Are sheeted dykes significant? (January 2009)

More than abyssal sediments, pillow basalt, differentiated gabbro and depleted peridotite sheeted dyke complexes have long been a primary identifier for oceanic lithosphere preserved in ophiolites. That assumption has recently been questioned (Robinson, P.T. et al. 2008. *The significance of sheeted dyke complexes in ophiolites*. GSA Today, v. 18 (11), p. 4-10; DOI: 10.1130/GSATG22A.1). Ian Gass first discovered units made up solely of dykes that intrude one another with no intervening screens of other host rocks in the Troodos ophiolite of Cyprus in 1968. Sheeted dyke complexes became widely regarded as characteristic of extensional, sea-floor spreading environments connected to basaltic magma chambers, each increment of extension being filled with magma. They have also been imaged in eroded walls of ocean fracture systems and cut through by ocean drill cores, supporting this notion. In fact, many ophiolites are devoid of sheeted complexes, despite having all the other components of mafic-ultramafic lithosphere. Robinson et al. argue that sheeted dykes only form where spreading rates and magma supply are balanced, as expected at true constructive plate margins but far less likely at other extensional zones associated with plate tectonics, such as those in back-arc basins above subduction zones. Even at true spreading centres that generate new ocean floor magma supply may not balance extension, for instance where spreading rates are slow. Moreover, a great many ophiolites show geochemical affinities that are more akin to supra-subduction magmatic processes than those that produce mid-ocean ridge basalt.

Plate tectonics in time and space (January 2009)

Seismic tomography becomes increasingly revealing as the capacity of supercomputers grows. On top of that, more sophisticated software allows present-day mantle cross
sections to be reverse modelled with surface plate motions to reconstruct an idea of mantle dynamics back to Mesozoic times. Geophysicists at the California Institute of Technology give a taste of the possibilities from the subduction history of North America (Liu, L. *et al*. 2008. *Reconstructing Farallon plate subduction beneath North America back to the Late Cretaceous*. *Science*, v. 322, p. 934-938; DOI: 10.1126/science.1162921). Investigating 3-D evolution is the key to connecting rigid plate tectonics and fluid convection that has long been postulated but remains obscure. However, while reasonable reconstructions of global plate motions are possible using sea-floor magnetic stripes that go back to the Cretaceous, seismic tomography only images the mantle’s present structure. So it might seem that generating a 3-D ‘geomovie’ is more of an expensive illusion than a model of past realities.

The logic behind the modelling is that today’s mantle temperature structure – that is what tomograms show – stems from past plate activity. For instance, a deep cold, slab-like anomaly dipping eastward beneath eastern North America can reasonably be inferred to be a relic of the Farallon Plate, which formerly constituted floor of the eastern Pacific. That plate was subducted beneath the west edge of the continent until around 40 Ma, when the East Pacific Rise that had driven it was subducted. The present thermal structure shown by the tomogram has, in a sense, ‘faded’ as a result of thermal relaxation of the original anomalies by heat diffusion. Choosing geologically reasonable starting conditions for long-term evolution of a mantle segment enables iterative forward modelling to try and achieve the present set-up. While there is an element of circularity in this logic, such a dynamic model has a predictive aspect; i.e. as cold, dense material in the mantle sinks it tends to pull the surface downwards, allowing marine flooding of continental interiors. During the Late Cretaceous this did happen spectacularly in North America, and Liu *et al*’s model shows this. Yet sea level also rose globally at the time, thereby amplifying the inundation. Although geomodellers will be excited by Liu *et al*’s developments, it is modelling and even the

Relics of the Farallion Plate (magenta) beneath the western USA (Credit: Karin Sigloch)
simplest of models is acutely sensitive to the chosen starting conditions, as meteorologists with vastly more real data at hand have discovered again and again.

3-D model of Mesozoic subduction beneath the US. Surface colours show rising (yellow to brown) and sinking (yellow to blue) of the surface. Vertical faces show mantle-temperature distribution from cool (yellow to blue) to warm (yellow to red). (Credit: Steinburger 2008)

Rheic Ocean reviewed *(March 2009)*

Since the late 1960s when John Dewey and a few other geologists began to apply plate-tectonic ideas to palaeogeography, most of us when asked to name an ancient ocean would have blurted out ‘Iapetus’. Yet another Palaeozoic ocean, the Rheic Ocean, left a far more profound mark on the Palaeozoic world: its closure around the end of the Palaeozoic Era united all the continents in Wegener’s Pangaea supercontinent, and threw up a vast mountain belt at the suture. The earlier evolution of the Rheic Ocean involved the spalling of a series of microcontinental slivers from the flank of the earlier Gondwana supercontinent. Damien Nance and Ulf Linneman review the fascinating story of the Rheic Ocean in a nicely succinct way (R.D. Nance & Linnemann, U. 2008. *The Rheic Ocean: Origin, evolution and significance*. GSA Today, v. 18 (12), p. 4-12; DOI: 10.1130/GSATG24A.1).

Archaean ‘Waterworld’ *(March 2009)*

Readers might remember with some pain the 1995 film Waterworld, starring Kevin Costner: an actor so wooden he could not sink. That was based on the unlikely scenario that if all the ice caps melted the continents would be drowned entirely. In fact that global melting would raise sea level by a mere 67 m. A far higher sea-level rise took place during the Cretaceous, arguably because fast sea-floor spreading and subduction created a larger volume of ‘warm’ and so less-dense ocean lithosphere than there is now. The volume of the ocean basins shrank as a result, displacing ocean water onto low-lying areas of the continents. Something more dramatic has been suggested for the Archaean Earth (Flament, N. et al. 2008. *A case for late-Archaean continental emergence from thermal evolution models and hypsomety*. Earth and Planetary Science Letters, v. 275, p. 326-336; DOI: 10.1016/j.epsl.2008.08.029).
The starting point for the discussion by Flament and his Australian and French colleagues from the universities of Sydney and Lyon is that the reason for the present hypsometric distribution of surface elevations between ocean floor and continents is cooling of the Earth that has changed the isostatic balance between oceanic and continental lithosphere. That progressively sharpens the topographic contrast thereby increasing continental freeboard. Archaean times involved a hotter mantle due mainly to greater radiogenic heat production. Flament et al. argue that would have lessened the rigidity of continental lithosphere, so reducing the ability of the crust to thicken, whereas ocean floor would have had a higher relative elevation, so reducing ocean basin volume. As in the Cretaceous oceans would have flooded continents, but to a far greater extent, so that as little as 3% of the Earth surface was land.

The swaddled mantle (May 2009)

A great deal of both theoretical petrology and tectonics hinges on how temperature changes with depth within the Earth. The geotherm, as this variation is termed, depends on how heat is conducted – by conduction, convection or radiation – and where it is produced – either as a relic of original heat of Earth’s accretion or through decay of radioactive isotopes. There are plenty of imponderables, and it would be safe to say that, below the depths at which we can measure temperature (a few km), geotherms are guesswork. Metamorphism, partial melting in crust and mantle, and the rigidity of rock depend on temperature and pressure. Rocks that are too cool to act in a plastic manner tend only to conduct heat, and they are poor conductors. This applies to most of the crust, especially the lower continental crust, which is also low in heat producing radioactive K, U and Th isotopes and rigid. The upshot of this is that the crust acts to insulate the mantle, and that implies build-up of heat and temperature just below the crust. A new means of measuring a rock’s thermal conductivity has revealed that thermal conductivity actually decreases as temperature rises (Whittington, A.G et al. 2009. Temperature dependent thermal diffusivity of the Earth’s crust and implications for magmatism. Nature, v. 458, p. 319-321; DOI: 10.1038/nature07818). The range of crustal temperatures in both continental and oceanic crust roughly halves conduction in the lower crust from previously measured values. This further increases insulation of the mantle, boosting the chances of partial melting.

This tallies with a coincidentally published account of how seismic shear waves change speed with depth beneath the oceanic crust (Kawakatsu, H. et al. 2009. Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates. Science, v. 324, p. 499-502; DOI: 10.1126/science.1169499). As well as sharply showing up the lithosphere-asthenosphere boundary, thought to be a transition from brittle to ductile behaviour, it detects thin layers of partially melted peridotite, which facilitates plate tectonics. A further coincidence is publication of an analysis of 15 years of global earthquake records that focuses on the base of the lithosphere (Rychert, C.A. & Shearer, P.M 2009. A global view of the lithosphere-asthenosphere boundary. Science, v. 324, p. 495-498; DOI: 10.1126/science.1169754).
Partial world map of depth to the asthenosphere; triangles are seismic stations used in the calculations. (Credit: Rychert & Shearer 2009; Fig. 2)

This approach effectively maps the top of the asthenosphere and therefore the thickness of tectonic plates across the planet, albeit crudely (previously both had been estimated from surface heat flow and theoretical models). Beneath cratons that have remained sluggish for more than a billion years, the asthenosphere is deep (~95 km) and thin, shallowing and thickening appreciably beneath more recently active continental belts, as the figure shows. Despite being the uppermost Earth and the stuff of plates and the medium upon which they move, respectively, the lithosphere and asthenosphere are less-well known than the mantle and even the core in terms of their mechanical properties. That may sound odd, but there is a good reason why it is so: more deeply travelled seismic waves are a great deal easier to record by the global network of seismic stations than are those travelling only through shallow regions.

**The Great Bend of the Pacific Ocean floor (May 2009)**

Ocean island chains are trackways of lithospheric plates moving relative to the underlying mantle. Mantle hotspots act in a similar manner to a candle that would burn a line in a sheet of paper were one to be passed over it. The largest, most coherent and best studied ocean island chain is that of the Hawaiian Islands and the Emperor Seamounts in the NW Pacific. The volcanoes that built the chain range in age continuously from Late Cretaceous (81 Ma) at the northern tip of the Emperor Seamounts where they touch the Kamchatka Peninsula to the present in the Big Island of Hawai‘i itself. So far, so good for the hotspot-track hypothesis. But the chain is bent into a WNW segment (Hawaii) and one that trends NNW (Emperor). That might seem to be superb evidence that the direction of West Pacific sea-floor spreading underwent a sudden, 60° change around 47 Ma (the age of the Diakakuji seamount at the apex of the bend). However, measurements in 2001 of palaeomagnetic latitude in sea-floor cores along the chain revealed clear palaeomagnetic evidence that the Hawaiian hot spot has not always been fixed relative to moving lithospheric plates. From Late Cretaceous to Late Eocene times the hotspot seems to have been was shifting southwards relative to the north magnetic pole at a rate comparable with that of sea-floor spreading, and then became stationary to explain the 60° bend in the chain.
The Hawaiian and Emperor Seamount chains, whose motions have spanned 0-47 and 47-81 Ma respectively

Further work has been done since 2001, and a review of the huge oddity that bucks John Tuzo Wilson’s 1963 theory of hotspots fixed in space and time is timely (Tarduno, J. et al. 2009. The bent Hawaiian-Emperor hotspot track: inheriting the mantle wind. Science, v. 324, p. 50-53; DOI: 10.1126/science.1161256). Data have moved on to suggest that the hotspot is indeed the head of narrow mantle plume originating deep down, perhaps even near the core – mantle boundary (CMB). But could such a massive structure change it’s behaviour so that its head would move? Some have suggested the development of a propagating crack in the Pacific lithosphere and then its closure, but no evidence points unerringly that way. After considering a range of possible mechanisms, the authors suggest that the great bend records past changes in mantle flow beneath the West Pacific, so that the plume would itself have bent in the vertical dimension. Seismic tomography has revealed apparently low-angled zones of hot, low-velocity mantle, such as one that may (or may not) connect with the Afar plume beneath the triple junction of the East African Rift, the Red Sea and the Gulf of Aden after rising from the CMB south of Cape Town. They are tantalising results, because the resolution is simply not good enough to be sure. It needs an order of magnitude better tomographic resolution of mantle features to truly make more headway.

Is there a giant impact basin beneath the Antarctic ice? (July 2009)

At present there are only two reliable means of surveying variations in the Earth’s gravitational field: at the surface using gravimeters and from space, by processing measurements the height of the ocean surface from radar measurements or by accurately measuring the variation in distance between two satellite travelling in tandem over the Earth’s surface. The last is used by the Gravity Recovery and Climate Experiment (GRACE)
designed by NASA and the German Space Agency. It is the only realistic means of usefully precise gravity surveys over Antarctica. A truly multinational team (von Frese, R.R.B. et al. 2009. *GRACE gravity evidence for an impact basin in Wilkes Land, Antarctica. Geochemistry, Geophysics, Geosystems*, v. 10, Q02014, DOI: 10.1029/2008GC002149) has discovered a prominent positive free-air gravity anomaly over a roughly 500-km diameter subglacial basin in Wilkes Land.

A basin filled with low-density ice would normally give a negative gravitational ‘signature’, so the positive anomaly suggests either unusually dense crustal rocks beneath it, or that the mantle is unusually close to the surface; i.e. the crust is thin. The authors suggest that the central anomaly is surrounded by roughly concentric circular features in the sub-ice topography, and that it is a hitherto unsuspected impact structure, three times larger than the Chicxulub structure (also mapped by gravity data off the Yucatan Peninsula of Mexico) that caused an upward bulge of the mantle. To my eye, the hypothesis only becomes convincing when concentric circles are drawn around the undoubted major anomaly, and the evidence for them is scant compared with the similarly detected structures of Mars and the Moon. What intrigues the authors is the position of the anomaly on a Permian continental reconstruction, It is at the antipode of the Siberian Traps flood basalt province, implicated strongly in the end-Permian mass extinction: the most devastating known. This harks back to speculation that the formation of the undoubted Chicxulub structure caused the mantle to melt beneath its antipode to form the Deccan Traps...

Evidence for Hadean continental crust takes a knock (*November 2009*)

The pre-4 Ga ages recorded by some of the detrital zircons from the 3 Ga Jack Hills sandstones have been used to suggest that continental crust formed from about 4.4 Ga onwards, which implies some kind of recycling process in the tectonics of the early earth to generate and fractionate the necessary silicic magmas. That assumes zircons only form in silicic magmas produced by fractionation in volcanic arcs. The plagiogranites found in small amounts in ophiolites also contain zircons, thereby countering the claim for Hadean continents. More revealing are zircons found in granite magmas that represent the last dregs of mafic melts formed by giant impacts (Darling, J. et al. 2009. *Impact melt sheet zircons and their implications for the Hadean. Geology*, v. 37, p. 927-930; DOI: 10.1130/G30251A.1). The huge impact-induced mafic to ultramafic melt sheet at Sudbury, Ontario, formed around 1.85 Ga. Zircons extracted from late-stage granites in the body are
similar in trace-element content, highly varied crystallization temperatures and inclusions to those with Hadean ages.

The march of the seismometers (November 2009)

It used to be a joke in the Geological Surveys of the Soviet Union that they employed so many thousands of geologists that the entire USSR could be mapped in a few years if they all linked hands and walked from east to west, notebooks and hammers in their hands. Geophysicists are trying for something similar to map the mantle beneath the USA in 3-D.

The schedule for using USArray

The USArray involves 400 portable seismometers, currently spread out at 10 km intervals in the western States, and is intended to act like a fly’s eye in monitoring arrival times of seismic waves from worldwide earthquakes. The plan is to steadily move the array eastwards until by 2013 it has reached the Atlantic coast. From that data the geophysicists hope vastly to improve the resolution of seismic tomographic images of the deep Earth (see Kerr, R.A. 2009. Scoping out unseen forces shaping North America. Science, v. 325, p. 1620-1621; DOI: 10.1126/science.325_1620a). The USGS is definitely going for a high ‘Wow factor’ rating. Yet it seems that there are other expletives floating around as the strangely knobly and discontinuous architecture that is emerging from early data processing refuses to fit many simple hypotheses being tested. Interestingly, it is possible to adopt one of the stations in the array for between US$ 30,000 to 37,000. You get to keep it at the end of the programme, and set up your own seismic recording station at a substantial discount!