Exposed continental crust

Deep geology out in the open

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UNTIL direct observation of the lower 20–30 km of the continental crust becomes feasible through drilling, earth scientists will continue to use surface observations as their primary source of information for the deep crust. Studies of uplifted cross-sections through parts of the crust, using integrated geological, geochemical and geophysical approaches, give critical links between surface geology and geophysical (seismic or electrical) soundings of the Earth at depth. A multidisciplinary group gathered recently* to review and assess the significance of proposed cross-sections from around the globe. In only a few rare examples, such as the study by A. V. Boland *et al.* in this issue (*Nature* **335**, 711–713; 1988), have geophysical links been made between the contemporary deep crust and out-of-place surface exposures, most of which are isolated by faults.

Almost by definition, one expects to see only the surface of continental crust, the deep crust being concealed by the intervening layers of rock. But at several major inclined faults, rooted in the lower crust, rocks have been raised from great depth to the surface, so that one can walk across the raised vertical cross-section (see figure). Because the uplift is rapid, rocks are frozen into the phases appropriate to the temperature and pressure of their original depth, and it is possible to see the history of metamorphism and crustal development at the exposed section.

On approaching the inclined fault, one observes an increase in metamorphic grade, commonly to granulite facies, a decrease in mineral radiometric ages and changes toward more mafic bulk compositions and higher seismic velocities: changes commonly associated with increased depth. Although these criteria have been used successfully to identify crustal sections of Archaean to Cenozoic age, uplift mechanisms vary considerably from the simple model in the figure, to extensional processes in the case of metamorphic core complexes. Most sections have experienced at least two uplift increments.

The meeting included an excursion across the 120-km-wide Kapuskasing uplift and a traverse of the spectacularly exposed Grenville Front near Killarney. Many similarities and differences emerged between the exposed cross-sections (including Ivrea, Calabria, Kapuskasing,

Pikwitonei, Prince Rupert, south India, Tehachapi, Doubtful Sound and Ruby Range). All sections contain magmatic components, and virtually all include supracrustal material (metamorphosed sediments) at the highest metamorphic grade, the deepest level.

A simple explanation of these components involves a common history of oceanic deposition, followed by arc magmatism and incorporation into the

Characteristics of exposed crustal cross-sections. Crustal thickness, 20–50 km; lateral extent of oblique cross-section, 20–150 km. Left-hand scale, seismic velocity (km s^{-1}); top and right-hand scale, palaeopressure (kbar). (After Fountain, D.M. & Salisbury, M.H. *Earth planet. Sci. Lett.* **56**, 263–277; 1981.)

margins of stable continental features (cratons), before the eventual uplift. If the sections are representative of the deep crust, then the similarities of lithology in the wide age range sampled suggest that much of the continental crust may record a similar evolution. But an important difference seems to distinguish Archaean from younger terranes. Whereas Cretaceous arcs such as created the Sierra Nevada batholith were active across narrow regions for long periods (J. Saleeby, California Institute of Technology), Archaean magmatism was widespread but short-lived (T. Krogh, Royal Ontario Museum).

Although exposed cross-sections have high-grade rocks at their base, most have not experienced pressures greater than 8–10 kbar, corresponding to a maximum depth of 25–30 km. This is less than the total thickness of the crust, and mid-crustal detachment is indicated, as discussed by Boland *et al.* in this issue.

Structural events with very different upper and lower crustal expressions have been recognized in several sections. Extensional shear zones at depth in the Ivrea zone (K. Brodie, Imperial College, London; M. Handy, University of Bern) are associated with formation of high-level rift basins. Deep-level unroofing of a core complex at Doubtful Sound is correlated with Cretaceous rifting in New Zealand (G. Gibson, Darling Downs Institute). Geochemical depletion of melted pelites (clays) in the Calabria zone may be related

to the formation of higher level, S-type granites (derived from sedimentary material; V. Schenk, University of Kiel).

Crustal structure studies face the problem of an imperfect record. A pseudo-stratigraphic approach to constructing a composite crustal section from depth-calibrated fragments was advocated by D. Fountain (University of Wyoming). Significant steps towards quantifying three-dimensional structure, by linking surface structures to depth, have been made by reflection profiling over high-grade terranes in Canada (A. Green, Geological Survey of Canada). For example, deep crustal reflections, traced to the surface in the Kapuskasing uplift, arise from compositionally layered gneisses.

High-grade terranes help elucidate the nature of the lower crust only if the structural links can be established. Boland *et al.* present results of a study aimed at constraining the subsurface structure of the Kapuskasing uplift by seismic refraction methods. Several models have been proposed to explain this feature, describing it as a suture, a failed rift arm, a transcurrent (strike-slip) fault or an intracratonic thrust (Percival, J.A. & Card, K.D. *Geology* **11**, 323–326; 1983). The new refraction work supports the last hypothesis.

Data from a line crossing the uplift demonstrate the presence of material with an unusually high seismic velocity (6.6–6.7 km s⁻¹) at shallow depths beneath the high-grade Kapuskasing rocks. The anomaly can be traced, dipping at about 15° to the west, to normal levels for material of this velocity, at about 20 km. The Moho (separating the crust and mantle) deepens from an average of 40 km to as much as 54 km below the uplift. Together, the block of high-velocity material extending towards the surface and the Moho downwarp indicate crustal shortening. The 20-km level may mark a delamination horizon during shortening, separating lighter material that was thrust up and denser material that flowed down to form a root. Crustal delamination (Oxburgh, E.R. *Nature* **239**, 202–204; 1972) seems common during shortening in orogenic (mountain-building) belts; the Kapuskasing data could be an intracratonic example.

Identification of the sole of the thrust at 20 km implies that rocks from below this level (fully 20 km of contemporary lower crust) are not represented in the exposed cross-section. Some constraint on the nature of this material is provided by its velocity of 7.2–7.7 km s⁻¹. Rocks with similar velocities (mafic gneiss, anorthosite), exposed near the base of the exposed section, can be inferred to become more abundant with depth. □

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