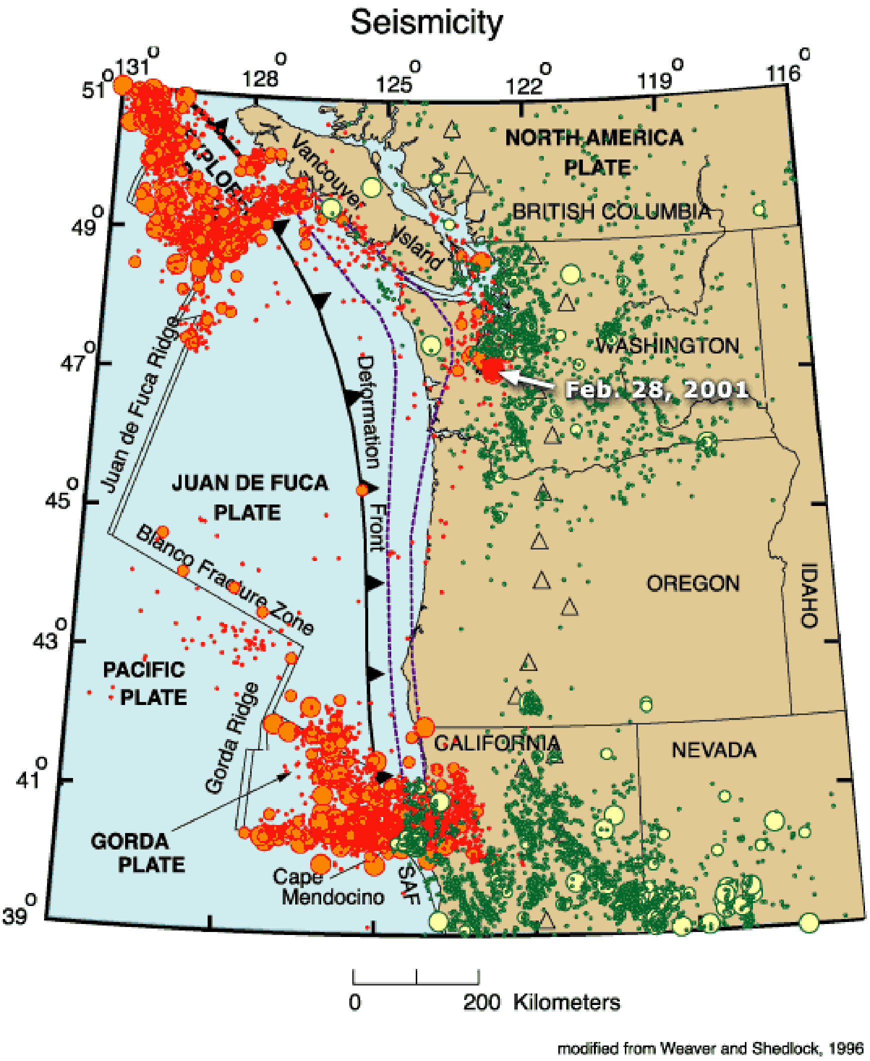
Tectonics

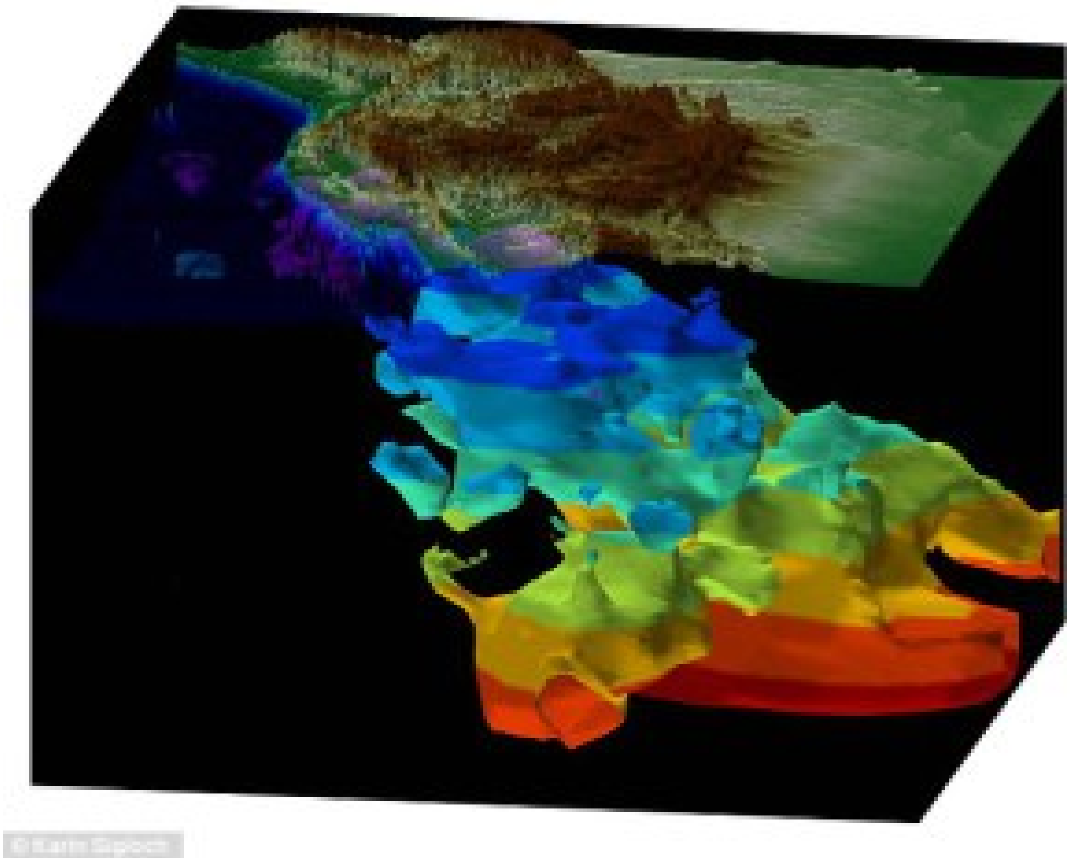
Cordilleran terrane accretion in western North America (*April 2013*)

Most of the Earth's continental material has accumulated since the end of the Hadean Eon, around 4 billion years ago. Its crudely speaking granitic composition most likely arose through a two stage magmatic process, first by oceanic lithosphere forming directly by partial melting of mantle rocks followed by subduction, dehydration of descending oceanic crust and water-induced partial melting of mantle above the subduction zone. Basalt to andesite magmas produced by the last process rose to partly crystallise in deep-crustal chambers, the residual magma of more silica-rich composition being added to the middle and upper crust. In a nutshell, that is what is currently happening in the continental magmatic arc of the Andes and also in the many volcanic island arcs that comprise much of the rest of the circum-Pacific 'ring of fire'.



Map of active subduction beneath north-western North America(credit: USGS)

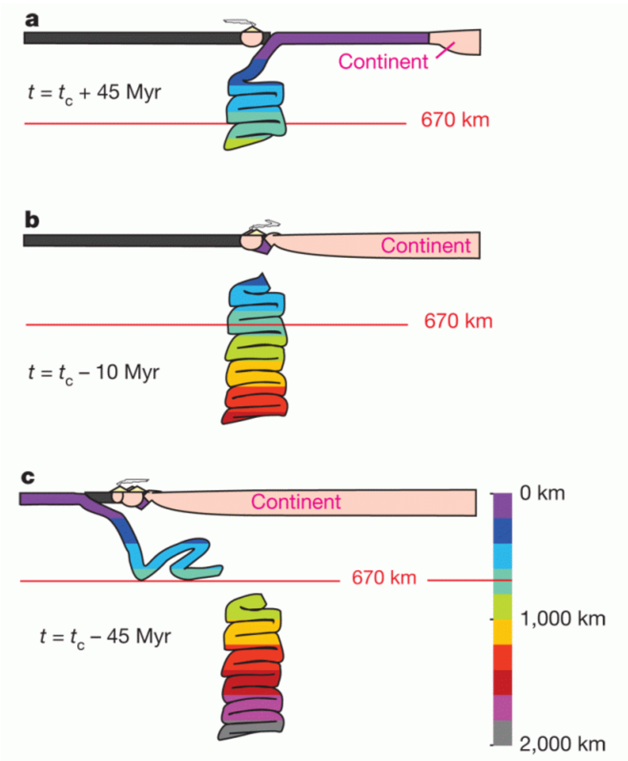
Examination of the deeper parts of much older continental crust, such as the 800 to 600 Ma old Pan African orogenic belts of NE Africa and Arabia reveals the fate of oceanic island arcs. That huge crustal sector comprises a great many linear arrays of oceanic-arc volcanic, sedimentary and plutonic rocks that now lie side by side, sometimes separated by fragments of oceanic lithosphere caught up between them as they were rammed together around 650 Ma ago. The arc terranes are sufficiently different from one another to suppose that they formed in different places far apart. Their assembly can best be explained by accretion of low-density arc crust as the intervening oceanic lithosphere disappeared down numerous subduction zones. Structures in some of the terranes and at their shared contacts with others suggests that some accretion was oblique, in the manner of large ships docking, while other assemblages met side-to-side. Similar tectonics characterise the great mid- to late-Palaeozoic orogens of eastern North America and western Europe. But one of the key areas for unravelling the range of tectonic processes involved in the assembly of continents lies in the Western Cordillera of North America, again made up of dozens of slivers of mutually exotic terranes of different kinds. The difference is that their upper parts largely remain intact and dateable using fossils or radiometric dating and through assiduous palaeomagnetic research it is sometimes possible to chart their motions over time to see the manner in which they approached and collided with one another. It is now possible to link such a complex process with underlying tectonics, not by inference but through direct observation of the remains of subducted slabs in the mantle deep beneath (Sigloch, K. & Mihalynuk, M.G. 2013. Intra-oceanic subduction shaped the assembly of Cordilleran North America. *Nature*, v. **496**, p. 50-56; DOI: 10.1038/nature12019).



The crumpled Farallon Plate beneath western North America, colours showing different depths in the mantle (credit: Karin Sigloch)

The key to achieving this breakthrough is seismic tomography of the mantle beneath North America produced from global records of seismic wave paths through the mantle and new results from a dense array of seismographs that has been ‘marched’ across the continent;

the Earthscope USArray. What is emerging are several almost vertical 'walls' of cool rock with high P-wave speeds that record the fates of at least three major subduction systems. Aligned roughly N-S they have been overridden by the North America Plate as it progressively moves westwards, driven by sea-floor spreading along the mid-Atlantic ridge. So the easternmost 'wall' is the oldest relic of subduction and that in the west from the more recent subduction that still continues beneath the NW US states and western Canada and Alaska. Sigloch and Mihalynuk explain the walls as crumpled descending slabs, 'nipped' off once each subduction system is overridden by the continent and breaks; rather like a scarf dropped vertically. So they are a great deal thicker than the originally descending oceanic lithosphere. The depth to the top of a wall is related to the age when subduction stopped. Each marks the former site of a trench and the authors have correlated each with major arc accretion events for which there is plenty of data from field geology. The outcome is a much more intricate tectonic story during the Mesozoic to early Tertiary than previously imagined. It resulted from the vagaries of the now vanished eastern complement to the Pacific Plate to the west of the East Pacific Rise, which seems to have been similar to the multiple system of island arcs now seen in the West pacific basin. There must have been flips of subduction direction as well as initiation and death of destructive margins.



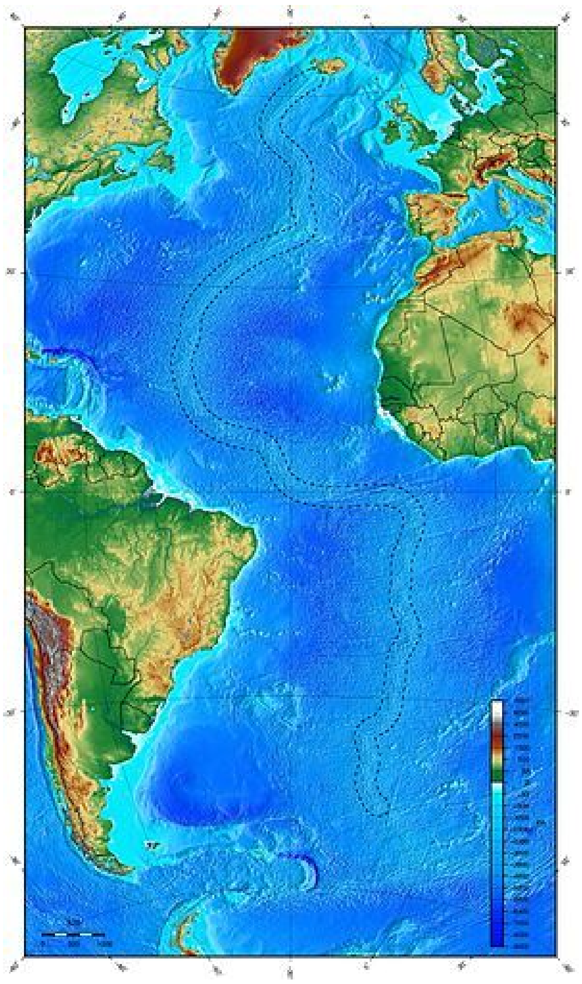
How subducted slab 'walls' might form. (credit: Sigloch & Mihalynuk 2013; Fig. 2)

Tanya Atwater, now retired, first visualised the vanished tectonics of the eastern Pacific and North America purely from on-shore geology and magnetic stripe patterns of the ocean floor more than 40 years ago in one of the most celebrated analyses of early plate theory. One can imagine how thrilled she must be to see her vision fulfilled and amplified.

Related articles: Sigloch, K. 2011. Mantle provinces under North America from multi-frequency P-wave tomography. *Geochemistry Geophysics Geosystems*, v. **12**, doi:10.1029/2010GC003421; Goes, S. 2013. Western North America's jigsaw. *Nature*, v. **496**, p.35-37

Insulation by continental crust (*May 2013*)

Way back in the mists of time, say around 1970-71, an idea was doing the rounds that because the thermal conductivity of continental crust is lower than that of the ocean floor it should allow thermal energy to build up in the mantle beneath. In turn that might somehow encourage the formation of hot spots and a shallower depth to the asthenosphere: the outcome might be to encourage rifting of weakened lithosphere and ultimately a new round of sea-floor spreading. The case often cited was the Atlantic – North and South – since there are eight hotspots currently on the mid-Atlantic ridge. Africa was another popularised case with a great many broad domes associated with Cenozoic volcanism, and the link between formation of the East African Rift System, hot spots and doming had already been suggested. Africa has barely drifted for around 100 Ma and the domes were supposed to have formed by the build up of heat in the mantle beneath. Geoscience moved on to clearly demonstrate the coincidence of large igneous provinces and flood basalt volcanism with the initiation of Atlantic spreading in the form of the Central Atlantic and Brito-Arctic LIPs during initial opening of the South and North Atlantic at the end of the Triassic and during the Palaeocene respectively. But the role of continental insulation became a bit of backwater compared with notions of mantle plumes emanating at the core-mantle boundary. Well, it's back.



The Mid-Atlantic Ridge

There is now a vast repository of ocean-floor lavas that formed at mid-ocean ridges in the past, thanks to the international Deep Sea and Ocean Drilling Programmes begun in 1968; roughly when the heyday of plate tectonics really got underway. In the last 45 years there have also been great advances in igneous geochemistry and its interpretation, including relations with mantle melting temperatures. Geochemists at the Friedrich-Alexander-Universiteit in Erlangen, Germany have re-examined the major-element geochemistry of 184 glassy ocean-floor basalts from drill sites of different ages on the floor of the Atlantic Ocean and compared them with 157 from the Pacific. To avoid the possible influence of plume-related heating, the sites were chosen well away from the tracks of existing hot spots. Mantle temperature can be assessed from the sodium and iron content of basalts, Na decreasing with higher temperatures and Fe doing the reverse (Brandl, P.A. et al. 2013. High mantle temperatures following rifting cause by continental insulation. *Nature Geoscience*, v. 6, p. 391-394; DOI: 10.1038/NGEO1758). Atlantic samples show increasing Na and decreasing Fe contents in progressively younger basalts, i.e. a trend with time of decreasing mantle temperature such that the oldest (~166 Ma) record 150°C higher mantle temperature than the youngest, with a similar result for the Indian Ocean floor. No such trend is present in samples from the same age range of the Pacific Ocean floor. At around 170 Ma the mid-Atlantic Ridge was close to the continental lithosphere of the Americas and Africa, whereas the East Pacific Rise was at least 2000 km from any continental margin. Younger Atlantic samples formed progressively further from its shores record cooling of the mantle source.
A prediction of the model is that the converse, continental accretion to form supercontinents such as Pangaea, should rapidly have caused considerable warming in the mantle beneath them. This suggests that the formation of supercontinents, or even less substantial continents, should carry the seeds of their re-fragmentation, as Africa is currently demonstrating by the separation of Arabia since the Red Sea began to open some 15 Ma ago, which Somalia and much of eastern Kenya and Tanzania seem destined to follow once the East African Rift System 'gets steam up'.

Related articles

Langmuir, C. 2013. Older and hotter. *Nature Geoscience*, v. 6, p. 332-333; DOI: 10.1038/ngeo1810.

In the mantle, wet may not imply soft (*June 2013*)

For half a century the Earth's planetary dynamism – plate movements, mantle convection and so on – has been ascribed to its abundance of water. Experiments on the ductility of quartz seemed to show that it became much weaker under hydrous conditions. That was assumed to hold for all common silicates, a view backed up by experimental deformation of minerals under varying conditions. It was widely believed that even a few parts per million of water in a deeply buried rock would weaken it by orders of magnitude, a view that increasingly dominated theoretical tectonics on scales up to the whole lithosphere and at different mantle depths. Strangely, the founding assertion was not followed up with more detailed and sophisticated work until the last year or so. The dominant mineral in the mantle is olivine and that is likely to be a major control over ductility at depth, in plumes and other kinds of convection.

Peridotite xenoliths – olivines are light green crystals, pyroxenes are darker

Experimentation at the temperatures and pressures of the mantle has never been easy, and that becomes worse for the real mineral composition of the materials being investigated, rather than artificial substitutes. High-T, high-P research tends to focus on as few variables as possible: one mineral and one variable other than P and T is the norm. This applies to the latest research (Fei, H. *et al*. 2013. Small effect of water on upper mantle rheology based on silicon self-diffusion coefficients. *Nature*, v. **498**, p. 213-215; DOI: 10.1038/nature12193) but the measurements were of the rate at which silicon atoms diffuse through olivine molecules rather than direct measurements of strain. The justification for this approach is that one of the dominant processes involved in plastic deformation is a form of structural creep in which atoms diffuse through molecules in response to stress – the other is 'dislocation creep' achieved by the migration of structural defects in the atomic lattice at a larger scale.

Contrary to all expectations, changing the availability of water by 4 to 5 orders of magnitude changed silicon diffusion by no more than one order. If confirmed this presents major puzzles concerning the dynamics of Earth's mantle and lithosphere. For instance, the weak zone of the asthenosphere cannot be a response to water and nor can the relative immobility of hotspots. Confirmation is absolutely central, in the sense of repeating Fei *et al*.'s experiments and also extending the methods to other olivine compositions – magnesium-rich forsterite was used, whereas natural olivines are solid solutions of Mg- and Fe-rich end members – and to materials more representative of the mantle, e.g. olivine plus pyroxene as a minimum (Brodholt, J. 2013. Water may be a damp squib. *Nature*, v. **498**, p. 18-182; DOI: 10.1038/498181a)

Afar: the field lab for continental break-up (*July 2013*)

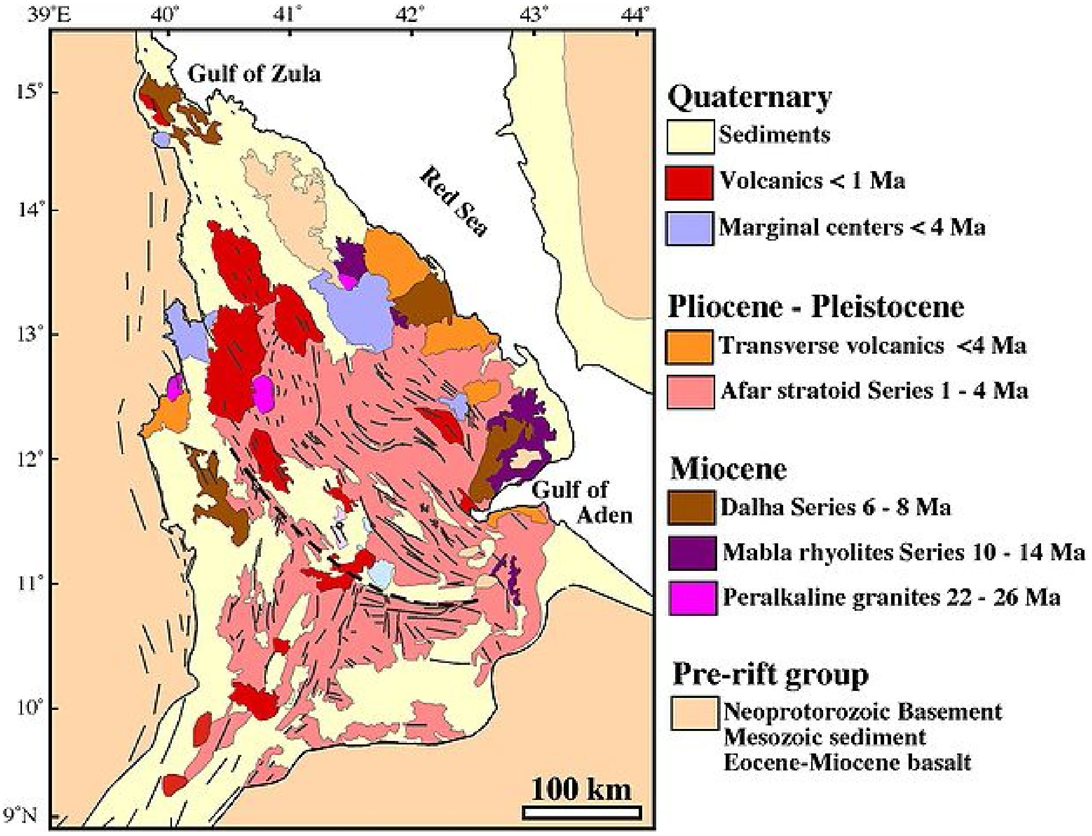
The Afar Depression of Ethiopia and Eritrea is a feature of tectonic serendipity. It is unique in showing on land the extensional processes and related volcanism that presage sea-floor spreading. Indeed it hosts three rift systems and a triple junction between the existing Red Sea and Gulf of Aden spreading centres and the East African Rift System that shows signs of future spalling of Somalia from Africa. Afar has been a focus of geoscientific attention since the earliest days of plate theory but practical interest has grown rapidly over the last decade or so when the area has become significantly more secure and safe to visit. Two recent studies seem to have overturned one of the most enduring assumptions about what drives this epitome of continental break-up.

Simulated perspective view of the Afar depression from the south

From the obvious thermal activity deep below Afar, linked with volcanism and high heat flow, a mantle host spot and rising plume of deep mantle has been central to ideas on the tectonics of the area. A means of testing this hypothesis is the use of seismic data to assess the ductility and temperature structure of deep mantle through a form of tomography. The closer the spacing of seismic recording stations and the more sensitive the seismometers are the better the resolution of mantle structure. Afar now boasts one of the densest seismometer networks, rivalling the Earthscope USArray and it is paying dividends (Hammond, J.O.S. and 10 others 2013. Mantle upwelling and initiation of rift segmentation beneath the Afar Depression. *Geology*, v. **41**, p. 635-638; DOI: 10.1130/G33925.1). The study brought together geoscientists from Britain, the US, Ethiopia, Eritrea and Botswana, who used data from 244 seismic stations in the Horn of Africa to probe depths down to 400 km with a resolution of about 50 km.

The tomographic images show no clear sign of the kind of narrow plume generally associated with the notion of a 'hot spot'. Instead they pick out shallow (~75 km depth) P- and S-wave low-velocity features that follow the axes of the three active rift systems. The features coalesce at depth; in some respects the opposite of a classic plume that has a narrow 'stem' that swells upwards to form a broad 'head'. If there ever was an Afar Plume it no longer functions. Instead, the rifts and associated lithospheric thinning are associated with a mantle upwelling that is being emplaced passively in the space made available by extensional tectonics. This is closely similar to what goes on beneath active and well-established mid-ocean spreading centres where de-pressuring of the rising mantle results in partial melting and basaltic magmatism along the rift system. Perhaps this is a sign that full sea-floor spreading in Afar is imminent, at least on geological timescales.

For once, mantle geochemists and geophysicists have data that support a common hypothesis (Ferguson, D.J. and 8 others 2013. Melting during late-stage rifting in Afar is hot and deep. *Nature*, v. **499**, p. 70-73; DOI: 10.1038/nature12292). This US-British-Ethiopian team compares the trace element geochemistry of Recent basaltic lavas erupted along the axis of the Afar rift that links with the Red Sea spreading centre with equally young lavas from volcanoes some 20 km from the axis. Both sets of lavas are a great deal more enriched in incompatible trace elements that are generally enriched in melt compare with source than are ocean-floor basalts sampled from the mid-Red Sea rift. Modelling rare-earth element patterns in particular suggests that partial melting is going on at depths where garnet is stable in the mantle instead of spinel. This suggests that a strong layer, about 85 km down in the upper mantle is beginning to melt – magmas formed by small degrees of partial melting generally contain higher amounts of incompatible trace elements than do the products of more extensive melting. Estimates of the temperature of melting from lavas extruded at the rift axis than off-axis are significantly higher than expected at this depth suggesting that deeper mantle is rising faster than it can lose heat.

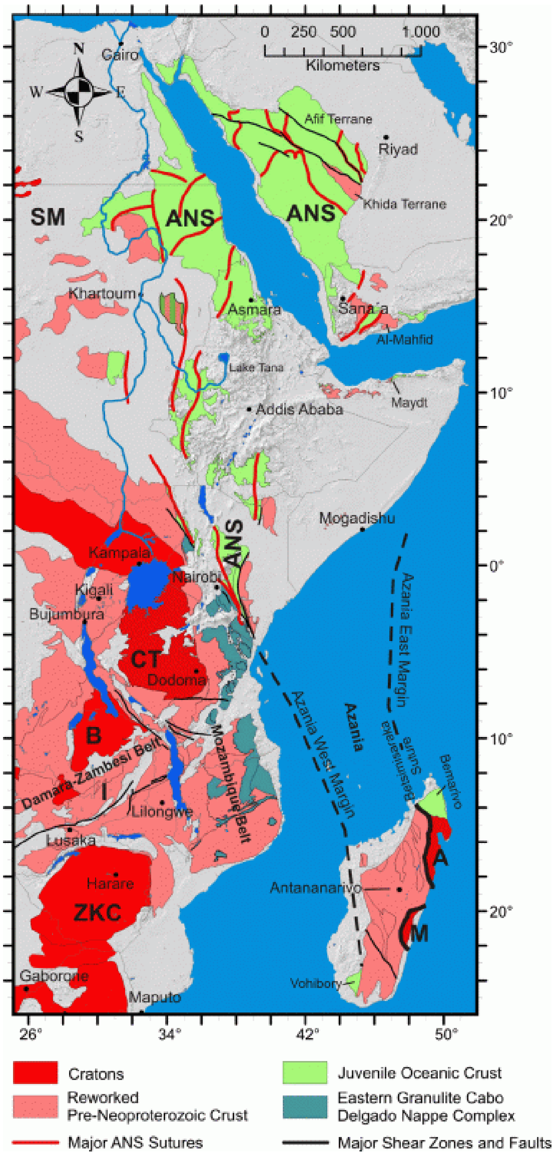


Simplified geologic map of the Afar Depression. (Credit: Mohamed Abdelsalam)

The depth of melting tallies with the thermal feature picked out by seismic tomography. The two teams converge on passively induced upwelling of hot asthenosphere while the Afar lithosphere is slowly being extended. The degree of melting beneath Afar is low at present, so that to become like mid-ocean ridge basalts a surge in the fraction of melting is needed. That would happen if the strong mantle layer fails plastically so that more asthenosphere can rise higher by passive means. The geochemists persist in an appeal to an Afar Plume for the 30 Ma old flood basalts that plaster much of the continental crust outside Afar. Those plateau-forming lavas, however, are little different in their trace element geochemistry from off-axis Afar basalts. Yet they are not obviously associated with an earlier episode of lithospheric extension and passive mantle upwelling. Most geologists who have studied the flood basalts would agree that they preceded the onset of rifting but have little idea of the actual processes that went on during that mid-Oligocene volcanic cataclysm.

The East African Orogen: Neoproterozoic tectonics on display (*September 2013*)

Between 825–550 Ma the fragmentation of a supercontinent, [Rodinia](), drove a round of sea-floor spreading and continental drift that culminated in reassembly of the older continental pieces and entirely new crust in a new supercontinent, Gondwana. The largest source of evidence for this remarkable tectonic turnaround is a belt stretching N-S for over 3000 km from southern Israel through East Africa to Mozambique. At its widest the belt exposes Neoproterozoic rocks and structures for some 1700 km E-W from west of the Nile in northern Sudan almost to Riyadh in Saudi Arabia. This [Arabian-Nubian Shield]() tapers southwards to thin out completely in northern Tanzania between far older cratons in a state of high-grade metamorphism.



Simplified geological map of the East African Orogen courtesy of the authors of Fritz et al 2013

This East African Orogen has long been considered the best exposed bowels of former mountain building that there are: results of continent-continent collision and the bulldozing together of many oceanic arcs and remnants of oceanic lithosphere that once separated the cratons. This was much more complex than a case of head-on tectonics. The northwardswelling Arabian-Nubian Shield showing all the signs of being like a gigantic 'pip' squeezed out northwards from two cratonic jaws during the last stages of what is often called the Pan African Orogeny. Interestingly, the line of the orogen is now followed roughly by East Africa's other giant feature, the Rift Valley; actually two of them following different Pan African terranes. A continental scale anisotropy has been reactivated and subject to extensional tectonics, and maybe in future during a new round of sea-floor spreading that has begun in the Red Sea, some half a billion years after it formed.

Now there is an opportunity for anyone to download and read a digest of East African orogenic processes compiled by researchers from several countries along the belt and their colleagues from North America, Europe and Australia who have been privileged to work in this vast area (Fritz, H and 13 others 2013. Orogen styles in the East African orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. *Journal of African Earth Sciences*, v. **86**, p. 65-106; Open Access version; DOI: 10.1016/j.jafrearsci.2013.06.004). The authors present superb simplified geological maps of each major part of the orogen, a vast array of references and well-written accounts of its sector-by-sector tectonic and metamorphic evolution, variations in style and broad tectonic setting.