Mountain roots and the survival of cratons

What controls the deformation of the continents, the survival of ancient cratons and the roots of mountains? James Jackson explains in his Harold Jeffreys Lecture, 12 November 2004.

ABSTRACT

In the last few years, evidence from the apparently unconnected fields of earthquake seismology, gravity, geochemistry, rock mechanics, mineralogy and petrology has come together to provide simple insights into the fundamental geological questions: why do the continents deform differently from the oceans, and why do the ancient interiors of the continents (the cratons) survive apparently intact and undeformed for so long?

This is a detective story in the Earth sciences. From the earliest days of plate tectonics it was known that the continents do not deform in the same way as the oceans. This is evident from a map of earthquake epicentres (figure 1), showing the narrow bands of earthquakes in the Indian ocean, contrasting with the epicentres distributed over the broad mountainous regions of the Middle East and Central Asia. Earthquakes occur when faults move, so a map of earthquakes is a map of active deformation. Plate boundaries in the oceans are essentially single faults, defined by joining the epicentre dots on a map, whereas the very concept of plate boundaries on the continents is often unhelpful: it is meaningless to ask what plates Lhasa or Athens are on, since Tibet and Greece are both parts of wide deforming regions, and not parts of any rigid plate.

The ocean–continent contrast is not unexpected. The plates make up the lithosphere, the outer strong layer of the Earth, typically about 100 km thick and consisting of the crust and part of the underlying mantle. In the oceans the crustal part is a fairly uniform 7 km thick, whereas on the continents it is typically 30–80 km. The crust is less dense than the mantle, so a plate with thick continental crust is more buoyant, preventing it from sliding beneath another plate at collision zones. Instead it crumples to make mountains. Attempts to understand this process require a knowledge of the mechanical properties of continental lithosphere, and it is recent developments in this area that are the subject of this article.

Earthquakes and collisions

As so often occurs in Earth sciences, focus on one question inadvertently illuminates another. The earthquakes in figure 1 result from the ongoing collision between India and Asia, whose geological boundary lies in the Himalaya. Yet, whereas Asia has crumpled up as far north as Mongolia, ~3000 km from the geological contact, India is virtually undeformed. India is part of the Jurassic Gondwanaland supercontinent that fragmented to make Africa, South America, Australia and Antarctica. The interiors of all these continents are ancient (usually older than 3 billion years), flat and have remained undeformed for a very long time: they are called shields or cratons. They have a history of colliding with other cratons to form mountain belts between them, which later split apart again along the same sutures, leaving the cratons themselves intact and undeformed. The ancient cratons have an ability to survive that has long puzzled geologists.

For many years people have used the depth distribution of earthquakes and the gravity anomalies associated with topographic loads as indicators of lithosphere strength, by which is meant the ability to sustain elastic stresses over geological timescales with negligible flow.

In the case of earthquakes, a temperature-dependent change from shallow, friction-dominated slip on faults to deeper, aseismic creep processes is expected, and in most continental regions, earthquakes are indeed restricted to the upper half of the crust. But variations are seen, and in particular, in some of the old cratons, such as north India and parts of East Africa, earthquakes occur throughout the thickness of the crust (figure 2). There is little evidence for earthquakes in the mantle beneath the continents, in spite of there being many earthquakes in the oceanic mantle, beneath the much thinner oceanic crust. (I am not referring here to the very deep earthquakes in cold oceanic lithosphere that is transported back into the mantle at oceanic trenches, but to earthquakes at depths up to ~40 km within the stable ocean basins.)

The wavelength on which the lithosphere bends, and creates gravity anomalies to support
topographic loads, can be used to estimate the thickness of the strong elastic layer providing the support, in the same way that a thick plank bends on a longer wavelength than a thin one. Recent reviews of this rather technical and controversial subject (McKenzie and Fairhead 1997, Maggi et al. 2000, McKenzie 2003) found that the effective elastic thickness \( T_e \) determined from gravity and topography tracked the thickness of the layer in which earthquakes occur \( T_s \). Thus larger values of elastic thickness were found where earthquakes occur throughout the crust. Although \( T_e \) is not always well resolved by the data, they found, in general, that \( T_e < T_s \) and they found nowhere where the data required that \( T_e > T_s \). As they pointed out, the simplest interpretation of these results is that the long-term strength of the continental lithosphere resides in the layer that generates the earthquakes; which is either the upper crust or the whole crust, but does not include the mantle.

These results immediately contrasted the continents with the oceans, where the mantle both generates earthquakes and contributes to long-term elastic strength, but where the crust is much thinner. They also focused attention on the ancient cratons, and in particular north India, where the values of both \( T_e \) and \( T_s \) suggested that the Indian shield was unusually strong (figure2).

**Crustal thickness**

As patterns in the earthquake depths and gravity anomalies became clearer, so too did our knowledge of crustal thickness variations. Modern, broadband digital seismometers can be used to determine the crustal thickness by detecting converted longitudinal-to-transverse waves generated by the crust–mantle interface. These waves arrive a little later than direct longitudinal waves from distant earthquakes and the delay depends on the crustal thickness. Widespread use of this technique on the continents produced two important results for this story.

Firstly, it was found that the thickness of the crustal root beneath southern Tibet reaches 80–90 km (figure 2): significantly thicker than we previously thought. It was always known that the crust was thick beneath continental mountains: the crust floats on the mantle like ice on water (though the mantle is solid, not liquid, and deforms by creep), and high elevations are supported by deep, buoyant roots. But a thickness of 80–90 km poses other problems: at those depths the minerals in typical continental rocks should transform to a different, much denser, mineral assemblage called eclogite (figure 3). They cannot have done so in the Himalayan root, or its greater density would mean both that Tibet would be at much lower elevation and that its higher velocity would make the crust–mantle interface there undetectable. The crust must somehow have remained in the less-dense mineral assemblage called granulite; but why?

An extra surprise was that some unusually deep earthquakes, 80–90 km beneath southern Tibet, were now seen to be so close to the crust–mantle boundary that we could not really distinguish which side they were on.

Secondly, there were more signs that the cratons were odd. For example, in Finland, part of the ancient Scandinavian craton, the crust can reach 65 km thickness, the same as that in the Alps, even though the country is essentially at sea level. Younger continental regions at sea level, such as the United Kingdom, usually have a crustal thickness around 30 km. Something must be unusual about the mantle part of the lithosphere beneath the crust in the cratons.

**Lithosphere thickness**

At this point, bearing in mind the puzzle that gravity and earthquake evidence appeared to show the continental mantle was weak, whereas...
the oceanic mantle appeared strong, we looked for independent evidence of lithosphere thickness and temperature. Such evidence exists in two forms: the geochemistry of mantle nodules brought to the surface in volcanic eruptions, and the imaging of velocity structure in the Earth by seismic tomography.

Figure 4a shows an estimate of the temperature profile beneath the NW part of the ancient Canadian craton. It uses pressure and temperature estimates from the chemical compositions of mantle nodules, to which are fitted a steady-state geotherm that has to connect with the convecting interior beneath the plate, whose temperature is known. An important feature of this profile is that the temperature gradient is much steeper in the crust, where radioactive isotopes of K, U and Th are concentrated, than in the mantle lithosphere, where there is no significant internal heat production. The other important feature, incorporated here for the first time, is that conductivity in the mantle is a strong function of temperature, changing by a factor of two over the thickness of the lithosphere, and is compatible with observations from the chemical compositions of mantle nodules at the Jericho mine, in the northern Canadian craton (green circles). The lithosphere consists of the crust (lightest green) and part of the mantle, which in turn includes a rigid mechanical boundary layer (MBL) and a lower thermal boundary layer (TBL) that connects with a convecting interior below the plate. (Figure from Dan McKenzie)

Fossil earthquakes in Norway
A remaining puzzle is why the cratons, such as north India, are both unusually strong and produce earthquakes in the lower crust. There are two obvious possibilities: that they are unusually cold, or that they are dehydrated (even very small amounts of water reduce creep strength dramatically). A clue to this puzzle came from an unexpected source: evidence of earthquakes about 400 million years old in Norway.

In the early 1990s, Håkon Austrheim and colleagues from Oslo described some friction-generated melts from the exposed ancient root zone of the Norwegian Caledonian mountains (the same mountain system that formed the Appalachians and Scottish Highlands). These melts formed in earthquakes as the result of heating on fault-slip surfaces at high confining pressures (figure 5), and were immediately quenched to form glass. What is unusual about these melts
is that their mineralogy, which in electron micrographs shows the original dendritic and skeletal forms characteristic of rapid growth in quenching, is that of the eclogite assemblage (figure 3). These were fossil earthquakes at depths of at least 60–70 km, yet the host (unmelted) rock is still in the granulite assemblage. This indicates that the granulite was metastable and could only form the stable mineral assemblage when it melted. Austrheim’s group was able to show that the key to this process is water: very small amounts of hydrous mineral phases are seen in the eclogite melts, but the host granulite is completely anhydrous. Infiltration of water along cracks led to more pervasive eclogite formation, accompanied by a dramatic loss of strength: the eclogite is deformed by ductile flow, whereas the granulite is essentially undeformed except where offset by brittle slip on melt-generating surfaces.

Two things stand out from Austrheim’s remarkable work. The first is the all-important effect of water, whose catalytic effect is that of an on–off switch: with no water the granulite–eclogite transformation simply does not occur, and the granulite remains metastable. This is not that surprising, as the transformation involves a wholesale reorganization of both chemistry and mineral structure and is known to be very difficult to achieve in the solid state unaided by a catalyst. The second is the association between metastability and mechanical strength. The metastable granulite retains its mechanical integrity and (inherited) internal structure until it transforms to eclogite and becomes weak.

Survival of cratons and roots

Thus we return to India. Whereas being either cold or anhydrous would account for the strength of Indian craton and its lower crust, penetrating beneath southern Tibet to form the massive Himalayan crustal root, the message from Norway is clear: only being dry will allow the Tibetan root to survive as metastable granulite. This is likely that the unusual strength of the cratons derives from their dry lower crust: granulite is an anhydrous assemblage left behind after melting in the past extracted granite (and with it all the water) from the crust.

In Norway it seems that the transformation of granulite to eclogite along fractures is initiated by water, introduced during earthquake rupture; it may even be that water induces the fracture itself. At depths of 60–80 km the only reasonable source of water, given that the granulite is dry, is likely to be the mantle itself, possibly from the pressure-sensitive breakdown of hydrous mineral phases within it. Those ecnomic deep earthquakes beneath Tibet, so close to the crust–mantle boundary, may be modern analogues of the fossil earthquakes in Norway.

Thus we are beginning to see what is special about cratons: they achieve their extra strength through their dry lower crust. They also have unusually thick lithosphere, which is stabilized by chemically depleting the mantle beneath their crust. This too was achieved through earlier melting events, which are known to have removed garnet and reduced the iron content, thereby considerably reducing the density. The result is a mantle component of the cratonic lithosphere that is relatively buoyant compared to younger mantle lithosphere but, because it is much thicker than normal, reduces the overall buoyancy of the plate, thus allowing Finland, with its thick crust, to be at sea level. Cratons assembled of such material are virtually indestructible: much stronger than anything they are likely to run into, and too buoyant to be pushed back into the Earth’s interior. They can ram into weaker continental crust, as India has into Tibet, but eventually the upper part of the Himalayan crustal root will be removed by erosion or tectonic processes leaving the lower crust of India to survive.

A typical story?

It is common in the Earth sciences for apparently simple questions, such as “What is special about the continental cratons?”, to lead us in unexpected directions. This enquiry involved a range of clues, from earthquakes, gravity, mantle geochemistry, seismicity, rock mechanics and even the metastability of minerals and ancient fossil earthquakes. Along the way other puzzles are illuminated, such as why the mantle beneath the oceans produces earthquakes but not that beneath the continents. It is very likely, for instance, that the same effects are present on other planets. Venus has mountains that rise 10 km above the mean surface elevation. Because Venus contains much less water than Earth, such mountains are also likely to be supported by roots of metastable granulite. In many ways the story recounted here is a typical experience in the Earth sciences: important clues are in unexpected places; to recognize those clues requires a broad general knowledge of how the planet works; and focusing narrowly on what is apparently the core of the problem is often not the way to solve it. These lessons are all familiar to practising Earth scientists, but less so to scientific administrators and managers of directed science programmes.

References


The Harold Jeffreys Lecture

The Royal Astronomical Society awards this lecture each year to a scientist distinguished for their work in geophysics, in memory of Harold Jeffreys, RAS President and Gold Medalist.