How weak are the

Rob Butler examines the trial of strength facing the poor old continental lithosphere.

Gaze at a topographic map of the world and you are looking into one of the great geoscience debates of recent years. The mountain belts and the plate boundaries it portrays are richly varied. Some are narrow like the New Zealand and European Alps. On the other hand Tibet is over 2000km across and flanked by woven strands of mountains. It is all so much simpler in the oceans, where plate boundaries are almost knife-sharp.

Conventional wisdom, succinctly summarised by Peter Molnar[1], has it that oceanic tectonics are simple because oceanic plates are strong. Their strength is locked up in strong upper mantle. Once a plate boundary forms it is difficult to shift it elsewhere in the plate. At this scale continents appear less able to localise deformation, implying that continental lithosphere as a whole is weaker than oceanic.

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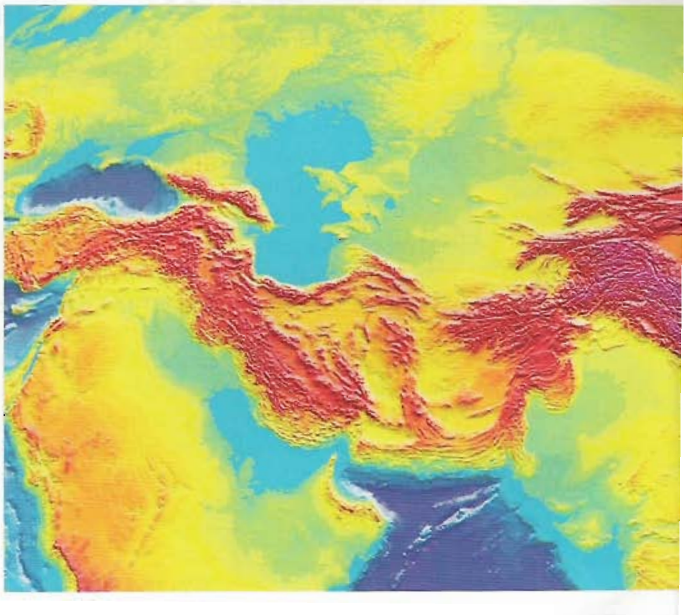
But to understand the complex variety of deformation in the continents we need to grasp their rheological structure; most pertinently, how strength varies with depth through the lithosphere. Not only is this now a topic of vibrant debate, but exciting new datasets from tectonically active areas like Tibet and the Himalayas may be changing the way we view continental tectonics.

Jelly or *crème brûlée?*

For a quarter of a century one model of how strength is distributed through continental lithosphere has held sway – generally called the "jelly sandwich". This views the continents as a three-layer system with a strong upper crust and upper mantle separated by weak lower crust – the jelly. It is believed that the strong layers serve to focus earthquakes, while the deep crust flows. But over the past five years a new idea has been proposed, one where the strength of the continents is strongly focused into the uppermost, seismogenic crust alone, with the underlying lithosphere weak and ductile. With tongue firmly in cheek, just missing a rather sweet tooth, Evgenii Burov and Tony Watts[2] have called this the "crème brûlée" model. So where do these models come from?

There are two well-established results from experimental rock deformation. First, friction sliding and brittle failure get more difficult with increasing pressure, so rocks get



continents?

stronger with depth. Second, rocks become softer with increasing temperature. The change from pressure-sensitive to temperature-sensitive deformation in the crust defines a change in structural style and sets a depth-limit to most earthquakes – variously termed the "brittle-ductile" or "seismic-aseismic" transition. For brittle failure, most rocks (e.g. limestone *vs* sandstone *vs* granite *vs* gabbro) behave the same. But, although all geological materials eventually become softer at higher temperatures, temperature-sensitive crystalline plasticity is profoundly influenced by composition-dependent attributes - such as the melting temperature of the material, and grain size. Of course, the details have long been debated in structural geology and tectonics, particularly the problems encountered in extrapolating laboratory conditions, especially in strain rate, over many orders of magnitude to scales appropriate to tectonic problems. The location of the brittle-ductile transition is a movable feast.

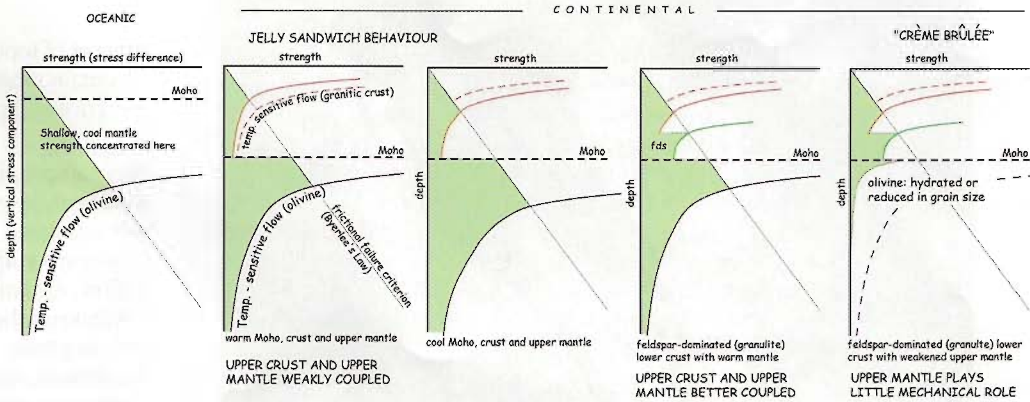


Figure 1. Schematic strength-depth profiles for different lithospheres and different models. For the oceans with crust just 7km thick, the transition from depth-dependent frictional failure to temperature sensitive flow (defining the "brittle-ductile" transition) happens in the upper mantle. Its position will depend largely on the thermal state of the upper mantle that, in the oceans, relates to the age of the plate. The more complex composition of continental lithosphere and the generally thicker crust are manifest by more complex strength-depth relationships as indicated.

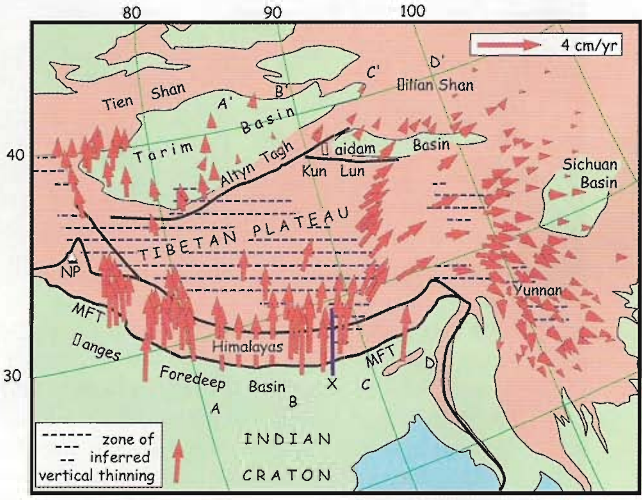
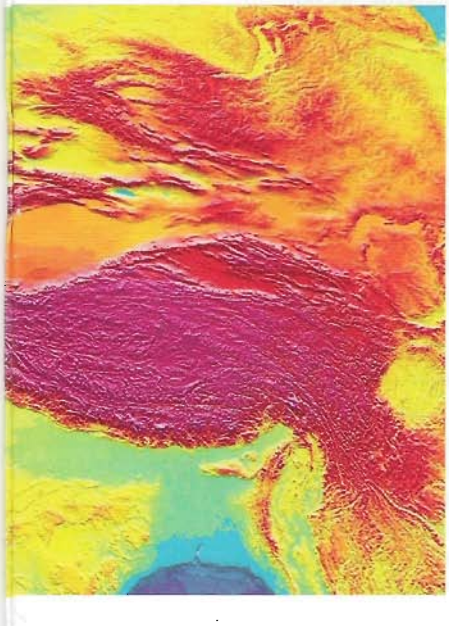


Figure 2. GPS results modified from Zhang et al. (2004) showing the displacements relative to stable Eurasia. The transects for Figure 3b are indicated (A-A', B-B', C-C', D-D'), as is the profile through the Himalayas (X - Fig. 4).



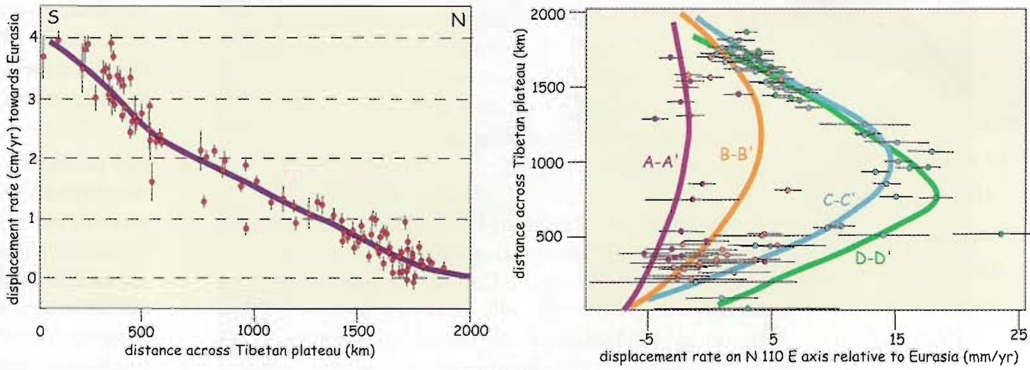


Figure 3. Compilation of GPS results for the Tibetan plateau area, modified from Zhang et al. (2004). a) All the Tibetan data compiled onto a single transect, showing the northward component of displacement, relative to stable Eurasia. The continuously varying profile suggests that, at this scale, N-S convergence across the plateau is distributed smoothly, rather than be focused onto major faults. b) shows the component of displacement on a N110E axis, collated on four transects (shown on Fig. 2). These data are also consistent with continuous deformation and have been interpreted in terms of lateral extrusion of Tibetan crust towards Indo-China.

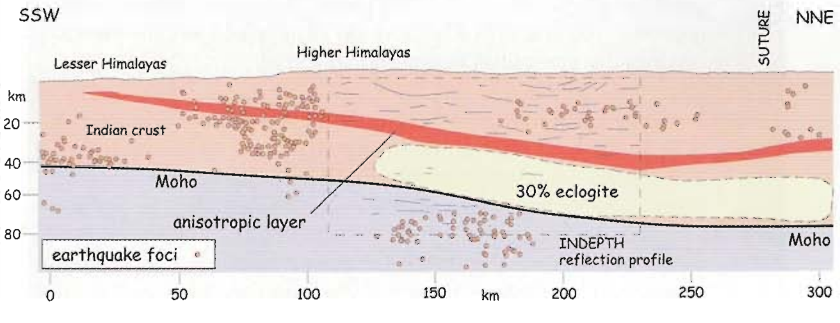
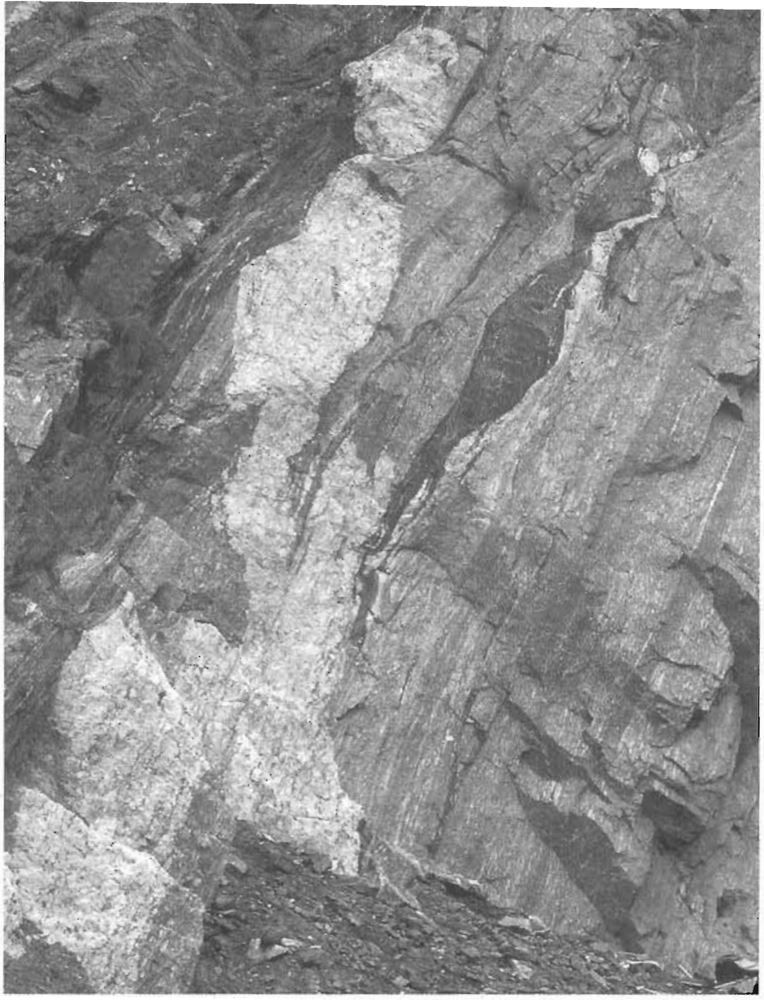


Figure 4. A crustal cross-section (located on Fig. 2) with geological interpretation of collated seismological results, modified after Schulte-Pelkum et al. (2005).



The lower part of the sandwich is made of mantle, which because of its higher melting temperature will be stronger than the deep crustal "jelly". So earthquakes should form in two layers - upper crust and upper mantle. For granitic crust deforming under typical geological strain rates, the "brittle-ductile" transition occurs at around 450-500°C, less if the feldspars have been broken down to mica and quartz. Recent determinations, made by McKenzie and co-workers from Cambridge[3], of lithosphere thermal structure beneath shields indicates Moho temperatures of around 600°C. So if the deep crust of the shields is granitic it should flow very easily – like jelly. In contrast the upper mantle, compositionally dominated by strong olivine, should itself be correspondingly stronger.

> *" a range of models is needed to allow for all the different compositions and thermotectonic properties of different lithospheres"*

You might think, then, that McKenzie and others advocate the jelly sandwich model. But they don't. For the past five years the Cambridge group has argued forcibly that the jelly sandwich model be abandoned in favour of one where the strength is concentrated in the seismogenic crust alone – the *crème brûlée* model. The evidence behind this is eloquently summarised by James Jackson[4]. Better estimates of Moho depth, coupled with modern determinations of focal depths, suggest that almost all the earthquakes assigned to the upper mantle in support of the jelly sandwich in fact occurred in the lower crust. Deep crustal earthquakes in regions with a high Moho temperature are deemed to occur in dry granulites, not granitic material.

In contrast, the mantle is weaker than predicted by experiments, perhaps because it is slightly hydrated. Indeed, Jackson argues that mantle dehydration may at times promote deformation and earthquakes in the deep crust. He also marshals a further argument against a strong upper mantle required by the jelly sandwich model by suggesting that the effective elastic thickness (Te) of the continental lithosphere, the approximation used to model flexural support of topographic loads such as mountain ranges, has traditionally been overestimated.

For example, the Te of the Indian continent flexed by the Himalayas was estimated by Tony Watts and colleagues in the 1980s at around 120km, the world's strongest plate. For Jackson the Te modelled from free air gravity is just 36.5km. This is the highest value determined by the Cambridge group for the continents, so India can retain its world record; but it is lower than values for parts of the oceans. The value broadly matches the thickness of the seismogenic part of the Indian continent. By this argument, lithosphere rheology is broadly the same, be it subjected to the stresses associated with earthquake generation or the long-term support of topographic loads.

Crème brûlée, with continental upper mantle weak (often weaker than the deep continental crust) has raised the temperature in the geodynamics kitchen. Mark Handy and Jean-Pierre Brun[5] argue that the model is simply incompatible with field data and geophysical imaging of large-scale mountain belt structures. In their 2006 article, Burov and Watts argue forcibly for the jelly sandwich, pointing out that a strong upper mantle is needed to when modelling a range of tectonic phenomena from subduction to the topographic stability of mountain ranges.

Are earthquake distributions and determinations of Te appropriate ways to estimate the rheological behaviour that pertains to the formation of large-scale continental deformations such as reflected in orogenic belts? These various loading conditions are rather different. Deformation of continental lithosphere that holds most of its strength in the seismogenic crust alone (*crème brûlée*) is likely to be governed by fault zones within which the ideal strength of the surrounding lithosphere is greatly reduced. Arguably this behaviour is most appropriate to contractional tectonics outside mountain belts – where basin inversion is commonly identified with the reactivation of pre-existing faults. The applicability of such behaviour to the world's active or indeed ancient orogenic belts is by no means widely accepted.

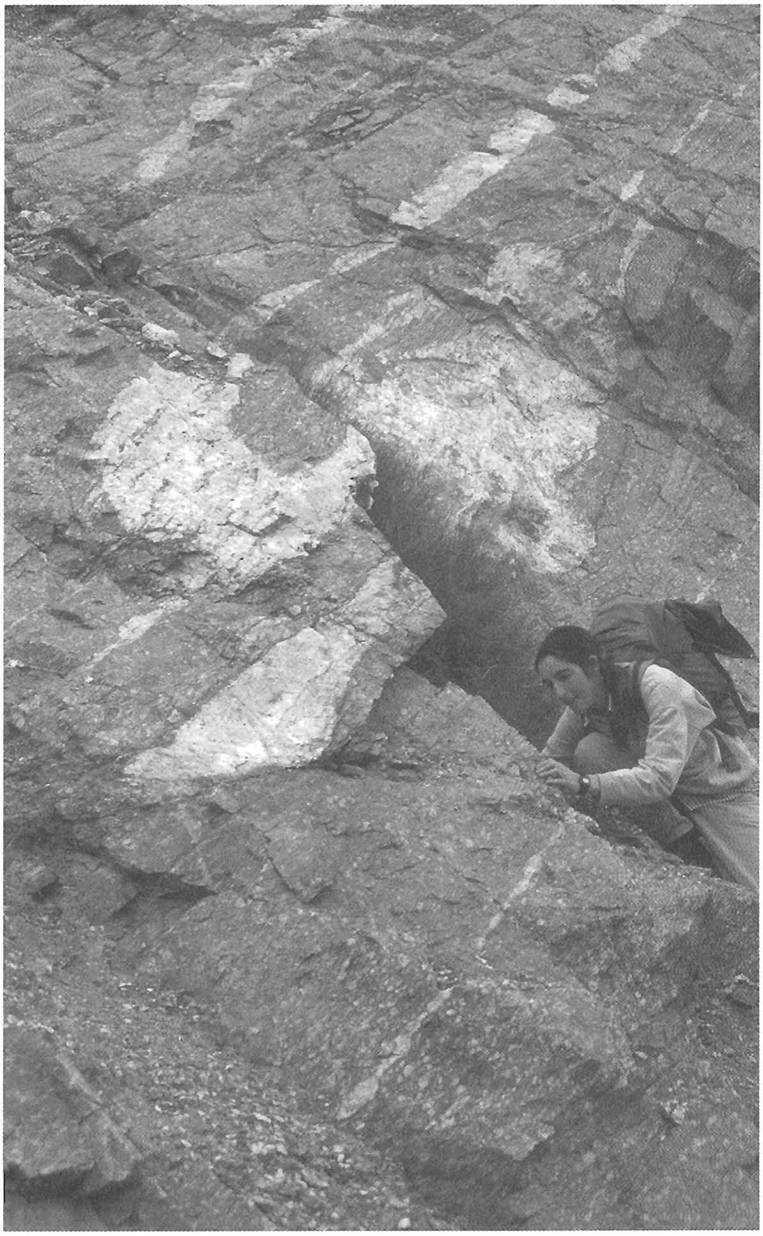
India-Asia collision

Take the India-Asia collision system. For 25 years it has been established that the distribution of the 2000km+ bulk convergence in this system is distributed unevenly. At this scale India shows only minor contraction (the Himalayas), perhaps accounting for about 20% of the contraction budget. The remainder is accommodated by crustal deformation on the Eurasian side of the suture, most markedly by the development of the Tibetan plateau. A well-known, first order deduction is that the rheology of these two continental lithospheres is different, even allowing for differences in erosional unloading of the shortening crust. The different approaches to explain Tibetan deformation can be framed in terms of the rheological debate. One view, most vocally propounded by Paul Tapponnier of the *Institut de Physique du Globe* in Paris, suggests Tibet deforms as fault-bounded flakes, ejected eastwards by the relentless northward drive of India. A contrasting view, proposed by Philip England and Greg Houseman (now at Oxford and Leeds universities respectively) is that the Tibetan crust flows continuously, essentially behaving as a viscous fluid. The inferred lateral flow of crust from SE Tibet has been termed "topographic ooze" by MIT's Marin Clark and Leigh Royden[6].

Tibetan tectonic models can now be tested by spectacular geodetic data collected by collaborative GPS campaigns carried out, especially, by Chinese scientists over the past decade and more[7]. These confirm the broadly N-S convergence and eastward extrusion of the plateau. If the flaky model is correct, large areas of the Tibetan plateau should behave as rigid blocks. Yet GPS results show that, at the scale of the crust, deformation is continuous. It is as if there were no faults. The pattern of smoothly varying strain is seen both on a N-S axis and in the direction of extrusion. But how can we understand what is happening below the surface, beyond the reach of simple geodetic approaches? The answer may come from seismology.

For a long time now seismic anisotropy has been used to understand mantle geodynamics. Olivine crystals transmit seismic waves faster in particular directions than others, depending on the orientation of their mineral lattices. The difference is only a few percent, but this makes for several seconds in the split times for the arrival of shear waves with different polarities passing through large volumes of mantle within which the olivine lattices are preferentially aligned. For seismologists working on mantle structure, the most useful data come from SKS events - S-waves generated from P-waves as they emerge from the core. As more and more three-component, broadband seismometers have been deployed around the world, this research has generated maps of shear wave anisotropy and inferred directions of mantle flow. These in turn have stoked the fires of debates such as concern the driving mechanisms of plate tectonics, the deep structure of plumes and geodynamic coupling between core and mantle.

A slightly different approach is needed to image crustal structure. SKS waves are generally not practical because their anisotropy is dominated by the 2900km of mantle through which they must pass before they reach the crust. However, P-waves are partially converted to S-waves at other boundaries with impedance contrasts, including the Moho. Those P-to-S conversions generated near seismic recording stations are called Receiver Functions (RFs) and their use is now a hot-topic in seismology and tectonics. Using arrivals of P-waves and S-waves in tandem means Moho depths and the detailed seismic velocity structure of the crust directly



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under the recording station can be determined. Should the crust have a structure such that S-waves are transmitted faster in one direction than another, this will be detected in the RFs. Clearly S-wave anisotropy from RFs is unlikely to be caused by olivine – because it is not a major constituent of the continental crust. Most researchers propose that the culprit is a different mineral group that has strongly anisotropic petrophysical properties – namely, mica. We know from outcrops of deformed metamorphic rocks that micas commonly form the dominant tectonic fabric, or schistosity. Consequently, RFs offer a way of mapping the orientation of schistosity *in situ*, within continental crust that is actively deforming. For the past few years it is this approach that has been applied to Tibet.

Viscous creep

Arda Ozacar and George Zandt of the University of Arizona at Tucson[8] used RFs to identify three layers of seismically anisotropic crust beneath central Tibet. The upper two layers are shallower than 20km, presumably too shallow to relate to active ductile flow. They may however record fossil deformation fabrics, most plausibly related to crustal shortening. The deeper layer, some 10km thick and 30km down is more interesting. It implies subhorizontal alignment of mica lattices, just the arrangement that would result from crustal thinning. A similar conclusion was reached by Nikolai Shapiro and colleagues of the University of Colorado at Boulder[9] from a study of Rayleigh and Love waves to map radial anisotropy in the middle and lower crust of Tibet. To explain this they proposed that the deep Tibetan crust was spreading out, thinning in all directions. It seems like the deformation is most dependent on the viscous creep of deep crust – the shallow faults just go with the flow. But what happens at the edges of the plateau?

After deploying 29 broadband seismometers across the mountains and leaving them to record earthquakes for 18 months, Vera Schulte-Pelkum and colleagues[10] obtained startling new images of crustal structure. Using RFs, this group from the University of Colorado at Boulder were able to trace the Moho of the Indian continent, some 40km deep under the foreland to about 80 km depth under southern Tibet. They also showed that the lower crust increases in its seismic velocity as it gets deeper beneath the Higher Himalayas.

The team explain this as reflecting metamorphism in action – the granulites of the deep Indian crust transformed to eclogites as they are incorporated into the orogenic belt. Using S-wave anisotropy recorded by the RFs they detected a layer of anisotropic middle crust that projects up to the active Main Frontal Thrust of the Himalayas. Unlike for Tibet, where such anisotropy has been considered to result from crustal thinning, Schulte-Pelkum and co-workers interpreted the sub-Himalayan anisotropy to result from shear, the ductile roots of the low angle Main Frontal Thrust. The implication here is that unlike Tibet, it is the fault that controls the deformation.

The Himalayan seismic study contains a bonus. Apart from detecting teleseismic events and using their RFs to study crustal structure, the team from Boulder also recorded over 1700 local earthquakes that, because of the number of seismometers deployed, could be very precisely located. The Indian crust of the foreland looks like *crème brûlée*, with lots of lower crustal earthquakes and few in the upper mantle. This result confirms the earlier studies of the Cambridge group. But under the High Himalayas and Tibet the earthquakes form in two distinct levels, one in the upper crust and one in the upper mantle – jelly sandwich. So, the Indian lithosphere changes its behaviour. It starts in the foreland as strong lithosphere, with the lower crust making a large contribution to this strength. As it becomes involved in the orogenic belt the lower crust metamorphoses to eclogite, weakening in the process. The now reduced strength of the lithosphere is supported by a fragile upper crust and perhaps the upper mantle.

The lessons from Tibet and the Himalayas suggest that no single description of continental lithosphere applies to all cases. In making the same point more generally, Juan Carlos Afonso and Giorgio Ranalli[11] state that a range of models is needed to allow for all the different compositions and thermotectonic properties of different lithospheres. Continental collision often means distinctly different lithospheres interact, and, as orogenesis progresses, the state of the lithosphere including its composition and thermal structure evolve too. It may be that we need to fathom the initial heterogeneities of continental lithospheres to understand if it these that are selectively amplified to form the various mountain belt structures in modern settings. Sorting these issues out needs everyone to get involved, not just the geophysicists but also field geologists studying ancient systems that offer up mountain roots for direct observation.

Many of the issues in the great continental strength debate are not new. Like his forebears, in the 1920s Emile Argand was aware of the variety of mountain belts and proposed varying amounts of thrusting and thickening to explain them. Other field geologists have argued about the tectonic significance of broad tracts of deformed crystalline basement, the exhumed relics of ductile flow in the deep continental crust. Yet others have argued over the significance of fault zone weakening as a focusing agent in continental tectonics. It will be interesting to see how these debates move on as geophysics gradually improve the opportunities of doing structural geology *in situ*, linking deductions of the strain state in the deep crust with the measurements of active deformation at the Earth's surface. Will we ever be able to look upon the mountains in quite the same way again?

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