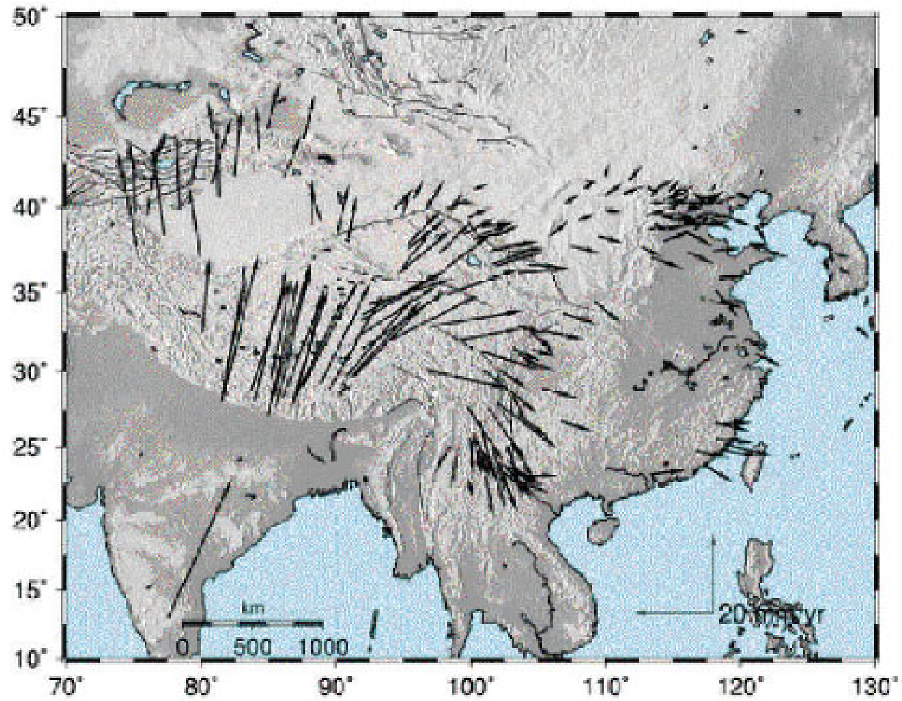
Tectonics

Quantifying motions inside continents (*February 2004*)

If you are a member of the Geological Society of America you will either have heard or read the 2003 Address of its President (Burchfiel, B.C. 2004. New technology; new geological challenges. *GSA Today*, v. **14**, p. 4-10). His topic is how the use of ever-increasing precision of satellite global positioning (GPS) has revolutionised continental neotectonics, since it began to be used by geoscientists in the late-1980s. The illustrations have a backdrop of what I suspect to be the 90m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), and show the fine topographic detail that stems very much from active tectonic movements. Superimposed on them are estimates of the speed at which points on the surface are moving and the directions of motion, gathered using GPS technology. Measured in mm per year, these velocities stem from the most precise positional measurements, with the degradation built into the GPS satellite signals for US military reasons (turned off in 2001) removed using differential processing. They are averages representing motions over the last 17 years or so.



Crustal motions in East Asia derived from GPS, (Credit: Burchfiel 2004; Fig, 6)

The most dramatic example covers the Tibetan Plateau and areas to the east of it, based on extensive work by Chinese scientists.. In general it shows a sort of clockwise swirling away of expelled crust east of the Eastern Himalayan Syntaxis (the "big bend" at the eastern termination of the Himalaya) in the ranges through which the headwaters of the Irrawaddy, Salween and Mekong rivers flow, rather than the eastward expulsion towards the China Sea first postulated by Tapponier in the early 1980s. Field studies suggest that this kind of motion has been going on for at least the last 4-6 Ma. Another conflict with expectation lies in the area of the Longmen Shan mountains and the huge Sichuan Basin of western China. A simple model of crust being expelled from the zone of the India-Asia collision suggests that

Tibetan crust would be moving eastwards here to throw up the steep front of the Longmen Shan above the Sichuan Basin. There is in fact very little sideways movement at the surface. Explaining this requires deep crust from Tibet moving in a ductile manner far below, thereby "inflating" the Longmen Shan where entirely different kinds of crust are juxtaposed.. Many of the motions in East Asia can only be explained in terms of differential movements at different levels in the lithosphere, and the influence of subduction systems, such as the Indo-Burman and West Pacific, as well as the long-suspected expulsion of over-thickened crust in Tibet due to increased gravitational potential there.

Mesoproterozoic large igneous province and Rodinia (*May 2004*)

Flood basalt events in the Phanerozoic seem generally to have preceded the break-up of supercontinents, and many geoscientists believe that their formation is implicated in the mechanism of continental disaggregation. So it comes as something of a surprise to learn that the assembly of most continental lithosphere to form the Rodinia supercontinent about 1100 Ma ago, which ranks in size with Pangaea, was probably accompanied by massive igneous activity (Hanson, R.E. *et al*. 2004. Coeval large-scale magmatism in the Kalahari and Laurentian cratons during Rodinia assembly. *Science*, v. **304**, p. 1126-1129; DOI: 10.1126/science.1096329). The Proterozoic sediments of southern Africa and once-adjacent Antarctica are intruded, wherever they occur, by basaltic sills up to hundreds of metres thick. In a few places relics of flood basalts above the sedimentary groups have the same composition and age, around 1100 Ma. Like Phanerozoic large igneous provinces, most of the magmatism occupied only a few million years, perhaps less than 1Ma. The distribution of the probable feeder intrusions for the few relics of CFBs suggests that the province in the Kalahari craton formerly covered about 2 million km^2, so it ranks in size with most Phanerozoic LIPs.

In North America, cored by the craton of Laurentia, there occurs the Keeweenawan dyke swarm and other mainly mafic intrusions, that probably fed another veneer of CFBs. Dating them using the same single-crystal U-Pb method reveals ages that are within error of those from southern Africa. Combined, the two LIPs are much larger than the biggest know LIP from the Phanerozoic – the Ontong-Java Plateau that formed on the floor of the West Pacific Ocean during the Cretaceous. So, were there two massive, but short-lived igneous events while Rodinia was assembling, or one that unites both the Kalahari and Laurentian cratons? In many models of Rodinia, stitched together using orogenic belts that formed in the late Mesoproterozoic between1150 and 950 Ma, the Kalahari craton has been placed against Laurentia; both LIPs could be a single super-province. However, the same authors also measured palaeomagnetic pole positions from the southern African igneous rocks. They are different from those revealed by the Laurentian LIP, and imply considerable separation of the two continental masses at the time of igneous activity. That suggests either separate melting events in the mantle beneath both cratons at the same time, or that both are parts of an even larger magmatic upheaval that spanned about 1/5 of a hemisphere. Whichever turns out to be the case, this ancient large-scale mantle event bucks the Phanerozoic trend of LIPs' presaging or accompanying continental break-up. Maybe the rare mantle upwellings thought to generate LIPs are really random in their positioning, and "just happened" to rise beneath Pangaea and its fragments from the Devonian onwards.

Plastic deformation beneath Tibet (*July/August 2004*)

Plate tectonics' basic tenet is that discrete segments of the lithosphere behave as rigid bodies, whose motion is accommodated by extensional, overriding and strike-slip faulting at equally discrete boundaries. That is true to a first approximation for the parts of plates made up from oceanic lithosphere, which is rheologically strong because of its mineralogical composition. Continental lithosphere is weakened by its quartz-rich crust, which tends to behave plastically at high temperatures deep within it. So it is no surprise that opposed motions of plates induce large-scale shortening and thickening of continental lithosphere that they carry, but there are no orogens in the ocean basins. The largest site of active continental shortening and thickening is, of course, the Alpine-Carpathian-Himalayan orogen. The Tibetan Plateau is underpinned by continental crust that is in the process of being thickened as India drives north-eastwards into Asia, at about 4 to 5 cm per year. Consequently it the largest area of high-elevations on the planet. In the 1973 John Dewey and Kevin Burke speculated that forces involved in continent-continent collisions with irregular margins might expel thickened continental lithosphere sideways, at right angles to the opposed plate motions. Peter Molnar of the University of Colorado in Boulder and Paul Tapponnier of the Institute of Global Physics in Paris applied this on a grand scale to the neotectonics of the Tibetan Plateau and East Asia in 1975. They considered that south-eastward expulsion was channelled by the many enormous strike-slip faults in the region. In a sense, this notion considers the continental tectonics to be akin to the rigid-body behaviour of oceanic parts of plates. If the overall motions involving Tibet and continental lithosphere to the east was dominated by plastic deformation in the deep crust and mantle, the motion would be taken up by a host of smaller faults in the brittle upper crust. Geodetic measurements using GPS over the last 17 years do conflict with the movement of discrete blocks of East Asian crust (see *Quantifying motions inside continents* above).

Two papers published in July 2004 also lean towards plastic behaviour of the bulk continental lithosphere. One uses data from surface seismic waves to show about 30% ductile thinning in the middle and lower crust beneath Tibet (Shapiro, N.M. *et al*. 2004. Thinning and flow of Tibetan crust constrained by seismic anisotropy. *Science*, v. **305**, p. 233-236; DOI: 10.1126/science.1098276). The other is based on interferometric analysis of radar data from satellites, which involves measuring signal differences between radar data captured on different dates, in this case between 1992 and 1999 (Wright, T.J. *et al*. 2004. InSAR observations of low slip rates on the major faults of western Tibet. *Science*, v. **305**, p. 236-239; DOI: 10.1126/science.1096388). The technique has mainly been used to look for vertical displacements associated with earthquakes and volcanoes. By eliminating the effects on signals by terrain, using an accurate digital elevation model, InSAR results can estimate the motion of the surface along and opposite to the illumination direction of the radar pulses, thereby detecting horizontal ground movements over a period of several years with sub-centimetre precision. Rather than revealing large movements in the two opposed directions that are expected on either side of large strike-slip faults, such as the Karakorum and Altyn Tagh Faults, there was none. In a zone crossing western Tibet from NNE to SSW, much of the orogen appears to be moving slowly eastwards, irrespective of the large faults. Tapponnier still maintains the importance of the big faults, and perhaps the InSAR survey coincided with a period of tectonic quiescence.

Mantle dripping off mountain roots (*September 2004*)

Continental arcs, such as the Andes, parts of the Himalaya and Tibetan Plateau and the Sierra Nevada of the western USA, are stuffed with granite intrusions. Large volumes coalesce to form classic batholiths. It is now well-accepted that very little of the granitic magma originated by melting of older continental crust, but by processes of fractionation from more mafic parent magmas. That presupposes a layer of dense, mafic to ultramafic cumulates below and complementing up to 30 km of batholithic crust. The overall density of the continental arc crust would be high relative to that of the granites themselves. So the fact that many batholithic cordilleras are topographically high suggests one of several processes: either the granitic part of the crust has become tectonically thickened relative to its denser root, or that root has separated from the continental lithosphere as a whole, and sunk into the mantle. Such decoupling, or delamination, would induce the remaining lithosphere to rise dramatically. Also, its descent could result in partial melting to produce peculiar potassium-rich basaltic magmas. The latter occur in Tibet and their presence there has been linked to foundering of deep lithosphere, that may have triggered the relatively recent surge in Himalayan uplift. Proving the existence of a descending lump of lithosphere is not easy, but developments in seismic processing can make a crucial contribution, if sufficient data are available for a suspected zone of delamination. The western USA is blessed with lots of seismic stations, so is a natural place to try out the new techniques as a test of the hypothesis. George Zandt of the University of Arizona, and other US colleagues have come up with interesting results (Zandt, G. *et al*. 2004. Active foundering of a continental arc root beneath the southern Sierra Nevada in California. *Nature*, v. **431**, p. 41-46; DOI: 10.1038/nature02847). Their analyses of seismic data shed light on a late stage in the development of the Sierra Nevada. During the Mesozoic Era, subduction beneath North America of the now disappeared Farallon plate of Pacific Ocean lithosphere built up the Sierra Nevada batholith. About 10-16 Ma ago, subduction stopped and the plate margin became one of transpression, the most prominent feature of which is the San Andreas Fault. At that stage, a “drip” of dense cumulates began to form, and subsequently separated to descend into the mantle. Cruustal rebound was not simple but included zones of extension, as well as tell-tale high-K volcanism during the Pliocene.

The boys on the black stuff (*November 2004*)

Tectonic activity continually re-paves the oceanic part of the Earth, though not in the manner of the awesome night-time machines seen frequently by owlish drivers as they negotiate the contraflows and cones on highways, large and small. Slab-pull helps ease plates apart, forcing asthenospheric mantle to rise and partially melt as pressure falls off. Or, at least that is widely believed, for active mid-ocean processes can only be observed at second-hand through samples scraped from the exposed ridge surface for analysis. What once lay at the guts of spreading centres emerges only when slabs of ocean lithosphere slide nicely over continental margins because of compressive forces related to plate subduction. Gravity demands that such obduction is a rare and special process, since oceanic lithosphere is denser than that of continents. Indeed, as ocean floor ages and cools it become increasingly likely to founder into the deep mantle. Ophiolites represent oddly buoyant parts of the ocean floor, almost certainly because they were once thermally anomalous or quite young at the time of their emplacement. There is no guarantee that they represent run-of-the-mill oceanic lithosphere. However, structures in them, especially a subsurface layer made of innumerable basaltic dykes and little else, show concretely that magmatism was dominated by continual extension; exactly as expected for a former spreading centre.

The most studied ophiolite is that of the Semail Mountains in Oman, which exhibits every definitive layer of lithosphere that point to magmatism in an extensional oceanic environment. The crustal part is not the best guide to the ophiolite's genesis, because melt chemistry varies so much with pernickety vagaries of melting and fractionation. It is the mantle sequence that reveals what went on (Le Mée, L. *et al*. 2004. Mantle segmentation along the Oman ophiolite fossil mid-ocean ridge. *Nature*, v. **432**, p. 167-172; DOI:10.1038/nature03075). Laurent Le Mée and colleagues from the University of Nantes focus on chemistry and mineralogy of the well-preserved ultramafic rocks in the Oman ophiolite's mantle layers. Their results show how a whole number of petrogenetically important chemical features vary systematically parallel to the original axis of spreading, to define three distinct axial segments. Within each are other regular fluctuations that define segments of lesser magnitude. This along-axis chemical variability can be modelled in terms of large variations in the degree of mantle melting (between 10-30%), with the lowest degree coinciding with the major segment boundaries. Those discontinuities also tally with increased numbers of mantle-cutting dykes (not the crustal sheeted dykes). Major segments probably formed from regional upwellings of asthenosphere, whereas those with shorter wavelengths reflect individual diapirs. Along active spreading centres, segmentation of chemical affinities in basalt lavas seems to link with various magnitudes of transform faulting, and it is this local tectonics that shows up so nicely in the Oman mantle sample.