PROGRESS TOWARDS UNDERSTANDING THE KAAPVAAL LITHOSPHERE: GEOPHYSICAL AND GEOCHEMICAL PERSPECTIVES

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A major goal of the earth sciences has been to understand the structure and evolution of continents, and in particular the ancient cratonic nucleii. It is now generally recognized that continental lithosphere includes a significant volume of mantle isolated from convective disruption that must migrate with the rigid plates. Continents have roots that appear to have as complex an evolution as the sialic crust with which they are linked, and Jordon (1978, and a series of other papers) formalized the concept of compositionally, mechanically and thermally definable tectosphere beneath continents, but the extent of and processes by which this may have evolved remain controversial (e.g. Anderson, 1990; Pollack, 1986).

Acquisition of geophysical information is of key importance is deciphering present-day craton structure. The occurrence of comparatively fast shear-wave seismic velocities for considerable thicknesses beneath continents in general and the Kaapvaal in particular has been known for some time from tomographic and inversion studies (e.g. Montagner and Tanimoto, 1991; Zielhuis and Nolet, 1994), but detailed studies remain comparatively few in number. In one case, Safronov et al. (1994) indicate that Siberian kimberlites are correlated with areas of higher than normal compressional sesimic wave velocity at Moho depths. On the Kaapvaal Craton, the Anglo American group has supported teleseismic studies conducted by BPI personnel over the past few years, and some of the results of the work are highlighted in this contribution. Determination of heat flow using drill holes throughout southern Africa has been an ongoing project conducted by Jones and co-workers for several years. In short, geophysical evidence for the existence of Kaapvaal lithosphere considerably in excess of circa 200 km suggested on petrological grounds is growing.

Electrical resistivity data acquired nearly twenty years ago have been difficult to interpret using 'typical' mantle models (De Beer, 1976), and are more easily reconciled with the presence of continental lithosphere thickness considerably in excess of 200 km.

Seisimic information directed at determining crustal thickness collected prior to 1988 has been obtained mainly from mine tremor observations on the craton, as well as long line refraction studies off the Kaapvaal Craton in the northern Cape and in Namibia. This work generally shows average Kaapvaal crustal thicknesses of 32 to 36 km, and slightly greater off-craton depths to the Moho of about 41 km. Relatively thicker off-craton, Proterozoic mobile belt crust compared to Archean cratons is observed elsewhere, as highlighted by Durrheim and Moody (1994).

A variety of broad-band teleseismic results are based on data collected from an array of eight seismic stations positioned from the southwest border of the Kaapvaal Craton in the Cape Province to the vicinity of the Thabazimbi lineament in north-central Transvaal. Spectral ratio analysis of P and PKP arrivals are particularly sensitive to crustal thickness, and generally confirm the depths to Moho obtained in previous studies. However, it is clear that there are significant variations in crustal thickness within the craton. Compared to the craton average of about 35 km, areas centered on the Johannesburg Dome are closer to 42 km, and areas in the western Transvaal are up to 43 km in crustal thickness. The 'topography' on the base of the crust is supportive of models of craton formation involving amalgamation of sialic fragments early in the earth's history such as proposed by de Wit et al. (1992).

Wave form inversion techniques have been used to produce synthetic seismograms for comparison with real arrival times. Using three of the stations, Cichowicz and Green (1992) showed that there are significant variations in shear wave velocity within the cratonic lithosphere to depths of the order of 200 km, and that there is a strong correlation between surface tectonic provinces and subcrustal velocity variation.

Delay time modeling based on P, PKP, S and SKS arrivals is in essence a tomographic technique based on differences between observed travel times at the stations compared to standard travel times for average earth models for the specific distance and depth of a given seismic event. Least squares inversion techniques are used to generate maps of velocity variation in three dimensions. Results to date appear to demonstrate significant lateral and vertical seismic structure within the craton, with a comparatively 'fast' root apparently characteristic of the southwestern and northwestern parts of the craton in particular to between 200 and 300 km, and perhaps deeper. A seismic discontinuity may be present at about 200 km in places, but this is not a 'robust' observation.

Use of P- to S-wave conversions allows high lateral resolution and the construction of a velocity - depth profile that can be compared with a global average model (IASP91 used here). This technique in particular highlights the apparently unique character of the Kaapvaal Craton, as well as an apparent thickness of the order of 400 km. S-wave velocities are anomalousy fast relative to the global average to depths in excess of 380 km, with a significant low velocity zone at 380 to 420 km followed by a gradual increase in normal mantle values by about 520 km. The significance of the low velocity zone is uncertain, but could reflect the presence of a partial melt, a change in fabric or a change in composition.

Studies of shear-wave splitting (Vinnik et al., in press) indicate significant anisotropy (presumably olivine fabric) with a preferred NE-SW orientation parallel to the direction of migration of the African plate during the Cretaceous, and therefor possibly caused by resistive drag within the lithosphere. However, the depth and vertical extent of the ansiotropy is unknown, possibly occurring in relatively thin zone(s) or throughout the depth range of 100 to 400 km. Assigning the anisotropy to the LVZ zone at 380 km is highly speculative, and at one station in the western Transvaal at least part of the anisotropy is a comparatively shallow (less than 200 km) azimuthal dependence component associated with the Thabazimbi lineament and frozen into the upper mantle.

Differences in heat flow between on- and off-craton environs has been known for some time, with cratonic values being consistently less than 60 mw/m^2, and non-cratonic areas being consistently greater. Modeling of heat flow and heat production data from the center of the Kaapvaal Craton yields lithosphere temperatures in close agreement with geothermal gradients inferred from kimberlite xenolith studies (Jones, 1988). If, as is commonly assumed, the transition from conductive to convective heat transfer occurs at a temperature of about 1300 degrees C, the 'thermal' thickness of the lithosphere (conductive boundary layer) is only 250 km. While this is further evidence that both low- and high-temperature xenoliths occur within stable lithosphere, it is not compatible with seismic evidence. A thicker lithosphere can be accomodated if the transition between conductive and convective regimes is +/- 200 degrees C higher. Two dimensional modeling undertaken by Ballard and Pollack (1987) allows lithosphere thickness of up to 400 km, depending on input parameters, but with lithospheric temperatures essentially the same as those of Jones (1988). Pollack (1986) proposed that higher transition temperatures could be achieved through devolatilization of the upper mantle during cratonization by elevating the solidus and increasing subsolidus viscosity so that the conductive boundary layer thickens beyond depths through simple cooling or Fe/Mg depletion. A basal temperature of 1600 degrees would result in lithosphere thicknesses of 350 to 400 km, and would also permit partial melting at similar depths if volatiles were reintroduced from below.

The geophysical observations and implications are consistent with characteristics of xenolith suites in kimberlites, and further imply lithospheric layering. A low-temperature, major-element depleted but trace element enriched group of harzburgitic rocks is generally believed to represent ancient cratonic lithosphere of probable Archean age (e.g. Richardson et al., 1984). The less depleted, high-temperature peridotite xenoliths are of probable deeper derivation, and are also likely to have been isolated from convective mantle for long periods of time (Walker et al., 1989). High-temperature xenoliths, many type I eclogites, and Cr-poor megacryst suites have HIMU-like isotopic character, similar to the isotopic character of the source rocks of Group I kimberlites. Derivation of Group I kimberlite from depths exceeding 300 km (Edgar et al., 1993; Ringwood et al., 1992) implies deep lithospheric origins for these materials. Proterozoic as opposed to Archean eclogitic diamond inclusion ages in addition to the chemical differences implies formation of the deeper tectosphere in post-Archean time by different processes and from different protoliths compared to the Archean components.

Petrologic, geochemical, isotopic and geophysical evidence is therefor consistent with the existence of continental lithosphere of the order of 400 km thick. Moreover, a three-layer model comprising the crust, depleted peridotite of Archean age and a deeper regime consisting of a mixture of less depleted oceanic-like peridotite and eclogite of probable Proeterozoic age is required. While the necessity for a two-layer mantle portion of the lithosphere (Helmstaedt and Schulze, 1989; Kesson and Ringwood, 1989) that formed at different times (Boyd, 1989; Gurney, 1990) and probably by different processes has been recognized in some evolution models, most proposed schemes address only the uppermost depleted and older portion or do not address the apparent age and compositional distinctions between the components (e.g. Pollack, 1986; Canil, 1991 and 1992; de Wit et al., 1992; Herzberg, 1993 and references therein).

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