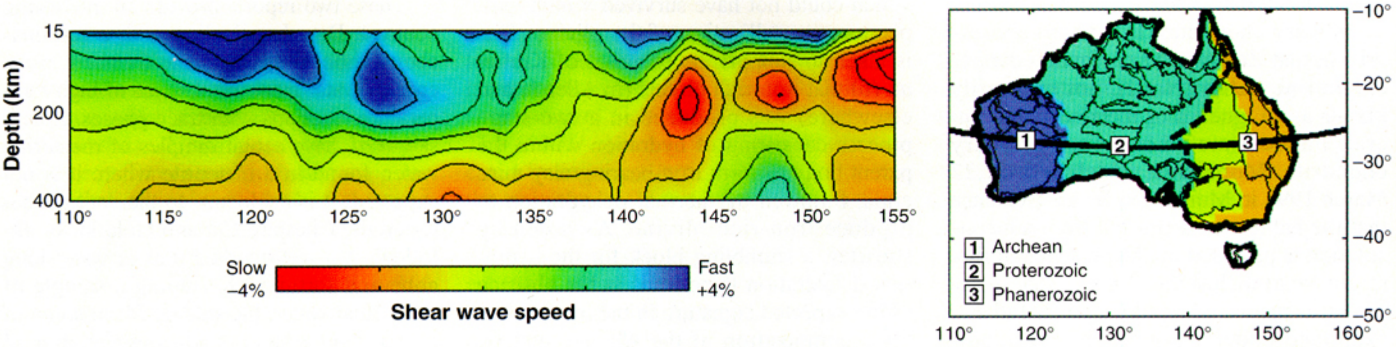

Continental keels reveal their secrets. (Right) Seismic wave speed anomalies in the mantle beneath Australia averaged within crustal age domains; up to about 200 km in depth, wave speeds systematically increase with crustal age. **(Left)** An upper mantle profile of wave speed anomalies beneath Australia (see map for profile location) further illustrates the dramatic variation in lithospheric mantle structure across the continent. The Phanerozoic (<570 Ma) domains in the east are characterized by a thin lithosphere, whereas in the central Proterozoic (570 to 2500 Ma) and western Archean (>2500 Ma) parts of the continent, the keel extends 200- to 250-km depth.

fast wave speeds characteristic of lithospheric mantle are generally concentrated above 250 km (see the figure), although in a few regions they reach depths of 300 km or even 350 km. The data indicate that keels are largely confined to Earth's upper mantle (at depths of less than 410 km) and are not anchored in the transition zone (from 410 to 660 km) to the lower mantle.

This conclusion is corroborated by studies of upper mantle discontinuities. The mineralogical phase boundary between olivine and wadsleyite creates a discontinuous jump in seismic wave speed at average mantle depths of about 410 km, but shallower in colder regions. High-resolution studies of discontinuity depths across keel margins in the eastern and western United States and in Tanzania (*12*) imply that in these regions the cold keels do not reach depths of 410 km and that, at least today, cold vertical downwelling beneath them is insignificant.

Anisotropic variations in wave speed likely reflect strain-induced alignment of olivine crystals in the mantle and thus provide a measure for deformation processes. The presence of azimuthal anisotropy in the mantle to depths of about 200 km just outside the keel in eastern North America provides further evidence that mechanical decoupling between the keel and the surrounding mantle occurs well above the transition zone (*13*). However, tomographic images of the upper mantle beneath Brazil have been interpreted as showing an upwelling plume that moves with the South American plate, implying that surface plate motion and upper mantle flow in this region are coherent to much larger depths (*11*).

The seismic array studies also show that the margins of continental keels and cratonic crust are not coincident everywhere and that lithospheric thickness may vary substantially even within domains of similar geological age or crustal evolution. These results suggest that either keels may form with complex morphologies or that they have been extensively altered by continental collisions and rifiting in certain regions, but not in others. Beneath the Tanzania craton, the keel appears to be largely intact despite rifting and plume activity around its margins during the past 30 Ma (*8*). In contrast, broad areas of former cratonic crust, or what used to be cratonic crust, now lie above low wave speed, nonkeel mantle in the western and northeastern United States (*10, 14*), southwestern Fennoscandia, and eastern China (*5*). Elsewhere, keels seem to extend beyond the surface craton, for example, in eastern Australia (*9*).

Anisotropies in continental mantle wave speeds are also more diverse and complex than suggested by earlier, sparser data sets (*7, 15*). This may be a result of different thermal and tectonic histories and keel morphologies. Neither lithospheric strain correlated with surface geology nor simple predictions of sublithospheric flow alone can explain these data on a global basis. Furthermore, substantial heat flow variations can occur within provinces of a single geological age, challenging the validity of universal heat flow–age relations (*16*). Global generalizations regarding keel properties and processes should thus be considered with considerable caution.

Near horizontal, sometimes anisotropic, layered structures have been isolated within keels to depths of 250 km (*7, 17*), including a striking example of a deep mantle discontinuity that appears to be the continuation of a shallowly dipping ancient subducted slab imaged in seismic reflection profiling (*17*). This result provides the strongest evidence to date that keel formation involved stacking of subducting lithosphere during collisions between continents or island arcs (or both).

These higher resolution studies reveal continental keels to be upper mantle features that contain great variability within and between cratonic regions. To further understand the genesis and evolution of continents, concerted research efforts, such as USArray (*18*), are required. These must involve geophysical, geological, and geochemical mapping over a wide range of length scales, with particular emphasis on cross-disciplinary analyses that bridge the gap between conventional mantle imaging and high-resolution mapping of crustal structures.

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