ranging from the lowest metamorphic grade to that in which water and granitic magma was driven from the lower Pan African crust. The range of exposed crustal levels stems partly from the tectonics, but owes a lot to the 2-3 km of modern topographic relief, unique to NE Africa and Arabia. Yet it is not uncommon to come upon delicate features such as pillowed lavas, conglomerates and finely laminated volcanoclastic tuffs. Following tectonic welding, more brittle deformation opened subsiding basins that contain exclusively sedimentary rocks derived from the newly uplifted crust, both marine and terrestrial in formation (basins of this type, in Eritrea and Ethiopia, unfortunately do not figure in the regional maps). Much of the ANS is currently the object of a gold rush, encouraged by a rising world price for the ‘inflation-proof’ comfort blanket provided by the yellow metal. Consequently, newcomers to the stampede will be well advised to mug-up on the regional picture of occurrences and gold-favourable geology provided in the review, and may be interested by other exploration possibilities for rare-earth metals and other rising stars on the London Metal Exchange, such as tin, which are often hosted in evolved granites, that stud the whole region.