DESTRUCTION OF SUBCRATONIC MANTLE KEEL: THE WYOMING PROVINCE.

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Evidence of Keel. Kimberlite diatremes in the Front Range of Colorado-Wyoming (e.g. Eggler *et al.* 1987) and in the Missouri Breaks area of Montana (e.g. Hearn and McGee 1984) contain mantle, lower-crustal, and upper-crustal xenoliths. Geothermobarometry of these xenoliths yields fossil geotherms that are cool (Fig. 1) and indicative of mantle that transfers heat by conduction, not convection. Thus in at least two places, one within the Wyoming Craton and one at its southern boundary, mantle lithosphere existed in the past that was at least 175 km thick. By the southern Africa model (e.g. Boyd 1973), such a lithosphere or keel had been welded to the Archean crust since the time of crustal formation. Also, by the southern Africa model, somewhat thinner mantle lithosphere underlay Proterozoic terranes around the old cratonic nucleus.

Cretaceous-to-Pleistocene magmas within the Wyoming Province, including the Absarokas, Crazy Mountains, Highwood and BearPaw Mountains, Smoky Butte, and Leucite Hills, are quite disparate in major-element chemistry, ranging from calc-alkaline and high-K rocks in the Absarokas to highly alkaline and from sodic series to potassic series. Yet the magmas share a number of trace-element and heavy-isotope similarities (review by Eggler *et al.* 1988). In particular, in a $^{143}Nd/^{144}Nd$ - $^{87}Sr/^{86}Sr$ diagram, they plot distinctly below the "mantle array", implying that they have been derived from ancient LREE-enriched sources. O'Brien *et al.* (1991) interpret that array as a mixing line between asthenosphere and a single LREE-enriched source. We interpret the array as heterogeneous sources and attach significance to Nd model ages. Those ages and Pb secondary isochrons can be interpreted as ages of separation of those sources from asthenospheric mantle, ranging from 3.8 Ga to 0.8 Ga, clustering around 1.8 Ga. The 1.8 Ga cluster in turn can be interpreted to represent metasomites added to the Archean mantle keel during accretional and collisional tectonics about the old continental core.

Heat-Flow Evidence for Destruction. Eggler *et al.* (1988) modeled the regional heat-flow data of Decker *et al.* (1980, 1984) and Sass *et al.* (1981) utilizing a best-guess model of the petrology of the crust and mantle lithosphere. Geotherms were calculated by solving equations for heat production and conduction. Fig 1 was produced by assuming a 1200^{o}C isotherm for the lithosphere-asthenosphere boundary. In this simplified approach, variations in surface heat flow are attributed almost entirely to variations in thickness of the conductive layer (lithosphere). Decker *et al.* (1988) arrive at a quite different interpretation of the heat-flow data using an assumption that most surface heat-flow variation is a result of upper-crust heterogeneities in heat production. Although our approach is based on petrology observed at the surface or from xenoliths, we freely admit that the

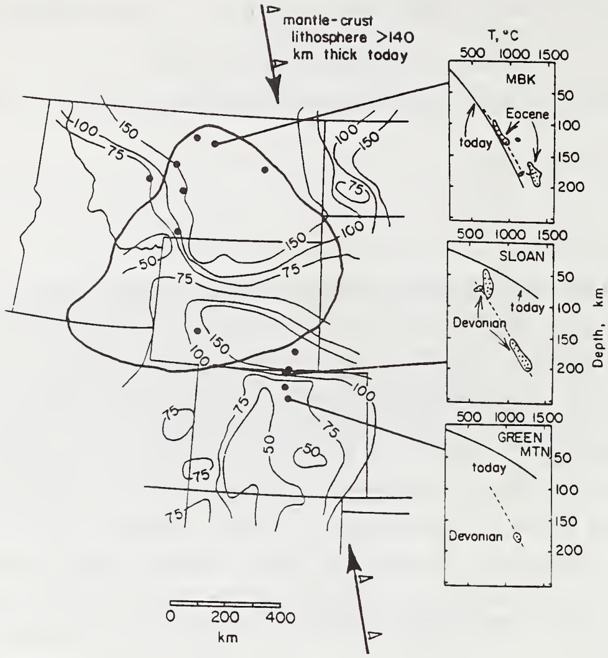

Figure 1. Minimum thickness of lithosphere, in km, calculated from heat-flow data. The lithosphere-asthenosphere boundary was taken as the 1200°C isotherm. Heavy arrows show the regional edge of thick (> 140 km) mantle lithosphere that presently exists beneath the Great Plains (Grand 1987). The heavy line encircles the Wyoming Craton; dots are magmatic centers or kimberlite pipes. Windows show fossil geotherms from xenolith localities together with computed present-day geotherms. Interpolated present-day heat flows: Missouri Breaks (MBK), 52 mW/m^2; Sloan, 73; Green Mountain, 80. The reference fossil geotherm (dashed line) is from southern Africa (Boyd 1973). An interpretation of this diagram is that thick mantle lithosphere that once was present throughout the Rocky Mountains now exists only in central Montana and southeastern Wyoming.

most probable shortcoming in the approach is an oversimplification of upper crust, the most heterogeneous unit and the greatest heat producer. Boundary depths of 50 km or less in Fig 1 undoubtedly represent upper-crust anomalies, because the temperatures imply partial melting that is not observed either by geophysics or by recent volcanism. The anomalies probably represent active or recently active magma bodies because they coincide with late Cenozoic volcanism, but they may also represent upper crust that is very high in K-U-Th and therefore in heat production. On either count, the calculated 1200°C isotherm would be too shallow, and the depths shown are minima.

Heat-flow modeling must be added to paleogeothermobarometry discussed above. The calculated geotherm in central Montana today (Fig. 1) is essentially the same as the conductive portion of the Eocene geotherm -- mantle lithosphere is at least as thick now as it was then and, presumably, as thick as it had been since the Archean. In northern Colorado-southern Wyoming, calculated geotherms today are much hotter than Devonian fossil geotherms -- mantle lithosphere is much thinner and has been destroyed. Regionally (Fig. 1), only two remnants of thick mantle lithosphere remain, one in central Montana and one in southeastern Wyoming.

Seismologic Evidence for Destruction. Eggler *et al.* (1988) discuss several geophysical surveys that indicate that mantle beneath the Great Plains is significantly different from that beneath most of the Rocky Mountains. The most definitive survey is a tomographic inversion for shear velocity (Grand 1987). Fig 2 is a simplified portion of Grand's cross-section B-B' that crosses the portion of Montana identified from heat-flow as underlain by thick mantle lithosphere. Block size for the velocity study was 500 km (horizonally), allowing the west-to-east transition from low to high velocities, above 400 km depth, to be up to several hundred km in width, although it may in fact be an extremely sharp feature. Because of the large block size, Fig 2 should not be overinterpreted. It does show, however, a high-velocity structure beneath the Great Plains that extends into Montana and that coincides with the old mantle lithosphere identified from xenoliths and heat-flow. Such structure is absent in Colorado, where the low-to-high velocity transition is east, not west, of the Front Range.

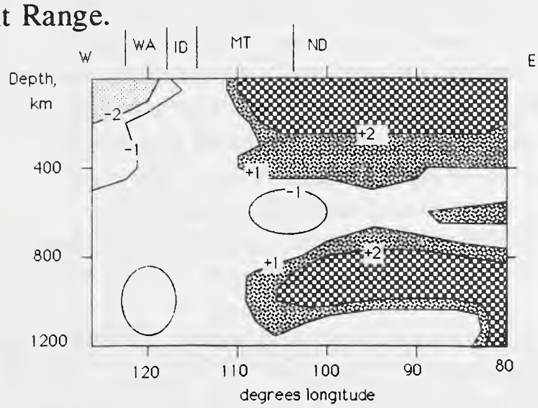

Figure 2. A simplified cross-section, after Grand (1987), of shear velocity across Montana and adjacent states. The line of section is approximately 46° latitude. Velocity changes are contoured with a unit that represents about 1.25% change above 320 km, about 0.62% from 320 to 405 km depth, and about 0.4% below 405 km depth.

Tectonic Implications. We believe that much of the central and northern Rocky Mountains was underlain by a keel of mantle lithosphere prior to Cretaceous time. The keel was tectonically stable and welded to old crust because it was buoyant -- although colder than asthenosphere, it was more magnesian (Jordan 1975). Cretaceous-to-Eocene tectonomagmatism destroyed much of that lithosphere eastward to the Great Plains, so that remnants exist today only in central Montana and southeastern Wyoming. That lithosphere was a clear impediment to low-angle subduction and the massive transport of lower crust and mantle lithosphere from southwest to northeast argued by Bird (1984, 1989). At the same time, some connection between subduction and tectonomagmatism cannot be denied. That connection began in the late Jurassic and continued into the mid-Tertiary. Eggler *et al.* (1988) and Meen *et al.* (1988) argue for a back-arc rather than arc setting for Montana magmatism; the main role of the plate was to induce back-arc asthenospheric upflow that accounts for a minor component of magmatism and for a major component of lithospheric thinning and partial melting. Other schemes may emphasize tears or rifts in lithosphere through which asthenosphere or slab-derived melts ascend.

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