Lithospheric mantle beneath southern Africa: Composition, structure and evolution

W. L. Griffin[1,2], Suzanne Y. O'Reilly[1] and L. M. Natapov[1]

1. GEMOC Key Centre, Dept. of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia. *email: bill.griffin@mq.edu.au*
2. CSIRO Exploration and Mining, North Ryde, NSW 2113, Australia

Introduction

The composition, thermal state and structure of the subcontinental lithospheric mantle (SCLM) have been examined beneath 23 areas across southern Africa, using trace-element analysis of >3500 Cr-pyrope garnets and >1000 chromites from >60 kimberlites. The depth context of each garnet grain has been established by referring its Nickel Temperature to a local paleogeotherm based on xenolith and/or xenocryst thermobarometry. The garnets have been classified into populations, using two novel statistical approaches, and these data provide a stratigraphic column for each area or time slice, showing the vertical distribution of rock types and processes. An inversion of the O'Neill-Wood olivine-garnet thermometer (Gaul et al., 2000) has been used to derive the mean %Fo of olivine at each level of the lithospheric mantle.

The aims of the project have been to:

- Characterise the SCLM beneath the different terranes of the Kalahari Supercraton, to see if these were different at time of craton amalgamation
- Examine changes in the SCLM between different time slices
- Quantify differences in SCLM beneath Archean terranes and Proterozoic fold belts, to evaluate the mechanisms that produce the observed secular evolution of SCLM
- Relate regional variations in SCLM type to the detailed seismic tomography now available.

Regional Geological Setting

Published summaries of the tectonics of the region show serious discrepancies; the new synthesis summarised here will be presented elsewhere with primary sources. The Kalahari Supercraton is made up of the Zimbabwe Craton, the Kaapvaal Craton, and the Limpopo Microcontinent. The Zimbabwe craton, which had been assembled by 2.7 Ga ago, was not sampled in this study. The Limpopo Microcontinent formed 3.2-3.8 Ga ago, and joined the Zimbabwe Craton before 2.6 Ga. The eastern part of the Kaapvaal Craton consists of three terranes with NE-trending boundaries: the Southeastern, Central and Pietersburg terranes, which joined >2.9 Ga ago and collided with the Limpopo microcontinent ca 2.6 Ga ago. The Western Terrane joined the rest of the craton ca 2.5 Ga ago, along an eastward-dipping subduction zone. The Proterozoic Kheis-Okwa-Makondi belt was the passive margin of the supercraton from ca 2.2-1.5 Ga, and was strongly deformed during convergence at ca 1.3 Ga, prior to the accretion of the Namaqua-Natal belt (0.9-1.2 Ga) along the southern margin of the supercraton.

Results and Discussion

Differences between terranes

Comparison of sections from different terranes within the craton is complicated by possible temporal changes in the SCLM. The closest comparison of contemporaneous SCLM sections is provided by Group 2 kimberlites (Western Terrane), the Kroonstadt area (SE Terrane) and the Limpopo Belt (Figure 1).

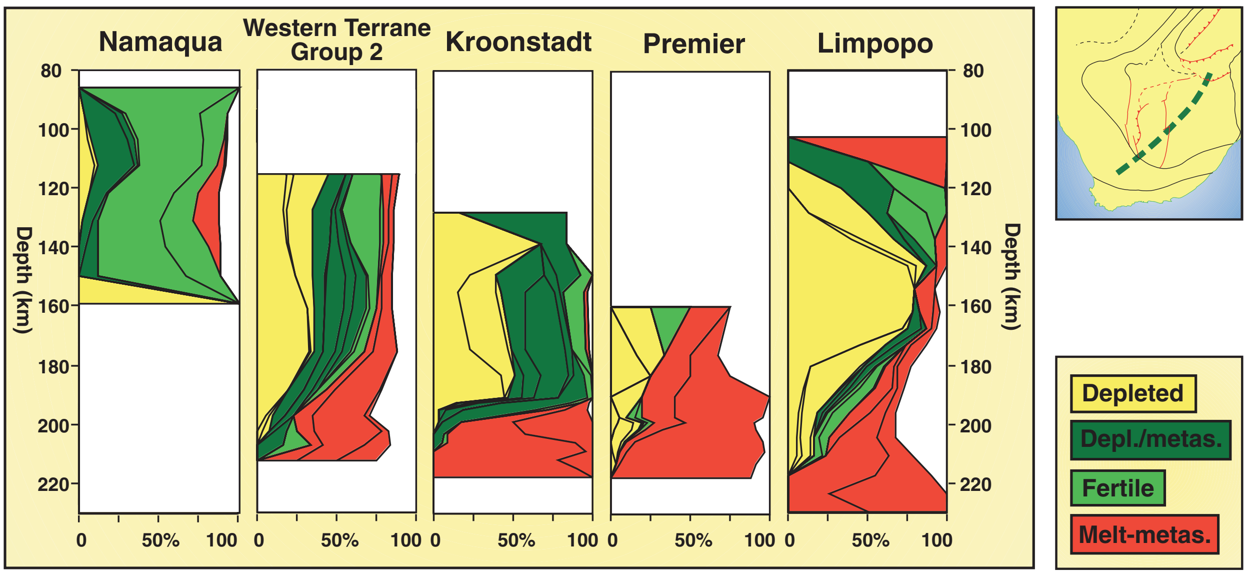

Figure 1: Lithosphere traverse across southern Africa (see inset), showing distribution of different rock types with depth, reconstructed from analysis of garnet concentrates.

The Limpopo section may be the most primitive, since the 500 Ma kimberlites erupted before the Karoo plume, which may have affected the Western Terrane section. The Limpopo SCLM is extremely depleted from 120-180 km, with a very high proportion of subcalcic harzburgites. The lower 20-30 km of the section is much less depleted, even ignoring the effects of melt-related metasomatism. Limited Re-Os data suggest the depleted SCLM is ancient, but the lower portion may contain younger material (Carlson et al., 1999). The Kroonstadt section (SE Terrane) shows a thick plug of depleted and depleted/metasomatised rocks with a well-defined lithosphere-asthenosphere boundary (LAB) at 190 km. It may originally have been as depleted as the Limpopo section, but was more metasomatised by the time it was sampled (120-220 Ma). The Western Terrane SCLM sampled by Group 2 kimberlites is overall less depleted; compared to the Kroonstadt section, it has more fertile rocks at shallow depth and more melt-related metasomatism at depth, making the LAB more transitional. This may reflect the influence of the Karoo plume (ca 180 Ma), or could be a primary difference.

The differences between sections suggest that each terrane was carrying its own lithospheric keel at the time of craton amalgamation (2.6-2.7 Ga), as in Siberia (Griffin et al., 1999). But ambiguity remains because of age differences in the kimberlites, and thus in the timing of post-accretion modification. This may only be resolved by detailed dating of mantle depletion and enrichment events.

Modification of cratonic SCLM: The Western Terrane SCLM sampled by kimberlites at >110 Ma and at <90 Ma is significantly different (Fig. 2).

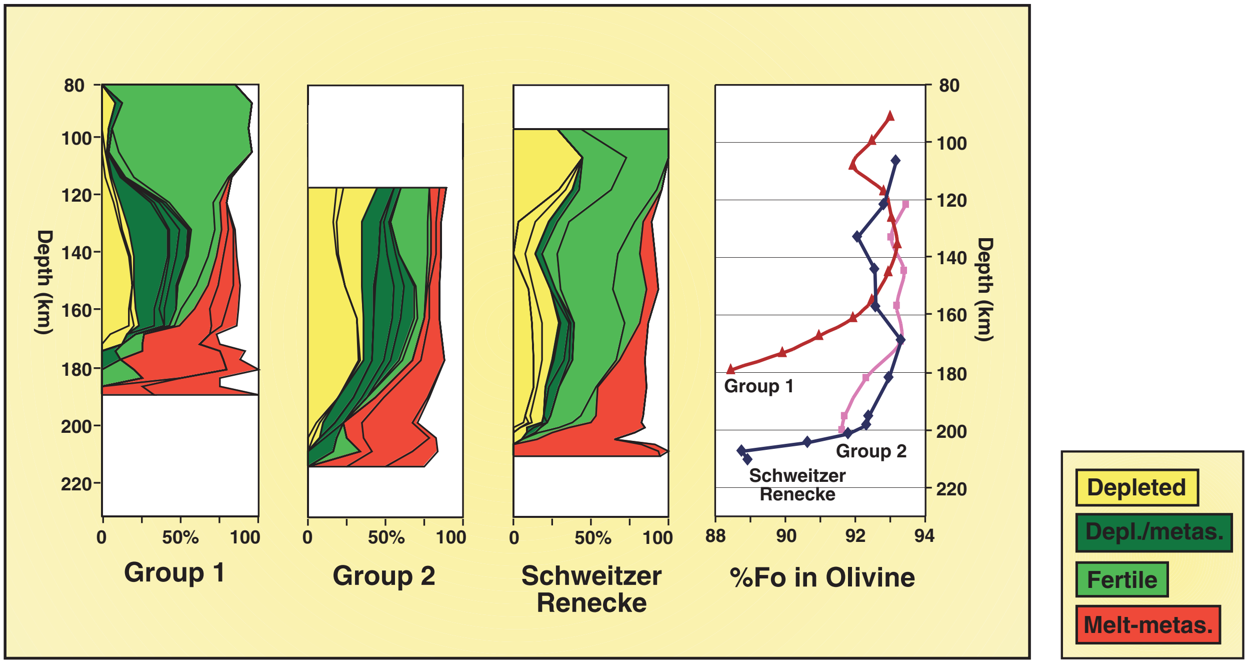

Fig. 2 – Lithosphere sections for the Western Terrane of the Kaapvaal craton. Group 1 and Group 2 kimberlites are from the southern part of the terrane, and intruded at ≤90 Ma and >110 Ma, respectively. Schweitzer Renecke kimberlites are inferred to be ≤90 Ma old. The younger sections are significantly more fertile, reflecting mantle metasomatism.

The younger section shows a much lower proportion of depleted rocks, a higher geotherm and a shallower and more transitional LAB due to a stronger influence of melt-related metasomatism. Pervasive phlogopite-related metasomatism at 80-120 km, accompanied by Fe introduction, has produced an overall rise in fertility. The %Fo is nearly constant through the older section, but has been reduced by metasomatism at the top and bottom of the younger section. The Schweitzer Renecke section, based on 500 alluvial garnets locally derived from small ilmenite-rich kimberlites (<90 Ma?), shows a similar pattern with relatively fertile rocks abundant at shallow depths, but less pronounced reduction in the abundance of depleted rocks, and on the mean %Fo of the whole section.

Some of the metasomatism of the SCLM may have occurred during the Karoo event, but the Group 2 kimberlites erupted after this, and show less modification. The major changes may be related to the "plume" activity that produced the widespread Group 1 kimberlites. The 90 Ma lithosphere erosion and rise in the geotherm coincide with major uplift and erosion across the Kaapvaal Craton (Brown et al., 1998).

Relationships to Tomography -- the Premier "Big Hole"

Detailed seismic tomography along a swath SW-NE across the area studied here (James et al. 2001) shows thick high-velocity roots beneath the SW Kaapvaal Craton and the Limpopo Belt. The extreme relief on the base of the high-velocity volume may reflect the metasomatic processes described above: magma conduits with high degrees of metasomatism become lower-velocity volumes, and appear as pipes through the keel, while less metasomatised volumes appear as "roof pendants" of higher-velocity material.

The tomography also reveals a belt of relatively low seismic velocity across the northern part of the Kaapvaal craton, underlying the Bushveld Intrusion and extending westward toward the related but unexposed Molopo Farm intrusion, linked to the Bushveld by an E-W trending dike swarm. Lower-velocity mantle can indicate higher temperatures, but the Premier section (1.2 Ga) shows extensive melt-related metasomatism and a mean %Fo (91.5) significantly lower than other Kaapvaal sections. This most likely reflects modification of the mantle by basaltic melts, producing iron enrichment and a consequent decrease in seismic velocity and increase in density (Griffin et al., 1999a; Poudjom Djomani et al, 2001). The low-velocity mantle seen beneath the Cape Fold Belt is consistent with the fertile SCLM found beneath Phanerozoic fold belts worldwide (Griffin et al., 1999a).

Proterozoic SCLM

Figure 3 compares craton-margin SCLM beneath Lesotho and Botswana with two of the cratonic sections.

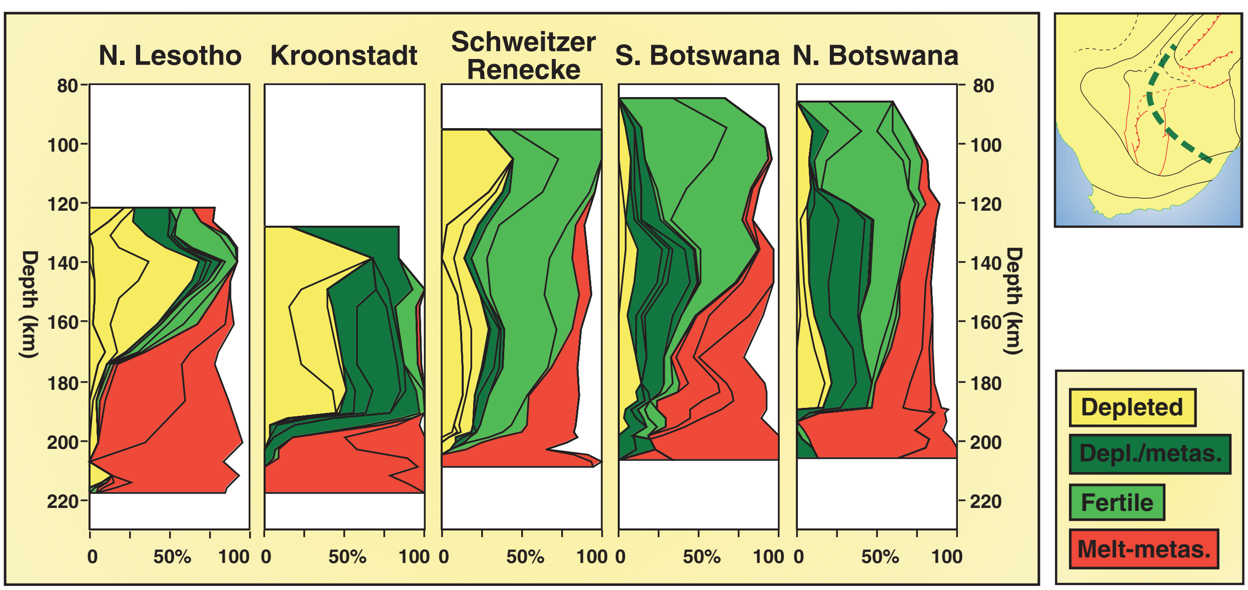

Fig. 3: SCLM traverse across the Kaapvaal craton, into the Kheis-Okwa-Makondi belt, showing the more fertile nature of SCLM (reworked Archean?) beneath the Proterozoic terrain.

The N. Lesotho (<100 Ma) section shows a low proportion of harzburgites, but a high proportion of depleted lherzolites suggests the SCLM was originally highly depleted, like the

Kroonstadt section in the same terrane. The differences suggest major modification of the N. Lesotho section, with shallowing of LAB to ca 170 km, which could related to either the Karoo plume or to continent-margin processes during the accretion of the Natal Province.

The Botswana sections are similar to many Proterozoic sections worldwide. They show a low proportion of depleted rocks generally, but a high proportion of depleted/metasomatised lherzolites in the lower portions of the sections suggests they were originally more depleted. Fertile rocks are very abundant at levels <130 km. Re-Os data indicate that at least the N. Botswana SCLM is Archean in origin (Carlson et al., 1999). Comparison with the time-related changes in the Western Terrane suggest the further progress of similar metasomatic processes, in the Kheis-Okwa-Makondi belt. It is unlikely that a plume has been active along this entire belt, and some kimberlite magmatism in S. Botswana precedes the Karoo plume. These sections suggest that similar metasomatic processes modified Archean SCLM during the rifting that produced the passive margin, and/or the subsequent collisional events.

The Namaqua Fold Belt SCLM (Fig. 1) may reflect similar processes; it is thin, but resembles the upper part of the Botswana sections.

Implications for secular evolution of SCLM

The worldwide correlation between SCLM composition and the tectonothermal age of the overlying crust (Griffin et al., 1998, 1999) also is seen in the data presented here. These observations, combined with available Re-Os dating, indicate that at least some Proterozoic SCLM represents reworked Archean SCLM, refertilised by metasomatic processes. This is not really surprising, since density modelling (Poudjom Djomani et al, 2001) shows that Archean SCLM is so buoyant and refractory that it cannot be "delaminated" or melted, and will tend to persist even during rifting and collision events.

Phanerozoic SCLM is very different; it is little depleted, and most of the garnet classes that dominate young SCLM sections are rare or absent in Archean and Proterozoic sections. There may have been only two regimes of SCLM formation in Earth history -- Archean-type SCLM , which is persistent and gradually refertilised, and Phanerozoic-type SCLM, which is so much denser that it is subject to cyclic delamination and replacement (Poudjom Djomani et al., 2001; O'Reilly et al., 2001). Any Phanerozoic-type SCLM that formed in Archean or Proterozoic time would have disappeared. The late Archean may mark an even bigger break in Earth's geodynamics than previously thought.

References

Brown, R.W., Gallagher, K., Griffin, W.L., Ryan, C.G., de Wit, M.C.J., BVelton, D.X. and harman, R., 1998. Kimberlites, accelerated erosion and evolution of the lithospheric mantle beneath the Kaapvaal craton during the mid-Cretaceous. *Ext. Abstr. 7th Int. Kimberlite Conf.*, Cape Town, 105-107.

Carlson, R.W., Pearson, D.G., Boyd, F.R., Shirey, S.B., Irvine, G., Menzies, A.H. and Gurney, J.J. 1999. Re-Os systematics of lithospheric peridotites: Implications for lithosphere formation and preservation, in *Proc 7th International Kimberlite Conference*, edited by J.J. Gurney, et al., pp. 99-108, Redroof Designs, Cape Town, 1999.

Gaul, O.F., Griffin, W.L., O'Reilly, S.Y. and Pearson, N.J. 2000. Mapping olivine composition in the lithospheric mantle. *Earth Planet. Sci. Lett.* 182, 223-235.

Griffin, W.L., O'Reilly, S.Y., Ryan, C.G., Gaul, O. and Ionov, D. 1998. Secular variation in the composition of subcontinental lithospheric mantle. *In* J. Braun, et al. (eds) Structure & Evolution of the Australian Continent, *Geodynamics Volume* 26, Amer. Geopyhys. Union, Washington D.C. pp. 1-26

Griffin, W.L., O'Reilly, S.Y. and Ryan, C.G. 1999a. The composition and origin of subcontinental lithospheric mantle. In: Y.Fei et al. (eds.) *Mantle Petrology: Field observations and high-pressure experimentation : A tribute to Francis R. (Joe) Boyd*, Geochemical Society Special Publication #6, The Geochemical Society (Houston). pp. 13-45

Griffin, W.L., Ryan, C.G., Kaminsky, F.V., O'Reilly, S.Y., Natapov, L.M., Win, T.T., Kinny, P.D. and Ilupin, I.P. 1999b. The Siberian Lithosphere Traverse: Mantle terranes and the assembly of the Siberian Craton. *Tectonophysics* 310, 1-35.

James, D.E., Fouch, M.J., VanDecar, J.C., van der Lee, S. and Kaapvaal Seismic Group 2001. Tectospheric structure beneath southern Africa. *Geophys. Res. Lett.* 28, 2485-2488.

Poudjom Djomani, Y.H., O'Reilly, S.Y., Griffin, W.L. and Morgan, P. 2001. The density structure of subcontinental lithosphere: Constraints on delamination models. *Earth Planet. Sci. Lett.* 184, 605-621.

O'Reilly, S.Y., Griffin, W.L., Poudjom Djomani, Y. and Morgan, P. 2001. Are lithospheres forever? Tracking changes in subcontinental lithspheric mantle through time. *GSA Today* 11, 4-9.