

Compositionally Stratified Cratonic Lithosphere: Petrology and Geochemistry of Peridotite Xenoliths from the Labait Volcano, Tanzania

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ABSTRACT

In northern Tanzania, manifestations of the East African Rift, such as crustal warping, rifting, and magmatism, are currently propagating into the margins of the Archean Tanzanian craton. In order to understand the factors that govern the origin and stability of cratonic mantle, we are studying peridotite xenoliths from the Quaternary Labait volcano, located on the northeastern edge of the craton. We find that refractory mantle (Mg# up to 92) persists to depths of at least 150 km, with a marked increase in fertility at depths > 120 km. This compositional stratification may be due to 1) an original variation in depth of degree of partial melting, 2) refertilization from below of a preexisting depleted mantle section, or 3) incremental downward growth of the lithosphere with time. Re-Os systematics favor the latter two hypotheses (Chesley *et al.*, 1998).

The refractory peridotites are less dense than pyrolite, and the preservation of old Re-Os ages beneath Labait attests to the perseverance of cratonic mantle despite proximity to rifting. However, high proportions (75 %) of dense, Fe-rich (Mg# < 88) dunites in the xenolith population and elevated temperatures at depth indicate that chemical and thermal interaction of the mantle section with asthenospheric magmas has and is occurring. Collectively, these features result in slow shear-wave velocities, consistent with the results of a recent seismic tomographic study, which shows that the effects of rifting are beginning to propagate into the cratonic mantle beneath Labait.

Keywords: xenolith, mantle, stratification, craton, density, delamination, stability, refractory, isopycnic

1. INTRODUCTION

Geologic and geochemical studies of mantle xenoliths suggest that cratons are underlain by an anomalously thick, cold mantle keel (Jordan, 1978; Boyd, 1989a), which can be stable over timescales greater than two billion years (Richardson *et al.*, 1984; Walker *et al.*, 1989; Pearson *et al.*, 1995). Cooler temperatures should increase density and hence decrease the buoyancy of mantle peridotite; if cold enough, entrainment into the convecting mantle would be expected. The observed longevity of cratonic mantle beneath Archean shields, however, requires an additional factor that compensates for the increased density caused by colder temperatures. One possibility is that cratonic mantle is intrinsically less dense than the surrounding mantle due to its more depleted chemical composition (Ringwood, 1966; Jordan, 1978), leading to the popular notion that cratonic keels are regions of tectonic stability immersed within a mobile and actively convecting mantle.

To determine how cratonic mantle is generated, stabilized, and potentially destabilized, we are conducting an integrated petrographic and geochemical study of mantle xenoliths from the Labait volcano, located on the northeastern margin of the Tanzanian craton. Because the Tanzanian craton is located within an intracontinental rift, our results have implications for the

effects of rifting on cratonic mantle. In addition, there are ongoing geophysical studies in the same region (Ritsema *et al.*, 1998), providing a unique opportunity to make direct comparisons between geophysical and geochemical datasets. Here, we show that the Tanzanian mantle is compositionally stratified, with a step-wise increase in fertility with depth. We also show that local Fe-enrichment is superimposed on the overall compositional stratigraphy and that dense, Fe-rich peridotites are the dominant xenolith types at Labait. We discuss the implications of these findings for the origin and potential demise of cratonic mantle.

2. REGIONAL GEOLOGY

The Tanzanian craton is an amalgamation of several Archean granitoid terranes, which formed primarily during three short periods (~2.9, ~2.7, and ~2.4 Ga) based on Sm/Nd, Rb/Sr, and U-Pb dating (Pinna *et al.*, 1996). In the northern portion of the craton, these granitoids intrude and separate many large and small greenstone belts (Borg and Shackleton, 1997). Re-Os depletion ages for mantle xenoliths from Labait yield minimum melt extraction ages of up to ~2.8 Ga, indicating that stabilization of the lithospheric mantle occurred by the end of the Archean (Chesley *et al.*, 1998). The craton is surrounded by several Proterozoic mobile belts. It is bounded to the east by the polycyclic collisional Mozambique belt (900-500 Ma), which consists of a region of reworked Archean crust directly east of the craton (based on Sm-Nd model ages; Möller *et al.*, 1998), and a region of younger, accreted crust further east and northeast (Pinna *et al.*, 1996; Möller *et al.*, 1998). To the east and southeast, the craton is bounded by the Usagaran Belt, which is a Proterozoic subduction zone (based on U-Pb dates of metamorphic minerals from eclogite facies rocks (Möller *et al.*, 1995)). To the southwest, the craton is bounded by the Early to Middle Proterozoic Ubendian Belt (2.0 Ga), to the west by the Late Proterozoic Karagwe-Ankolean Belt and the early Paleozoic Bukoban system, and to the northwest by the Ruwenzori Belt of Uganda.

In northern Tanzania, Cenozoic tectonism is dominated by rifting. The Eastern Branch of the East African Rift system, the Gregory Rift, is composed of three distinct rifts, the NW-trending Pangani rift, the N-S-trending Natron-Manyara-Balangida rift, and the NE-trending Eyasi-Wembere rift. The latter two rifts transect the boundary between Archean and Proterozoic crust (Ebinger *et al.*, 1997; Foster *et al.*, 1997). The present rift basins and volcanism are mostly younger than 2 Ma, with ages not exceeding 4 Ma (Dawson, 1992). The xenolith locality, Labait, is an olivine-melilitite volcano (4° 34'S, 35° 26'E) composed of flows and tuffaceous units and located in the Tanzanian section of the East African Rift, south of Mount Hanang on the northeastern edge of the Tanzanian craton (Dawson *et al.*, 1996). The eruption age is constrained to be Quaternary by U-Pb dating of metamorphic zircons in a mantle xenolith (Rudnick *et al.*, 1998).

Geophysically, the Tanzanian craton is characterised by high elevation, a negative Bouger gravity anomaly (Ebinger *et al.*, 1997), and low surface heat flow (Nyblade *et al.*, 1990). Results from a recent broad-band seismic experiment show that the Tanzanian mantle root is largely intact beneath the craton, that the uplift and negative gravity anomaly are due to hot, low density material beneath the cratonic root, and that erosion and/or heating of this ancient root is confined to the vicinity of the rift (Ritsema *et al.*, 1998).

3. OVERVIEW OF XENOLITH SUITES

To estimate the proportions of various xenolith types, we systematically collected all xenoliths encountered during the first half day of fieldwork ($n = 117$). Fe-rich dunites make up ~75% of the Labait xenoliths and were identified in the field by the dark green color of their olivine. Of these, 25% contain visible chrome diopside in hand-specimen. Residual peridotites make up 22% of the xenoliths and were identified by their light-green olivines. The remaining <3% consist of lower crustal xenoliths (granulites), glimmerites, and pyroxenites. In this paper, we focus on a smaller selection of samples, which consists of 38 residual peridotites, nine Fe-rich dunites, one wehrlite, and one glimmerite. Six garnet-bearing peridotites from Dawson *et al.* (1996) are also included. Modal mineralogies are shown in Fig. 1 and reported in Table 1. Xenolith sizes range from 5 to 30 cm in diameter and are mostly egg-shaped. Unlike kimberlite-hosted xenoliths, which are often heavily serpentized, the Labait peridotite xenoliths are serpentine-free and generally fresh.

Residual peridotites are harzburgites or clinopyroxene-poor lherzolites, and contain either hercynitic spinel, chromite, or garnet. We have classified these peridotites into garnet and spinel facies based on the presence of garnet or, in the absence of garnet, on spinel and orthopyroxene chemistry and calculated temperatures of equilibration. The Fe-rich dunites can contain Cr-diopside, chromite, or both. Wehrlites are also Fe-rich (LB15) and can occur as cross-cutting planar dikes in composite xenoliths (e.g. LB19). Only one glimmerite was collected. This sample consists of fine-grained phlogopite grains with interstitial ilmenites.

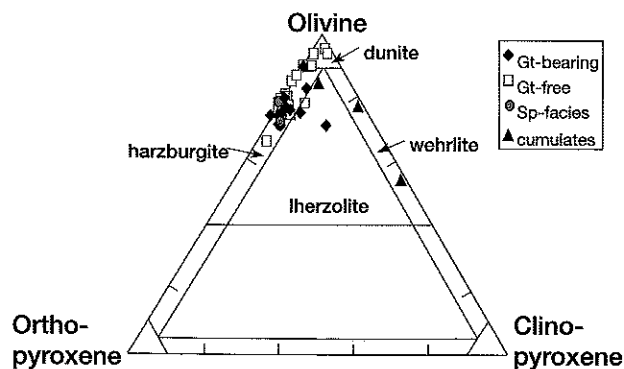


Figure 1. Modes calculated by least-squares regression of whole-rock and mineral elemental analyses for Labait peridotites (garnet and spinel normalized out). Garnet-free peridotites refer to peridotites containing chromite and low Al_2O_3 orthopyroxene and are distinct from true spinel-facies peridotites.

Table 1.

| | Modal Mineralogy* | | | | | Trace*** | |
|--|-------------------|-------|------|-----|-----|----------|----------------|
| | OL | CPX** | OPX | SP | PHL | | GT |
| Garnet-Lherzolites | | | | | | | |
| LB 12 | 70.1 | 7.0 | 15.3 | | | 7.6 | Sf |
| LB 45 | 60.8 | 14.0 | 9.8 | | | 15.4 | |
| Garnet Harzburgites | | | | | | | |
| LB 4 | 68.2 | 4.1 | 22.5 | | | 5.1 | Sf |
| LB 2 | 72.1 | 2.1 | 22.0 | 3.8 | | | |
| LB 24 | 76.9 | 1.0 | 17.6 | | | 4.5 | Sf |
| LB 34 | 88.2 | 1.1 | 8.2 | | | 2.6 | Ph |
| LB 50-1 | 72.8 | 2.5 | 20.3 | | | 4.4 | Sf |
| LB 53 | 77.3 | 5.1 | 10.2 | | | 7.5 | Sf |
| KAT 17 | 72.0 | 3.5 | 24.1 | | | 0.4 | |
| GL4202 | 73.7 | 4.2 | 18.0 | | | 4.2 | |
| GL4203 | 75.2 | 1.8 | 18.9 | | | 4.1 | |
| GL4206 | 71.2 | 0.0 | 23.6 | | | 5.2 | |
| Garnet-free Peridotites | | | | | | | |
| KAT 1 | 67.8 | 1.1 | 28.2 | 2.8 | | | |
| LB 1 | 77.7 | | 20.6 | 1.7 | | | Sf, Ph |
| LB 6 | 86.9 (2.22) | 6.8 | 2.4 | 1.7 | | | Sf |
| LB 7 | 87.9 (0.68) | 8.0 | 3.4 | | | | Sf, Ph |
| LB 8 | 79.9 (0.54) | 17.3 | 2.3 | | | | Sf, Ph |
| LB 9 | 76.7 (7.03) | 13.4 | 2.8 | | | | Ilm |
| LB 14 | 94.4 | 1.9 | 3.7 | | | | Ph |
| LB 16 | 78.4 | 1.3 | 19.4 | 0.9 | | | Sf, Ph, Hm |
| LB 17 | 75.0 | 1.1 | 21.7 | | 4.5 | | Sr, Rt, Zr |
| LB 21 | 96.1 (3.94) | | | tr | | | Sf, Ph, Rt, Pv |
| LB 22 | 77.6 | 1.5 | 18.2 | 2.7 | | | Sf, Ph, Pv |
| LB 23 | 79.6 | 1.5 | 17.1 | 4.3 | | | Sf, Ph, Rt, Pv |
| LB 26 | 85.9 | 0.3 | 13.8 | | | | Sf, Pv |
| LB 32 | 77.5 | 3.1 | 18.2 | 1.2 | | | Sf, Ph, Pv |
| LB 33 | 86.4 | 3.1 | 5.8 | | 4.7 | | Sf, Ph, Rt, Pv |
| LB 36 | 73.9 (2.62) | 21.9 | 1.6 | | | | Sf |
| LB 39 | 63.3 | 2.9 | 28.3 | 5.4 | | | |
| LB 40 | 79.4 | | 19.4 | 1.2 | | | Ilm |
| LB 54 | 73.8 | 5.1 | 19.1 | 2.0 | | | Sf, Ph |
| LB 55 | 75.7 | 1.6 | 19.9 | 2.7 | | | Sf, Ph |
| LB 60 | 79.2 | 0.9 | 17.8 | 1.2 | 1.0 | | Sf, Ph |
| LB 61 | 86.5 (0.63) | 11.4 | 0.8 | 0.7 | | | |
| Spinel-facies Peridotites | | | | | | | |
| LB 11 | 78.6 | 0.8 | 19.5 | 1.2 | | | Sf |
| LB 29 | 78.4 | | 20.3 | 1.4 | | | Pv |
| LB 31 | 69.7 | 3.4 | 22.2 | 4.7 | | | Sf |
| Fe-rich Dunites & Wehrlites | | | | | | | |
| LB 15 | 54.8 | 45.2 | | | | | |
| LB 46 | 83.7 | 7.7 | 6.9 | 1.7 | | | Ilm |
| LB 51 | 75.6 | 21.4 | 2.9 | | | | |
| LB 58 | 92.3 | 5.4 | 2.3 | | | | Crbn, Nph |
| LB 59 | 95.9 | | | | 4.1 | | |

* all modes have been normalized to 100 after least squares fitting

** Parentheses around secondary clinopyroxenes

*** 3rd column represents trace metasomatic phases not included in calculations

Sf=Sulfide; Rt=Rutile; Ph=Phlogopite; Zr=Zircon; Pv=Perovskite

Ilm=Ilmenite; Nph=Nepheline; Crb=Carbonate; Hm=Harmatome

LB 4 = calculated using garnet from LB 12

LB 17 = pervasive veining giving rise to poor least square fits

LB 34 = calculated using garnet from LB 12

LB 39 = calculated assuming no phlogopite

LB 50-1 = calculated using garnet from LB 12

GL's = data from Dawson *et al.* (1996)

4. PETROGRAPHY

4.1 Olivine

Olivines are fresh and range from fine-grained and equant to coarse-grained and tabular in shape. Undulose extinction due to kink-banding is observed in many samples. Mosaic-porphroclastic texture, reminiscent of Kaapvaal high temperature sheared peridotites, is typical of the garnet-bearing and higher temperature peridotites at Labait. In these xenoliths, there are sometimes two textural generations of olivine. One generation is characterized by small equant grains, which show varying degrees of grain boundary recrystallization. The other generation consists of larger olivine grains, which have a more tabular morphology, perhaps formed by partial annealing (Mercier, 1985). Olivine inclusions occasionally occur in garnet breakdown patches. Similar inclusions have been observed in fresh garnets from the Lashainé xenolith site, located approximately 150 km northeast of Labait (Rudnick *et al.*, 1994).

4.2 Orthopyroxene

Orthopyroxenes occur as small to large groundmass grains and also as products of garnet breakdown. Exsolution lamellae are confined to orthopyroxenes from spinel-facies xenoliths. In one sample (LB17), orthopyroxene is more abundant in a late-stage metasomatic vein that also includes zircon, rutile, phlogopite, sulfides, and ilmenite.

4.3 Clinopyroxene

Clinopyroxene commonly occurs as a secondary phase, where it rims chromite and orthopyroxene, in garnet breakdown patches, and in metasomatic veins and patches. These clinopyroxenes are characterized by small grain size and poorly developed morphology, typically appearing as amorphous interstitial blebs. Clinopyroxene also occurs as larger primary grains in wehrlites,

Fe-rich cumulates, and in garnet-bearing peridotites; these have better developed morphology compared to secondary grains.

4.4 Garnet

Garnets occur as discrete, round grains. All garnets (except for those in LB2) have a two-stage decomposition history based on the occurrence of texturally distinct outer and inner breakdown assemblages (Fig. 2a). The outer assemblage is coarser-grained than the inner assemblage and resembles coronas developed around garnets in crustal metamorphic rocks. These coronas consist of equidimensional grains of symplectic pale-brown spinel, orthopyroxene, and clinopyroxene (fine-grained) which embay the surrounding groundmass olivines. Phlogopite and sulfide occasionally occur as accessory phases (e.g. LB12, 34). In most samples, the petrography and textures suggest the following reaction: $gt + ol = opx + sp + cpx$ (Reid and Dawson, 1972; Smith, 1977; Jaques *et al.*, 1990). The occasional presence of sulfide and phlogopite in some of the garnet coronas shows that the process was not entirely isochemical.

The interiors of former garnets consist of very fine-grained kelyphite encased by the outer corona assemblage (Fig. 2a, b). Pristine garnet, if present, occurs at the center of these fine-grained cores or as tiny grains distributed within the inner kelyphite. In thin section, the inner kelyphite appears as an aphyric, feathery-textured mass. In some samples, the aphyric mass is composed of smaller, round subdomains with radiating fabric, which are remarkably homogeneous in back-scattered electron images, but which contain small amounts of Na, indicating that the kelyphite formation was not entirely isochemical.

In the breakdown assemblages described above, no glass was found. However, in LB2 there are round to oval-shaped patches consisting of clinopyroxene, orthopyroxene, glass (fresh), and occasionally olivine. Clinopyroxene and glass are the dominant phases, with clinopyroxene occurring as small

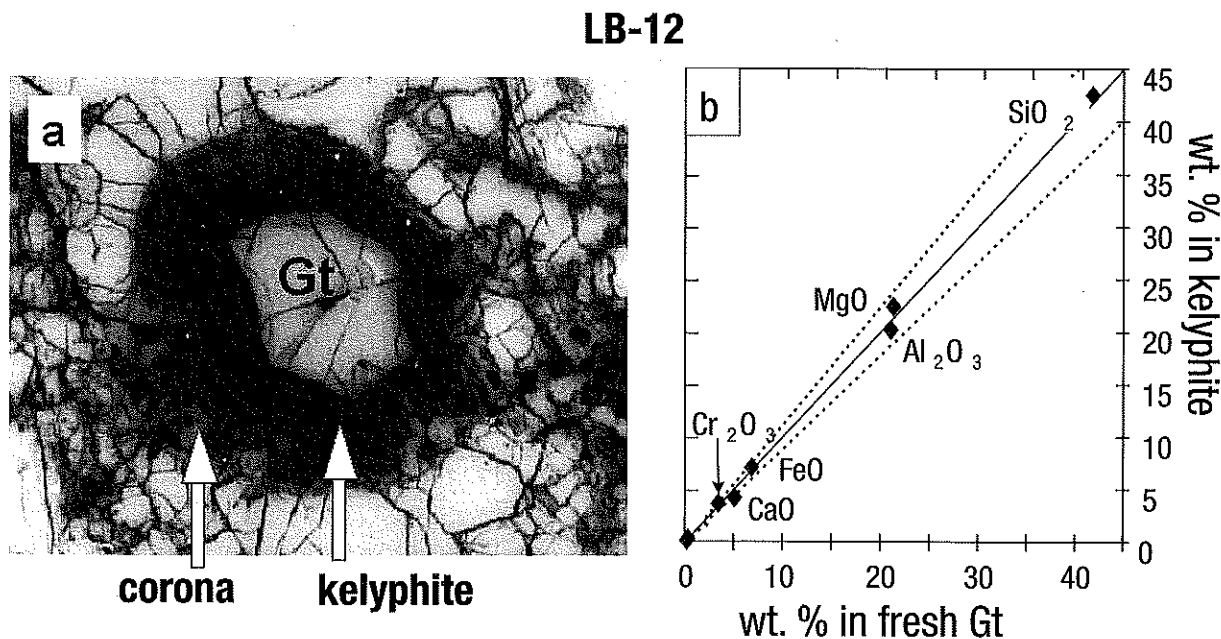


Figure 2. (a) Photomicrograph of a partially decomposed garnet in LB12 (plane-polarized light). Note that the fresh garnet core (clear) is enclosed by an outer coronal assemblage, consisting of aluminous spinel, orthopyroxene, and clinopyroxene grains, which itself encloses an inner kelyphite assemblage, characterized by a fine-grained aphyric mass. (b) Rastered probe analyses of the inner kelyphite assemblage versus that of the fresh garnet. Symbol in lower left corner is TiO₂. Dotted lines represent 10% deviation from 1:1 (solid line).

grains separated by thin glass films, resulting in a fishnet-like texture. In some cases, clinopyroxene aggregates within a single patch exhibit identical extinction. The glass and clinopyroxene also embay or intrude into the olivine wallrock, imposing a serrated appearance to the olivine grain boundaries. We interpret these patches also as former garnets.

4.5 Chromite and Spinel

Chromite or spinel is observed in almost all samples, with variations in composition and texture between samples. Chromite is generally opaque while spinels tend to be reddish-brown. Chromites are scarce in garnet-bearing peridotites, but aluminous spinels occur in the garnet breakdown patches. In harzburgites, chromite occurs as large, round blebs which form in the interstices of the primary mineral assemblage or as inclusions in olivine or orthopyroxene; these are presumed to be primary. The latter occasionally induce radial fractures in their host mineral. Chromites also occur as irregular, skeletal growths, which have distinct "herring-bone" textures. Many of the chromites appear to be mantled by secondary mineral assemblages. In harzburgites, some chromites have thin rims of rutile, which may have formed

by exsolution of Ti during cooling or by precipitation from a Ti-rich metasomatic fluid (Bodinier *et al.*, 1996). Late-stage metasomatic selvages consisting of clinopyroxene, phlogopite, and/or other phases may also mantle these primary chromites. In one Fe-rich sample, LB58, plate-like chromites are mantled by clinopyroxene, carbonate, glass, and other secondary minerals (Lee and Rudnick, 1998). Similar observations have been reported from other xenolith suites and attributed to carbonatite-metasomatism (e.g. Dautria *et al.*, 1992; Rudnick *et al.*, 1993).

4.6 Phlogopite

Phlogopite occurs mostly as a secondary phase, associated with metasomatic veins or patches but only rarely as a texturally primary phase. For example, in LB19C it occurs as large platy grains within the groundmass olivine. In this particular specimen, small skeletal chromites are included within the phlogopites.

4.7 Other minerals

In several samples, sulfides occur in association with metasomatic and garnet breakdown patches and as tiny inclusions in olivine or on grain boundaries. Other metasomatic phases such

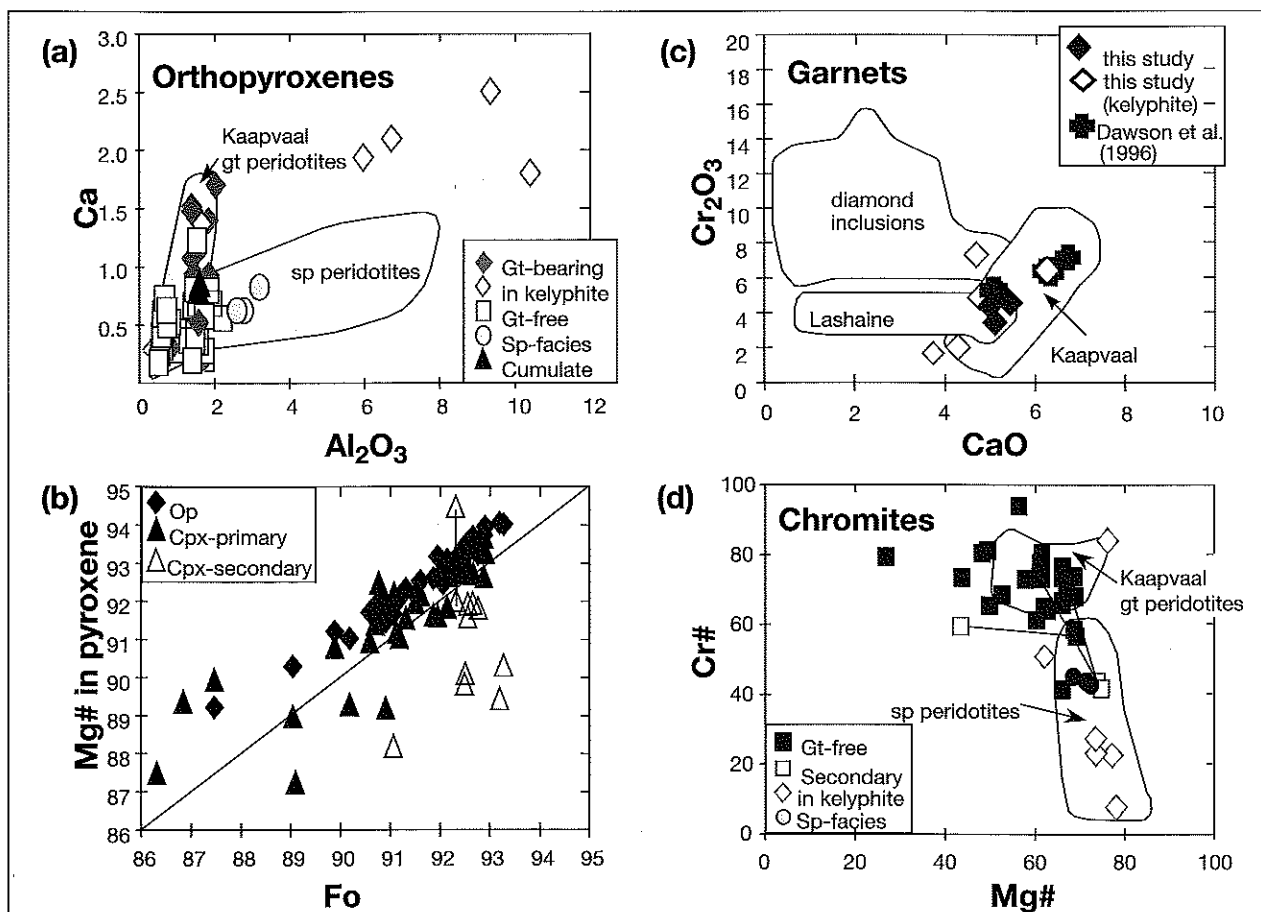


Figure 3. (a) Orthopyroxene compositions plotted with field of spinel peridotites and Kaapvaal garnet peridotites. Note the three samples with high Al_2O_3 (grey circles), which are true spinel-facies peridotites. Open diamonds represent kelyphitic orthopyroxenes associated with garnet breakdown. (b) Mg# (=100 Mg/(Mg+Fe)) of pyroxenes in all samples plotted against forsterite content of coexisting olivines. Solid line represents 1:1 correspondence. Orthopyroxenes exhibit a tight correlation, whereas clinopyroxenes are highly scattered. Those that plot well below the 1:1 line are not in equilibrium with the primary assemblage. Tieline connects two generations of clinopyroxene in one sample. (c) Garnet compositions compared to fields of Kaapvaal garnet peridotites, inclusions in diamonds, and Lashaine garnet peridotites. Open diamonds represent compositions measured from rastered probe analyses of fine-grained kelyphites in samples where fresh garnet is absent. (d) Chromite composition compared to field of spinel peridotites and Kaapvaal garnet peridotites. Tielines connect two generations of chromite in the same sample.

Table 2. cont.

| | Garnet Harzburgites | | | | | | | | | | | | | | | | | | |
|--------------------------------|---------------------|-------|----------------|---------------------|--------|-----------------------|-------|-------------------|--------|-------|----------------|--------|-------|--------|-------|-------|--------|--------|--------|
| | LB-34 | | | | LB-50 | | | | LB-53 | | | | | | | | | | |
| | opx | cpx | gt klyphite | sp p klyphite | ol | gt.incls. klyphite | ol | phlog klyphite | opx | cpx | gt klyphite | ol | opx | cpx | gt | ol | | | |
| SiO ₂ | 56.47 | 52.00 | 38.84 | 0.31 | 0.70 | 0.25 | 40.43 | 40.88 | 39.03 | 56.31 | 54.38 | 42.98 | 40.29 | 57.16 | 54.35 | 41.39 | 40.51 | 0.32 | 40.80 |
| TiO ₂ | 0.22 | 1.35 | 0.07 | 4.74 | 0.23 | 2.30 | 0.03 | 0.01 | 3.33 | 0.09 | 0.18 | 0.31 | 0.02 | 0.23 | 0.38 | 0.71 | 0.62 | 0.39 | 0.03 |
| V ₂ O ₅ | | | | 0.31 | 0.07 | 0.18 | | | | | | | | | | | | 0.10 | |
| Al ₂ O ₃ | 1.61 | 1.96 | 18.26 | 13.40 | 43.75 | 24.95 | 0.03 | 0.08 | 13.44 | 1.83 | 2.92 | 21.96 | 0.05 | 1.54 | 2.60 | 19.42 | 19.00 | 46.71 | 0.03 |
| Cr ₂ O ₃ | 0.56 | 1.28 | 7.31 | 43.63 | 24.84 | 39.28 | 0.04 | 0.10 | | 0.36 | 0.73 | 1.73 | 0.04 | 0.53 | 1.51 | 4.72 | 5.05 | 21.56 | 0.06 |
| FeO | 5.79 | 3.19 | 6.01 | 22.95 | 11.92 | 17.06 | 9.79 | 7.36 | 4.61 | 5.21 | 3.52 | 6.44 | 8.49 | 5.35 | 3.23 | 6.70 | 7.15 | 12.05 | 8.67 |
| MnO | 0.11 | 0.10 | 0.33 | 0.30 | 0.30 | 0.37 | 0.12 | 0.10 | 0.02 | 0.10 | 0.10 | 0.24 | 0.12 | 0.10 | 0.09 | 0.28 | 0.30 | 0.28 | 0.12 |
| MgO | 33.72 | 17.65 | 21.86 | 14.22 | 18.45 | 15.48 | 49.03 | 50.49 | 22.16 | 34.04 | 20.12 | 23.56 | 49.53 | 34.41 | 18.76 | 20.90 | 23.28 | 18.67 | 49.92 |
| NiO | | | | 0.33 | 0.07 | 0.25 | 0.35 | 0.38 | | | | | 0.39 | | | | | 0.08 | 0.38 |
| CaO | 0.78 | 20.45 | 4.74 | 0.03 | 0.04 | 0.03 | 0.05 | 0.05 | 0.01 | 1.40 | 16.01 | 3.72 | 0.11 | 1.19 | 17.21 | 5.42 | 4.05 | 0.03 | 0.08 |
| Na ₂ O | 0.27 | 0.69 | 0.39 | | | | | | 0.27 | 0.26 | 1.46 | 0.06 | | 0.24 | 1.67 | 0.06 | 0.11 | | |
| K ₂ O | | | | | | | | | 10.09 | | | | | | | | | | |
| F | | | | | | | | | 0.52 | | | | | | | | | | |
| Cl | | | | | | | | | 0.02 | | | | | | | | | | |
| Total | 99.53 | 98.67 | 97.81 | 100.25 | 100.37 | 100.17 | 99.87 | 99.45 | 100.00 | 99.60 | 99.42 | 101.00 | 99.04 | 100.75 | 99.80 | 99.60 | 100.07 | 100.19 | 100.09 |
| Cr/Cr+Al | | | | 68.60 | 27.58 | 51.37 | | | | | | | | | | | | 23.64 | |
| Mg/Mg+Fe | 91.21 | 90.80 | 86.64 | 52.49 | 73.40 | 61.80 | 89.93 | 92.44 | 89.55 | 92.09 | 91.06 | 86.71 | 91.23 | 91.97 | 91.19 | 84.76 | 85.30 | 73.42 | 91.12 |

| | Garnet-free Peridotites | | | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------|--------------|-------|--------------|-------------|-------|--------------|-------------|--------|-------------|------------|------------|-----------|--------|--------|-------------|--------|-------|
| | KAT 1 | | | | KAT 4 | | | | KAT 8 | | | | LB-1 | | | | | |
| | opx | cpx patch | sp | ol matrix | ol patch | sp | ol matrix | ol patch | opx | cpx core | opx rim | sp core | sp rim | ol | opx | sp 2ndry | ol | |
| SiO ₂ | 57.85 | 53.21 | 0.07 | 40.96 | 40.95 | 0.06 | 43.72 | 40.91 | 57.17 | 53.23 | 53.50 | 0.11 | 0.15 | 41.25 | 57.89 | 0.07 | 0.20 | 40.83 |
| TiO ₂ | 0.07 | 1.34 | 1.19 | 0.02 | 0.02 | 0.32 | 0.01 | 0.01 | 0.03 | 0.14 | 0.15 | 0.18 | 4.54 | 0.01 | 0.03 | 0.51 | 2.02 | 0.01 |
| V ₂ O ₅ | | | | | | 0.18 | | | | | | 0.17 | 0.24 | | | 0.18 | 0.57 | |
| Al ₂ O ₃ | 1.33 | 0.97 | 14.50 | 0.01 | 0.01 | 31.24 | 0.51 | 0.07 | 1.71 | 3.59 | 3.48 | 32.51 | 10.53 | 0.01 | 0.61 | 13.57 | 31.65 | 0.02 |
| Cr ₂ O ₃ | 0.40 | 0.41 | 51.95 | 0.05 | 0.11 | 36.99 | 0.11 | 0.20 | 0.25 | 0.97 | 0.78 | 35.60 | 43.51 | 0.04 | 0.19 | 55.93 | 36.61 | 0.01 |
| FeO | 4.50 | 3.99 | 16.25 | 7.30 | 7.34 | 13.24 | 6.93 | 5.75 | 4.99 | 2.64 | 2.93 | 13.86 | 24.85 | 7.77 | 4.43 | 13.66 | 11.77 | 7.13 |
| MnO | 0.10 | 0.09 | 0.19 | 0.09 | 0.11 | 0.00 | 0.15 | 0.10 | 0.13 | 0.09 | 0.11 | 0.16 | 0.30 | 0.11 | 0.12 | 0.22 | 0.11 | 0.10 |
| MgO | 36.01 | 16.81 | 15.31 | 50.67 | 50.56 | 15.70 | 17.72 | 51.46 | 35.59 | 17.86 | 18.55 | 17.43 | 13.75 | 50.54 | 36.51 | 15.41 | 18.50 | 50.76 |
| NiO | | | | 0.39 | 0.29 | 0.24 | 0.35 | 0.38 | | | | 0.20 | 0.19 | 0.39 | | 0.21 | 0.22 | 0.40 |
| CaO | 0.45 | 22.43 | | 0.06 | 0.12 | 22.03 | 0.02 | 0.10 | 0.28 | 20.23 | 19.74 | 0.02 | 0.04 | 0.07 | 0.31 | 0.05 | 0.01 | 0.04 |
| Na ₂ O | 0.14 | 0.62 | | | | 0.54 | | | 0.03 | 0.89 | 0.70 | | | | | | | |
| K ₂ O | | | | | | | | | | | | | | | | | | |
| F | | | | | | | | | | | | | | | | | | |
| Cl | | | | | | | | | | | | | | | | | | |
| Total | 100.85 | 99.87 | 99.46 | 99.55 | 99.51 | 98.55 | 100.21 | 99.05 | 100.18 | 99.64 | 99.94 | 100.28 | 98.15 | 100.19 | 100.15 | 99.83 | 101.68 | 99.30 |
| Cr/Cr+Al | | | | | | 44.27 | | | | | | 42.35 | 73.49 | | | 73.44 | 43.69 | |
| Mg/Mg+Fe | 93.45 | 88.25 | 62.68 | 92.52 | 92.47 | 91.32 | 70.47 | 92.39 | 92.70 | 92.34 | 91.86 | 69.16 | 49.66 | 92.06 | 93.62 | 66.79 | 73.70 | 92.70 |

Table 2. cont.

| Garnet-free Peridotites | |
|-------------------------|------|
| LB-6 | LB-9 |
| LB-7 | LB-8 |

Table 2. cont.

| | Garnet-free Peridotites | | | | | | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------|-------|----------------|-------|--------|-------------|--------|--------|-------|-------|-------|-------|-------|----------------|-------|-------|-------|----------------|--------|-------|--|
| | LB-6 | | | | LB-7 | | | | LB-8 | | | | LB-9 | | | | | | | | |
| | opx | cpx | cpx in vein | sp | matrix | ol patch | phlog | olx | opx | cpx | sp | ol | opx | cpx in vein | sp | ol | opx | cpx in vein | sp | ol | |
| SiO ₂ | 57.63 | 53.74 | 52.18 | 0.36 | 41.19 | 41.51 | 38.10 | 57.09 | 53.53 | 0.08 | 40.89 | 0.08 | 57.71 | 51.95 | 0.06 | 41.04 | 57.15 | 53.43 | 0.05 | 40.84 | |
| TiO ₂ | 0.00 | 0.16 | 0.71 | 0.20 | 0.00 | 0.01 | 4.18 | 0.18 | 0.80 | 1.88 | 0.02 | 0.20 | 0.01 | 1.55 | 0.30 | 0.00 | 0.00 | 1.02 | 0.31 | 0.01 | |
| V ₂ O ₅ | | | | 0.17 | | | | | | | | | | | | | | | | | |
| Al ₂ O ₃ | 1.29 | 2.01 | 2.58 | 13.26 | 0.01 | 0.04 | 14.86 | 1.53 | 1.17 | 15.88 | 0.02 | 0.20 | 0.54 | 1.66 | 13.37 | 0.01 | 0.50 | 0.67 | 11.88 | 0.02 | |
| Cr ₂ O ₃ | 0.26 | 1.26 | 0.52 | 54.05 | 0.03 | 0.16 | 0.78 | 0.78 | 0.87 | 50.12 | 0.05 | 0.16 | 0.22 | 0.78 | 55.91 | 0.01 | 0.11 | 0.00 | 58.17 | 0.02 | |
| FeO | 4.71 | 1.84 | 2.69 | 16.61 | 7.56 | 5.91 | 3.44 | 4.40 | 3.49 | 13.96 | 7.35 | 3.44 | 4.13 | 3.58 | 13.40 | 6.62 | 4.05 | 3.35 | 14.20 | 6.56 | |
| MnO | 0.11 | 0.05 | 0.06 | 0.22 | 0.10 | 0.10 | 0.02 | 0.11 | 0.12 | 0.15 | 0.10 | 0.10 | 0.11 | 0.08 | 0.18 | 0.09 | 0.02 | 0.03 | 0.19 | 0.09 | |
| MgO | 35.75 | 17.61 | 16.81 | 14.71 | 50.96 | 52.00 | 22.65 | 34.55 | 17.83 | 17.23 | 50.75 | 50.75 | 36.73 | 17.00 | 16.26 | 51.10 | 35.80 | 17.54 | 15.47 | 51.04 | |
| NiO | | | | 0.16 | 0.36 | 0.37 | 0.06 | 1.23 | 20.75 | 0.00 | 0.07 | 0.36 | 0.27 | 21.46 | 0.02 | 0.04 | 0.18 | 22.31 | 0.00 | 0.37 | |
| CaO | 0.37 | 22.71 | 23.23 | 0.02 | 0.03 | 0.19 | 1.46 | 0.21 | 0.72 | | | 1.46 | 0.03 | 0.68 | | | 0.02 | 0.62 | | 0.04 | |
| Na ₂ O | 0.10 | 0.59 | 0.51 | | | | 8.46 | | | | | 8.46 | | | | | | | | | |
| K ₂ O | | | | | | | 2.57 | | | | | 2.57 | | | | | | | | | |
| F | | | | | | | 0.00 | | | | | 0.00 | | | | | | | | | |
| Cl | | | | | | | | | | | | | | | | | | | | | |
| Total | 100.22 | 99.97 | 99.29 | 99.79 | 100.24 | 100.29 | 100.00 | 100.08 | 99.28 | 99.68 | 99.61 | 99.61 | 99.75 | 98.74 | 99.96 | 99.30 | 97.83 | 98.97 | 100.75 | 98.99 | |
| Cr/Cr+Al | | | | 73.22 | | | | | | 67.92 | | | | | 73.72 | | | | 76.66 | | |
| Mg/Mg+Fe | 93.11 | 94.46 | 91.76 | 61.22 | 92.32 | 94.01 | 92.14 | 93.33 | 90.11 | 68.75 | 92.49 | 92.49 | 94.06 | 89.44 | 68.39 | 93.23 | 94.03 | 90.32 | 66.01 | 93.28 | |

| | LB17 | | | | | | | | | | | |
|--------------------------------|-------|-------|-------|-------|-------|-------|--------|-------|-------|-------|--------|--------|
| | LB-14 | | | | | LB-16 | | | | | LB-17 | |
| | opx | cpx | ol | opx | cpx | ol | opx | cpx | ol | phlog | rutile | |
| SiO ₂ | 57.78 | 54.43 | 40.98 | 56.84 | 54.13 | 40.34 | 57.37 | 56.96 | 52.13 | 0.08 | 39.16 | 0.25 |
| TiO ₂ | 0.06 | 0.44 | 0.01 | 0.16 | 0.66 | 0.01 | 0.11 | 0.24 | 1.44 | 1.97 | 7.89 | 0.84 |
| V ₂ O ₅ | | | | | | | | | | 0.22 | | |
| Al ₂ O ₃ | 0.57 | 1.93 | 0.01 | 1.42 | 1.55 | 0.01 | 0.70 | 0.33 | 1.97 | 12.56 | 12.17 | 0.04 |
| Cr ₂ O ₃ | 0.23 | 2.16 | 0.01 | 0.63 | 1.58 | 0.03 | 0.27 | 0.07 | 0.49 | 50.82 | 0.05 | 1.71 |
| FeO | 4.15 | 2.17 | 6.88 | 4.97 | 3.10 | 7.97 | 5.32 | 6.68 | 4.13 | 19.17 | 9.43 | 5.19 |
| MnO | 0.09 | 0.06 | 0.10 | 0.11 | 0.10 | 0.11 | 0.61 | 0.15 | 0.12 | 0.19 | 0.12 | 0.06 |
| MgO | 36.25 | 16.92 | 50.84 | 34.94 | 19.09 | 50.51 | 35.38 | 34.69 | 17.30 | 14.76 | 50.25 | 19.89 |
| NiO | | | 0.35 | | | 0.38 | | | | 0.14 | 0.34 | 0.04 |
| CaO | 0.42 | 19.35 | 0.03 | 0.67 | 18.50 | 0.03 | 0.57 | 0.68 | 21.13 | 0.02 | 0.06 | 0.24 |
| Na ₂ O | 0.09 | 1.97 | | 0.17 | 1.17 | | 0.10 | 0.09 | 0.62 | | | 0.49 |
| K ₂ O | | | | | | | | | | | | 9.44 |
| F | | | | | | | | | | | | 2.89 |
| Cl | | | | | | | | | | | | 0.01 |
| Total | 99.64 | 99.43 | 99.21 | 99.91 | 99.88 | 99.39 | 100.43 | 99.89 | 99.33 | 99.98 | 99.46 | 100.00 |
| Cr/Cr+Al | | | | | | | | | 73.08 | | | 94.03 |
| Mg/Mg+Fe | 93.96 | 93.29 | 92.95 | 92.61 | 91.65 | 91.87 | 92.22 | 90.25 | 88.19 | 57.85 | 91.65 | 85.74 |

Table 2. cont.

| | Garnet-free Peridotites | | | | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------|-------|-------|---------|--------|--------|-------|-------|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| | LB-18 | | | LB-19-R | | | LB-21 | | | LB-22 | | | | | | | | | |
| | opx | cpx | sp | ol | phlog | rutile | opx | cpx | sp | ol | phlog | cpx | sp | ol | phlog | opx | cpx | sp | ol |
| SiO ₂ | 57.07 | 53.53 | 0.08 | 41.22 | 38.21 | 0.03 | 56.49 | 53.59 | 0.06 | 40.51 | 39.21 | 54.80 | 0.12 | 40.55 | 0.11 | 57.11 | 53.23 | 0.06 | 40.99 |
| TiO ₂ | 0.17 | 0.51 | 3.44 | 0.03 | 5.27 | 95.90 | 0.05 | 0.21 | 0.50 | 0.01 | 1.12 | 0.53 | 2.61 | 0.00 | 56.25 | 0.03 | 0.53 | 0.83 | 0.01 |
| V ₂ O ₅ | | | 0.20 | | | 0.84 | | | 0.27 | | | | 0.25 | | 0.48 | | | 0.20 | |
| Al ₂ O ₃ | 1.53 | 1.13 | 11.95 | 0.02 | 15.32 | 0.05 | 1.85 | 2.14 | 15.09 | 0.02 | 14.79 | 0.71 | 2.63 | 0.00 | 0.09 | 1.57 | 2.21 | 17.97 | 0.01 |
| Cr ₂ O ₃ | 0.77 | 1.57 | 50.21 | 0.06 | 1.67 | 1.67 | 0.31 | 1.78 | 43.15 | 0.02 | | 1.81 | 61.27 | 0.01 | 0.00 | 0.32 | 0.96 | 47.92 | 0.01 |
| FeO | 4.43 | 2.42 | 17.58 | 7.42 | 3.74 | 0.46 | 5.56 | 2.50 | 14.45 | 8.99 | 3.10 | 2.13 | 18.41 | 6.91 | 1.24 | 4.67 | 2.97 | 16.68 | 7.60 |
| MnO | 0.09 | 0.06 | 0.19 | 0.13 | 0.03 | 0.00 | 0.12 | 0.08 | 0.18 | 0.12 | 0.03 | 0.06 | 0.22 | 0.10 | 0.00 | 0.10 | 0.10 | 0.17 | 0.12 |
| MgO | 35.04 | 18.61 | 15.31 | 50.93 | 21.86 | 0.10 | 34.55 | 17.26 | 15.62 | 49.58 | 23.48 | 17.69 | 13.24 | 50.87 | 0.07 | 35.35 | 18.76 | 15.65 | 49.94 |
| NiO | | | 0.19 | 0.39 | | 0.00 | | | 0.09 | 0.36 | | | 0.15 | 0.40 | 0.03 | | | 0.16 | 0.36 |
| CaO | 0.69 | 20.76 | 0.00 | 0.05 | 0.03 | 0.00 | 0.80 | 21.36 | 0.00 | 0.06 | 0.02 | 20.45 | 0.06 | 0.04 | 37.55 | 0.36 | 19.78 | 0.03 | 0.04 |
| Na ₂ O | 0.28 | 0.69 | | | 0.46 | 0.00 | 0.11 | 0.97 | | | 0.84 | 1.50 | | | | 0.10 | 0.72 | | |
| K ₂ O | | | | | 9.97 | | | | | | 4.54 | | | | | | | | |
| F | | | | | 0.73 | | | | | | 0.90 | | | | | | | | |
| Cl | | | | | 0.01 | | | | | | 0.02 | | | | | | | | |
| Total | 100.07 | 99.28 | 99.16 | 100.25 | 100.00 | 99.05 | 99.84 | 99.89 | 89.44 | 99.67 | 100.00 | 99.68 | 99.00 | 98.88 | 95.93 | 99.61 | 99.26 | 99.71 | 99.08 |
| Cr/Cr+Al | | | 73.81 | | | | | | 65.73 | | | | 93.99 | | | | | 64.14 | |
| Mg/Mg+Fe | 93.37 | 93.20 | 60.83 | 92.45 | 91.25 | | 91.72 | 92.49 | 65.84 | 90.77 | 93.10 | 93.67 | 56.18 | 92.92 | 92.92 | 93.10 | 91.84 | 62.59 | 92.14 |

| | LB-25 | | | | | | | | | | | LB-26 | | | | | | | | |
|--------------------------------|-------|-------|-------|-------|--------|--------|-------|-------|-------|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| | opx | cpx | sp | ol | phlog | rutile | opx | cpx | sp | ol | phlog | opx | cpx | sp | ol | phlog | opx | cpx | sp | ol |
| SiO ₂ | 56.77 | 53.58 | 0.08 | 40.66 | 38.14 | 0.08 | 57.32 | 53.41 | 0.03 | 41.03 | 41.13 | 39.18 | 57.42 | 53.59 | 0.08 | 40.25 | 57.42 | 53.59 | 0.08 | 40.25 |
| TiO ₂ | 0.00 | 0.29 | 0.81 | 0.00 | 4.85 | 94.70 | 0.11 | 0.50 | 1.08 | 0.00 | 0.00 | 3.47 | 0.14 | 1.01 | 3.59 | 0.02 | 0.14 | 1.01 | 3.59 | 0.02 |
| V ₂ O ₅ | | | 0.22 | | | 0.94 | | | 0.28 | | | | | | 0.26 | | | | | |
| Al ₂ O ₃ | 1.49 | 2.12 | 14.82 | 0.01 | 14.41 | 0.05 | 0.72 | 1.54 | 10.61 | 0.00 | 0.01 | 13.62 | 0.84 | 1.13 | 10.35 | 0.01 | 0.84 | 1.13 | 10.35 | 0.01 |
| Cr ₂ O ₃ | 0.29 | 1.08 | 51.42 | 0.02 | 2.96 | 2.96 | 0.34 | 1.35 | 55.71 | 0.03 | 0.17 | 0.33 | 0.33 | 1.34 | 52.67 | 0.04 | 0.33 | 1.34 | 52.67 | 0.04 |
| FeO | 4.41 | 2.59 | 16.70 | 7.15 | 3.22 | 0.25 | 4.92 | 2.37 | 16.45 | 8.05 | 6.88 | 3.29 | 4.63 | 2.79 | 16.81 | 7.76 | 4.63 | 2.79 | 16.81 | 7.76 |
| MnO | 0.08 | 0.06 | 0.24 | 0.10 | 0.02 | 0.00 | 0.13 | 0.08 | 0.21 | 0.14 | 0.12 | 0.01 | 0.12 | 0.08 | 0.21 | 0.12 | 0.12 | 0.08 | 0.21 | 0.12 |
| MgO | 35.54 | 18.50 | 14.27 | 50.84 | 21.87 | 0.02 | 35.36 | 17.82 | 14.44 | 50.05 | 51.07 | 23.16 | 35.52 | 17.12 | 14.86 | 49.90 | 35.52 | 17.12 | 14.86 | 49.90 |
| NiO | | | 0.14 | 0.38 | | 0.00 | | | 0.14 | 0.37 | 0.31 | | | | 0.20 | | | | 0.20 | 0.38 |
| CaO | 0.43 | 20.24 | 0.06 | 0.05 | 0.02 | 0.02 | 0.63 | 21.53 | 0.03 | 0.04 | 0.17 | 0.00 | 0.53 | 21.38 | 0.01 | 0.06 | 0.53 | 21.38 | 0.01 | 0.06 |
| Na ₂ O | 0.09 | 0.76 | | | 0.87 | | 0.11 | 0.80 | | | 0.58 | | 0.13 | 1.04 | | | 0.13 | 1.04 | | |
| K ₂ O | | | | | 9.33 | | | | | | 9.91 | | | | | | | | | |
| F | | | | | 1.09 | | | | | | 1.16 | | | | | | | | | |
| Cl | | | | | 0.00 | | | | | | 0.00 | | | | | | | | | |
| Total | 99.10 | 99.22 | 98.78 | 99.21 | 100.00 | 99.03 | 99.64 | 99.40 | 99.01 | 99.71 | 99.86 | 100.00 | 99.66 | 99.48 | 99.06 | 98.54 | 99.66 | 99.48 | 99.06 | 98.54 |
| Cr/Cr+Al | | | 69.95 | | | | | | 77.89 | | | | | | 77.34 | | | | | 77.34 |
| Mg/Mg+Fe | 93.49 | 92.72 | 60.37 | 92.69 | 92.37 | | 92.76 | 93.06 | 61.01 | 91.73 | 92.97 | 92.62 | 93.18 | 91.62 | 61.18 | 91.98 | 93.18 | 91.62 | 61.18 | 91.98 |

Table 2. cont.

| | Garnet-free Peridotites | | | | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------|-------------|-------|--------------|-------------|-------------|------------|--------------|------------|-----------|--------|-------|--------|----------------|-------|-------------|--------------|-------------|--------|
| | LB-55 | | | | LB-60 | | | | LB-61 | | | | | | | | | | |
| | opx | opx lath | sp | ol matrix | ol patch | opx core | opx rim | opx 2ndry | sp core | sp rim | ol | phlog | opx | opx in vein | sp | sp 2ndry | ol matrix | ol patch | phlog |
| SiO ₂ | 57.21 | 53.69 | 0.72 | 41.04 | 41.31 | 57.35 | 56.41 | 52.95 | 53.39 | 0.04 | 0.05 | 40.99 | 38.20 | 56.64 | 52.49 | 0.07 | 41.37 | 41.44 | 37.90 |
| TiO ₂ | 0.00 | 0.10 | 0.10 | 0.01 | 0.02 | 0.14 | 0.25 | 0.96 | 1.15 | 2.36 | 2.55 | 0.02 | 4.70 | 0.10 | 1.74 | 0.66 | 0.01 | 0.03 | 7.37 |
| V ₂ O ₅ | | | 0.24 | | | | | | | 0.21 | 0.23 | | | | | 0.23 | 0.20 | | |
| Al ₂ O ₃ | 1.40 | 2.16 | 17.61 | 0.00 | 0.00 | 0.73 | 1.45 | 4.08 | 0.85 | 12.66 | 13.42 | 0.01 | 15.03 | 2.20 | 1.08 | 17.74 | 19.94 | 0.03 | 12.95 |
| Cr ₂ O ₃ | 0.28 | 0.60 | 48.94 | 0.00 | 0.02 | 0.24 | 0.71 | 2.90 | 0.71 | 52.36 | 51.69 | 0.05 | | 0.69 | 0.63 | 50.14 | 48.59 | 0.06 | 0.13 |
| FeO | 4.64 | 2.74 | 16.59 | 7.11 | 7.05 | 4.40 | 4.55 | 2.52 | 2.93 | 15.21 | 14.69 | 7.22 | 3.27 | 4.57 | 3.54 | 14.74 | 13.32 | 7.38 | 6.77 |
| MnO | 0.12 | 0.07 | 0.23 | 0.11 | 0.09 | 0.10 | 0.10 | 0.06 | 0.11 | 0.13 | 0.13 | 0.12 | 0.03 | 0.12 | 0.12 | 0.18 | 0.19 | 0.14 | 0.04 |
| MgO | 35.94 | 17.25 | 15.16 | 51.06 | 51.11 | 35.82 | 34.81 | 16.11 | 18.81 | 16.53 | 16.99 | 50.38 | 21.44 | 34.95 | 17.54 | 16.46 | 50.89 | 51.76 | 20.03 |
| NiO | | | 0.16 | 0.41 | 0.41 | | | | | 0.21 | 0.26 | 0.38 | | | | 0.15 | 0.42 | 0.32 | |
| CaO | 0.20 | 22.25 | 0.15 | 0.01 | 0.02 | 0.51 | 0.81 | 16.78 | 20.27 | 0.01 | 0.01 | 0.07 | 0.00 | 0.56 | 21.95 | 0.01 | 0.04 | 0.03 | 0.02 |
| Na ₂ O | 0.05 | 0.71 | | | | 0.14 | 0.22 | 2.81 | 0.48 | | | | 10.15 | 0.21 | 0.51 | | | | 0.81 |
| K ₂ O | | | | | | | | | | | | | 0.89 | | | | | | 8.93 |
| F | | | | | | | | | | | | | 0.01 | | | | | | 1.35 |
| Cl | | | | | | | | | | | | | | | | | | | 0.00 |
| Total | 99.84 | 99.57 | 99.94 | 99.75 | 100.03 | 99.43 | 99.31 | 99.17 | 98.70 | 99.74 | 100.04 | 99.24 | 100.00 | 100.04 | 99.60 | 100.42 | 100.71 | 100.34 | 99.51 |
| Cr/Cr+Al | | | 65.09 | | | | | | | 73.51 | 72.10 | | | | | 65.47 | 62.05 | | 100.00 |
| Mg/Mg+Fe | 93.24 | 91.82 | 61.97 | 92.76 | 92.82 | 93.55 | 93.16 | 91.93 | 91.97 | 65.96 | 67.34 | 92.56 | 92.12 | 93.16 | 89.83 | 66.57 | 69.57 | 92.48 | 84.06 |

| | Spinel-facies Peridotites | | | | | | | | | | | | | | | | | | |
|--------------------------------|---------------------------|--------------|---------------|-------|-------|-------|--------|-------|-------|----|-----|--------|--------|-------|-------|-----|----|----|-----|
| | LB-11 | | | | LB-29 | | | | LB-31 | | | | | | | | | | |
| | opx | opx 2ndry | sp high Ca | ol | sp | ol | opx | opx | sp | ol | opx | opx | sp | ol | opx | opx | sp | ol | opx |
| SiO ₂ | 56.03 | 53.39 | 52.77 | 40.77 | 0.06 | 40.77 | 56.55 | 0.04 | 40.55 | | | 55.91 | 53.53 | 2.16 | 40.62 | | | | |
| TiO ₂ | 0.07 | 0.35 | 0.28 | 0.53 | 0.02 | 0.17 | 0.08 | 0.24 | 0.00 | | | 0.06 | 0.15 | 0.35 | 0.00 | | | | |
| V ₂ O ₅ | | | | | | | | 0.09 | | | | | | 0.16 | | | | | |
| Al ₂ O ₃ | 2.78 | 3.37 | 3.22 | 30.15 | 0.02 | 0.02 | 2.59 | 31.58 | 0.03 | | | 3.19 | 3.68 | 30.10 | 0.01 | | | | |
| Cr ₂ O ₃ | 0.64 | 1.49 | 1.76 | 36.54 | 0.02 | 0.02 | 0.55 | 36.75 | 0.03 | | | 0.81 | 1.27 | 34.56 | 0.01 | | | | |
| FeO | 4.74 | 2.29 | 2.88 | 14.21 | 7.49 | 7.49 | 4.71 | 12.86 | 7.35 | | | 4.97 | 2.23 | 12.66 | 7.71 | | | | |
| MnO | 0.10 | 0.08 | 0.08 | 0.09 | 0.12 | 0.12 | 0.13 | 0.05 | 0.12 | | | 0.12 | 0.08 | 0.04 | 0.10 | | | | |
| MgO | 34.70 | 16.40 | 19.82 | 17.52 | 50.46 | 50.46 | 34.94 | 18.02 | 50.56 | | | 34.26 | 16.69 | 18.69 | 50.33 | | | | |
| NiO | | | | 0.14 | 0.39 | | | 0.16 | 0.38 | | | | | 0.19 | 0.40 | | | | |
| CaO | 0.63 | 20.30 | 17.85 | 0.00 | 0.04 | | 0.63 | 0.00 | 0.05 | | | 0.83 | 21.11 | 0.01 | 0.04 | | | | |
| Na ₂ O | 0.10 | 1.67 | 0.62 | | | | 0.17 | | | | | 0.09 | 1.29 | | | | | | |
| K ₂ O | | | | | | | | | | | | | | | | | | | |
| F | | | | | | | | | | | | | | | | | | | |
| Cl | | | | | | | | | | | | | | | | | | | |
| Total | 99.79 | 99.34 | 99.28 | 99.45 | 99.33 | | 100.35 | 99.82 | 99.07 | | | 100.24 | 100.03 | 98.96 | 99.22 | | | | |
| Cr/Cr+Al | | | | 44.84 | | | | 43.84 | | | | | | 43.51 | | | | | |
| Mg/Mg+Fe | 92.88 | 92.74 | 92.46 | 68.73 | 92.31 | | 92.97 | 71.41 | 92.46 | | | 92.47 | 93.03 | 72.47 | 92.09 | | | | |

Cr/Cr+Al 44.84 92.88 92.74 92.46 68.73 92.31 43.84 92.97 71.41 92.46 43.51 92.47 93.03 72.47 92.09
 Mg/Mg+Fe 92.88 92.74 92.46 68.73 92.31 43.84 92.97 71.41 92.46 43.51 92.47 93.03 72.47 92.09

Table 2. cont.

| | Fe-rich dumites and wehrlites | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------------|-------|--------|-------|--------|-------|--------|-------|--------|-------|-------|-------|-------|--------|--------|--------|
| | KAT 5 | | KAT 7 | | KAT 10 | | KAT 12 | | KAT 14 | | LB-15 | | LB-59 | | | |
| | sp | ol | ol | opx | opx | ol | ol | ol | ol | ol | ol | ol | ol | ol | phlog | |
| SiO ₂ | 0.44 | 39.97 | 40.01 | 56.23 | 51.06 | 39.49 | 53.23 | 39.86 | 53.40 | 0.11 | 39.67 | 54.36 | 0.13 | 39.77 | 39.42 | 36.67 |
| TiO ₂ | 6.17 | 0.02 | 0.03 | 0.31 | 1.89 | 0.04 | 0.37 | 0.01 | 0.51 | 5.41 | 0.03 | 0.43 | 1.53 | 0.00 | 0.03 | 3.75 |
| V ₂ O ₅ | 0.31 | | | | | | | | | 0.23 | | | 0.26 | | | |
| Al ₂ O ₃ | 7.52 | 0.01 | 0.03 | 1.60 | 1.88 | 0.01 | 1.24 | 0.03 | 0.96 | 11.96 | 0.02 | 1.86 | 8.51 | 0.02 | 0.04 | 15.81 |
| Cr ₂ O ₃ | 36.15 | 0.03 | 0.04 | 0.22 | 0.63 | 0.01 | 1.05 | 0.02 | 1.59 | 39.41 | 0.03 | 0.29 | 52.38 | 0.03 | 0.01 | 6.04 |
| FeO | 33.81 | 12.93 | 13.21 | 8.03 | 4.97 | 13.44 | 3.85 | 13.39 | 3.75 | 29.61 | 12.70 | 4.36 | 21.19 | 13.18 | 14.29 | 6.04 |
| MnO | 0.26 | 0.16 | 0.15 | 0.15 | 0.08 | 0.14 | 0.08 | 0.16 | 0.09 | 0.21 | 0.16 | 0.12 | 0.38 | 0.18 | 0.16 | 0.02 |
| MgO | 11.45 | 46.23 | 46.47 | 32.17 | 16.01 | 46.22 | 16.79 | 45.59 | 17.28 | 12.25 | 46.50 | 17.13 | 11.01 | 46.63 | 45.91 | 20.67 |
| NiO | 0.29 | 0.31 | 0.33 | 0.86 | 22.10 | 0.07 | 20.56 | 0.06 | 20.76 | 0.00 | 0.33 | 19.93 | 0.21 | 0.35 | 0.27 | 0.01 |
| CaO | 0.04 | 0.07 | 0.07 | 0.27 | 0.72 | | 0.79 | | 0.91 | | | 1.43 | | | 0.09 | 0.28 |
| Na ₂ O | | | | | | | | | | | | | | | 10.30 | 0.55 |
| K ₂ O | | | | | | | | | | | | | | | | 0.00 |
| F | | | | | | | | | | | | | | | | 0.00 |
| Cl | | | | | | | | | | | | | | | | 0.00 |
| Total | 96.46 | 99.71 | 100.33 | 99.84 | 99.34 | 99.75 | 97.96 | 99.39 | 99.25 | 99.46 | 99.51 | 99.91 | 95.81 | 100.20 | 100.22 | 100.00 |
| Cr/Cr+Al | 76.33 | | | 87.71 | 85.17 | 85.98 | 88.60 | 85.86 | 89.15 | 42.45 | 86.72 | 87.51 | 48.09 | 86.32 | 85.14 | 85.92 |
| Mg/Mg+Fe | 37.65 | 86.44 | 86.25 | 87.71 | 85.17 | 85.98 | 88.60 | 85.86 | 89.15 | 42.45 | 86.72 | 87.51 | 48.09 | 86.32 | 85.14 | 85.92 |

| | Fe-rich dumites and wehrlites | | | | | | | | | | | | | | | |
|--------------------------------|-------------------------------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|-------|
| | LB-19-C | | LB-46 | | LB-51 | | LB-58 | | LB-59 | | LB-49 | | | | | |
| | sp | ol | phlog | opx | opx | ol | ol | ol | ol | ol | ol | ol | ol | phlog | | |
| SiO ₂ | 0.06 | 39.98 | 39.06 | 56.08 | 52.55 | 39.82 | 53.64 | 0.13 | 39.90 | 51.35 | 0.03 | 39.93 | 40.10 | 39.81 | 39.28 | 0.02 |
| TiO ₂ | 5.26 | 0.04 | 3.63 | 0.28 | 0.86 | 1.12 | 0.50 | 5.87 | 4.61 | 1.37 | 1.08 | 0.00 | 0.01 | 5.81 | 3.78 | 49.19 |
| V ₂ O ₅ | 0.34 | | | | | | | 0.30 | 0.35 | 0.25 | | | | | | 0.37 |
| Al ₂ O ₃ | 7.48 | 0.02 | 13.63 | 1.56 | 1.61 | 0.06 | 1.20 | 9.80 | 6.83 | 2.04 | 16.10 | 0.01 | 0.02 | 11.18 | 12.86 | 0.12 |
| Cr ₂ O ₃ | 48.10 | 0.04 | 4.74 | 0.45 | 1.86 | 0.05 | 1.65 | 40.67 | 39.14 | 0.55 | 45.66 | 0.03 | 0.14 | 4.72 | 6.65 | 1.66 |
| FeO | 22.50 | 12.33 | 4.74 | 7.12 | 3.50 | 12.18 | 3.85 | 29.13 | 35.67 | 4.09 | 23.18 | 10.49 | 9.93 | 4.72 | 6.65 | 32.95 |
| MnO | 0.24 | 0.16 | 0.04 | 0.14 | 0.10 | 0.16 | 0.09 | 0.21 | 0.41 | 0.04 | 0.23 | 0.16 | 0.12 | 0.02 | 0.04 | 0.29 |
| MgO | 12.31 | 47.30 | 22.11 | 33.12 | 17.54 | 47.68 | 18.15 | 12.61 | 7.26 | 15.69 | 12.87 | 48.08 | 48.60 | 22.24 | 21.90 | 11.31 |
| NiO | 0.19 | 0.33 | | | | 0.32 | | 0.26 | 0.19 | 23.22 | 0.00 | 0.36 | 0.37 | 0.06 | 0.13 | 0.13 |
| CaO | 0.01 | 0.07 | 0.02 | 0.80 | 19.63 | 15.92 | 19.53 | 0.00 | 0.18 | 0.53 | 0.00 | 0.06 | 0.15 | 0.06 | 0.00 | 0.21 |
| Na ₂ O | | | 0.62 | 0.26 | 0.99 | 2.48 | 0.98 | | | | | | | 0.34 | 0.55 | 0.55 |
| K ₂ O | | | 9.59 | | | | | | | | | | | 10.01 | 10.05 | 10.05 |
| F | | | 0.59 | | | | | | | | | | | 3.93 | 0.48 | 0.48 |
| Cl | | | 0.02 | | | | | | | | | | | 0.01 | 0.00 | 0.00 |
| Total | 96.52 | 100.27 | 100.00 | 99.81 | 98.64 | 98.86 | 99.59 | 98.98 | 97.08 | 98.88 | 99.63 | 99.12 | 99.44 | 100.00 | 100.00 | 96.25 |
| Cr/Cr+Al | 81.18 | | | 89.23 | 89.93 | 87.63 | 89.37 | 43.56 | 26.63 | 87.24 | 49.75 | 89.10 | 89.72 | 89.36 | 85.45 | 85.45 |
| Mg/Mg+Fe | 49.38 | 87.24 | 89.27 | 89.23 | 89.93 | 87.63 | 89.37 | 43.56 | 26.63 | 87.24 | 49.75 | 89.10 | 89.72 | 89.36 | 85.45 | 85.45 |

Table 3. Whole-rock Major Element Chemistry.

| | SiO ₂ | TiO ₂ | Al ₂ O ₃ | FeO(t) | MnO | MgO | CaO | Na ₂ O | K ₂ O | P ₂ O ₅ | Total | Mg# |
|---------------------------|------------------|------------------|--------------------------------|--------|-------|-------|------|-------------------|------------------|-------------------------------|--------|-------|
| Garnet Lherzolites | | | | | | | | | | | | |
| LB 12 | 43.64 | 0.05 | 1.98 | 8.34 | 0.15 | 42.10 | 1.79 | 0.02 | 0.05 | 0.02 | 98.13 | 90.00 |
| LB-45 | 43.28 | 0.20 | 3.89 | 8.34 | 0.15 | 38.67 | 2.74 | 0.11 | 0.08 | 0.02 | 97.48 | 89.21 |
| Garnet Harzburgites | | | | | | | | | | | | |
| LB 2 | 43.49 | 0.06 | 1.18 | 6.59 | 0.13 | 45.94 | 0.50 | 0.00 | 0.12 | 0.02 | 98.02 | 92.55 |
| LB 4 | 44.64 | 0.03 | 1.54 | 7.55 | 0.14 | 43.30 | 1.06 | 0.00 | 0.03 | 0.01 | 98.30 | 91.09 |
| LB 24 | 43.21 | 0.06 | 1.21 | 6.92 | 0.12 | 45.68 | 0.61 | 0.00 | 0.05 | 0.01 | 97.87 | 92.17 |
| LB-34 | 41.09 | 0.17 | 0.68 | 9.28 | 0.14 | 45.78 | 0.43 | 0.00 | 0.09 | 0.01 | 97.69 | 89.79 |
| LB-50-1* | 43.75 | 0.05 | 1.37 | 7.79 | 0.14 | 44.16 | 0.98 | 0.00 | 0.03 | 0.01 | 98.28 | 91.00 |
| LB-50-2* | 43.76 | 0.05 | 1.32 | 7.72 | 0.14 | 44.07 | 0.95 | 0.00 | 0.02 | 0.01 | 98.04 | 91.05 |
| LB-53 | 42.57 | 0.12 | 1.73 | 7.93 | 0.14 | 43.89 | 1.34 | 0.00 | 0.04 | 0.01 | 97.75 | 90.80 |
| KAT 17 | 44.80 | 0.06 | 0.41 | 10.55 | 0.13 | 43.28 | 0.64 | 0.09 | 0.02 | 0.02 | 100.00 | 87.97 |
| GL4201† | 42.67 | 0.12 | 1.06 | 9.10 | 0.13 | 44.87 | 1.15 | 0.16 | 0.06 | 0.01 | 99.33 | 89.79 |
| GL4202† | 44.07 | 0.03 | 1.21 | 7.91 | 0.12 | 44.62 | 1.01 | 0.05 | 0.06 | 0.01 | 99.09 | 90.96 |
| GL4203† | 43.71 | 0.02 | 1.12 | 7.93 | 0.12 | 44.98 | 0.96 | 0.01 | 0.06 | 0.01 | 98.92 | 91.00 |
| GL4206† | 44.39 | 0.03 | 1.30 | 7.86 | 0.13 | 44.20 | 0.85 | 0.02 | 0.06 | 0.02 | 98.86 | 90.94 |
| Garnet-free Peridotites | | | | | | | | | | | | |
| KAT 1 | 45.54 | 0.106 | 0.65 | 7.04 | 0.109 | 45.97 | 0.39 | 0.07 | 0.09 | 0.042 | 100.01 | 92.09 |
| LB 1 | 43.83 | 0.08 | 0.40 | 6.38 | 0.12 | 47.34 | 0.25 | 0.00 | 0.04 | 0.02 | 98.45 | 92.98 |
| LB 6 | 41.43 | 0.12 | 0.65 | 7.38 | 0.13 | 47.67 | 0.56 | 0.00 | 0.15 | 0.04 | 98.13 | 92.01 |
| LB 7 | 40.84 | 0.11 | 0.55 | 7.50 | 0.13 | 47.98 | 0.28 | 0.00 | 0.13 | 0.02 | 97.53 | 91.94 |
| LB 8 | 42.83 | 0.05 | 0.34 | 6.40 | 0.11 | 47.38 | 0.18 | 0.00 | 0.05 | 0.01 | 97.36 | 92.96 |
| LB 9 | 41.97 | 0.06 | 0.36 | 6.50 | 0.12 | 47.45 | 0.22 | 0.00 | 0.05 | 0.02 | 96.74 | 92.86 |
| LB 14 | 41.28 | 0.08 | 0.33 | 7.15 | 0.12 | 48.88 | 0.04 | 0.00 | 0.07 | 0.01 | 97.95 | 92.42 |
| LB 16 | 42.89 | 0.12 | 0.60 | 7.21 | 0.13 | 46.29 | 0.40 | 0.00 | 0.07 | 0.03 | 97.74 | 91.96 |
| LB 17 | 44.23 | 0.24 | 0.56 | 7.41 | 0.14 | 44.85 | 0.42 | 0.00 | 0.07 | 0.02 | 97.93 | 91.52 |
| LB 18 | 41.57 | 0.10 | 0.42 | 8.31 | 0.13 | 47.15 | 0.38 | 0.00 | 0.06 | 0.01 | 98.13 | 91.01 |
| LB 19-R | 42.23 | 0.08 | 0.82 | 8.51 | 0.15 | 45.76 | 0.46 | 0.00 | 0.25 | 0.01 | 98.26 | 90.55 |
| LB 21 | 40.75 | 0.09 | 0.30 | 6.52 | 0.12 | 48.85 | 0.52 | 0.00 | 0.08 | 0.03 | 97.26 | 93.04 |
| LB 22 | 43.09 | 0.07 | 0.67 | 7.44 | 0.13 | 45.93 | 0.39 | 0.00 | 0.06 | 0.02 | 97.79 | 91.67 |
| LB 23 | 42.48 | 0.03 | 0.54 | 7.22 | 0.13 | 47.34 | 0.41 | 0.00 | 0.06 | 0.03 | 98.24 | 92.12 |
| LB 26 | 41.97 | 0.13 | 0.45 | 7.07 | 0.13 | 47.01 | 0.18 | 0.00 | 0.06 | 0.01 | 97.02 | 92.22 |
| LB 32 | 43.51 | 0.09 | 0.60 | 6.61 | 0.12 | 46.77 | 0.26 | 0.00 | 0.10 | 0.03 | 98.07 | 92.66 |
| LB-33 | 42.00 | 0.33 | 0.60 | 7.31 | 0.13 | 46.54 | 0.69 | 0.00 | 0.14 | 0.01 | 97.76 | 91.90 |
| LB-36 | 43.56 | 0.06 | 0.88 | 6.95 | 0.13 | 45.36 | 0.61 | 0.00 | 0.13 | 0.03 | 97.71 | 92.09 |
| LB-39 | 44.23 | 0.14 | 0.86 | 7.73 | 0.14 | 44.04 | 0.72 | 0.00 | 0.15 | 0.03 | 98.04 | 91.04 |
| LB 40 | 43.23 | 0.05 | 0.52 | 7.03 | 0.13 | 47.02 | 0.23 | 0.00 | 0.03 | 0.00 | 98.24 | 92.26 |
| LB-54 | 43.21 | 0.17 | 1.13 | 7.50 | 0.14 | 44.29 | 1.26 | 0.07 | 0.24 | 0.04 | 98.04 | 91.32 |
| LB-55 | 43.00 | 0.08 | 0.76 | 6.79 | 0.13 | 46.12 | 0.41 | 0.00 | 0.22 | 0.02 | 97.53 | 92.37 |
| LB-60 | 43.28 | 0.14 | 0.50 | 6.78 | 0.13 | 46.56 | 0.28 | 0.00 | 0.08 | 0.02 | 97.77 | 92.45 |
| LB-61 | 42.24 | 0.09 | 0.50 | 7.00 | 0.13 | 47.68 | 0.23 | 0.00 | 0.09 | 0.02 | 97.98 | 92.40 |
| Spinel-facies Peridotites | | | | | | | | | | | | |
| LB 11 | 43.07 | 0.04 | 0.84 | 7.18 | 0.13 | 46.37 | 0.30 | 0.00 | 0.04 | 0.00 | 97.97 | 92.00 |
| LB 29 | 42.89 | 0.06 | 0.88 | 7.10 | 0.13 | 46.52 | 0.30 | 0.00 | 0.06 | 0.01 | 97.96 | 92.11 |
| LB-31 | 43.69 | 0.04 | 1.02 | 7.30 | 0.14 | 45.25 | 0.96 | 0.00 | 0.08 | 0.01 | 98.48 | 91.70 |
| Cumulates | | | | | | | | | | | | |
| LB 15 | 45.80 | 0.25 | 1.23 | 8.63 | 0.16 | 32.36 | 8.38 | 0.84 | 0.07 | 0.01 | 97.73 | 86.99 |
| LB 19-C | 39.54 | 0.25 | 0.84 | 12.88 | 0.18 | 43.15 | 0.21 | 0.00 | 0.50 | 0.01 | 97.53 | 85.66 |
| LB 43 | 39.88 | 0.10 | 0.26 | 11.86 | 0.17 | 45.79 | 0.13 | 0.00 | 0.07 | 0.01 | 98.27 | 87.31 |
| LB-46 | 40.69 | 0.22 | 0.51 | 11.22 | 0.16 | 43.21 | 1.56 | 0.00 | 0.06 | 0.01 | 97.65 | 87.29 |
| LB-51 | 42.15 | 0.31 | 1.12 | 11.25 | 0.16 | 39.48 | 3.37 | 0.18 | 0.20 | 0.05 | 98.27 | 86.22 |
| LB-58 | 39.71 | 0.10 | 0.52 | 10.50 | 0.18 | 45.05 | 0.83 | 0.00 | 0.09 | 0.01 | 97.00 | 88.44 |
| LB-59 | 39.06 | 0.09 | 0.27 | 14.10 | 0.18 | 43.76 | 0.09 | 0.00 | 0.13 | 0.02 | 97.68 | 84.70 |
| LB49 | 39.36 | 5.339 | 12.56 | 8.32 | 0.05 | 21.13 | 0.32 | 0.42 | 9.68 | 0.064 | 97.25 | 81.91 |

*LB 50-1 was leached with acetic acid and LB 50-2 was leached with both acetic and dilute hydrochloric acid. †from Dawson *et al.* (1996)

Garnets in LB2 appear to have incongruently melted to an assemblage consisting of clinopyroxene, orthopyroxene, spinel, glass, and occasionally olivine. Hunter and Taylor (1982) described similar symplectic assemblages and also explained their origin by incongruent melting. Primary orthopyroxenes in LB2 have Al- and Ca-rich rims, suggesting that this xenolith was heated.

5.5 Chromite/Spinel

Chromite or spinel occurs in nearly all samples (Table 2, Fig. 3d). Three deep red hercynitic spinels (LB 11, 29, 31) with low Cr# (<50 (100 Cr/Cr+Al)) are typical of those found in spinel peridotites in alkali basalts (Fig. 3d). Because these spinels coexist with aluminous orthopyroxenes, these xenoliths are

presumed to represent the few true spinel-facies peridotites in our collection. Spinel in LB 36 also have low Cr# and are deep red in color, however the aluminum content of coexisting orthopyroxenes is low. Spinel precipitated during garnet breakdown in Labait samples are opaque and have high Cr# (>60), overlapping the compositional range for chromites in garnet peridotites from Kaapvaal. In some garnet-free harzburgites, two generations of chromite or spinel occur (Fig. 3d).

Chromites are absent in the garnet-bearing peridotites at Labait (which only have secondary low Cr# spinel). The high Cr content of spinels may depress the garnet-spinel transition (O'Neill, 1981). For Cr# of ~70, the garnet-spinel transition is depressed to approximately 3.6 GPa, which coincides approxi-

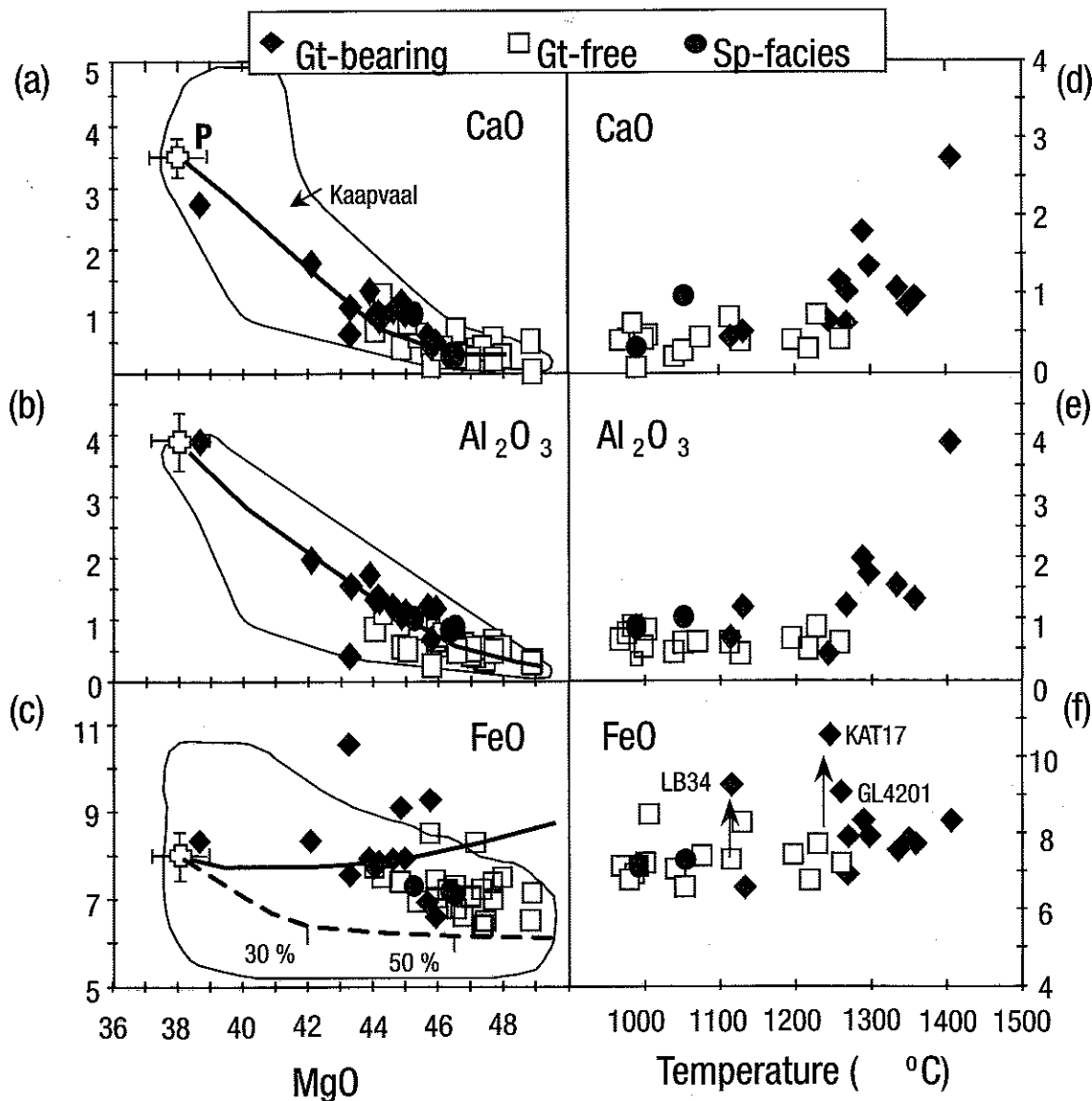


Figure 4. (a) (b) (c) Whole-rock CaO, Al₂O₃, and FeO (=FeO+Fe₂O₃) versus MgO, compared to Kaapvaal garnet peridotites. Partial melting curves for residues from Asimow (1998; solid lines) and Walter (1998b; dashed line). The former represent residues of polybaric batch melting calculated using MELTS and assuming a mantle potential temperature whose adiabat intersects the solidus at 2.5 GPa. The latter represents residues of isobaric batch melting at 7 GPa. Range of primitive mantle values taken from McDonough and Sun (1995) and Allegre *et al.* (1995). Note that three samples (KAT 17, LB34, and GL4201) show Fe-enrichment but no enrichment in CaO and Al₂O₃. (d) (e) (f) Whole-rock CaO, Al₂O₃, and FeO versus temperature. Temperatures calculated from two-pyroxene thermometer (Brey and Kohler, 1990). Arrows in (f) show direction of Fe-enrichment.

Table 4. Thermobarometry.

| | T (Celsius) P (GPa) | | T (Celsius) | | comments |
|----------------------------------|---------------------|------|-------------|-------------|--------------|
| | Garnet present | | No Garnet | | |
| | TBKN | PBKN | TBKN | T Ca-in-Opx | |
| Garnet Lherzolites | | | | | |
| LB-12 | 1290 | 4.4 | | 1239 | |
| LB-12* | 1290 | 4.4 | | | |
| LB-45* | 1406 | 4.7 | | 1382 | |
| LB-45* | | | | 1462 | gt breakdown |
| Garnet Harzburgites | | | | | |
| KAT-17 | 1245 | 4.0 | | 923 | |
| LB-2 | | | 1132 (3.5) | 926 | core |
| LB-2 | | | | 1054 | rim |
| LB-4* | 1336 | 4.4 | | 872 | matrix |
| LB-4* | | | | 1302 | gt breakdown |
| LB24 | 1265 | 4.4 | | 1182 | |
| LB-24* | 1269 | 4.4 | | 1190 | |
| LB-34* | 1115 | 3.7 | | 1141 | |
| LB-50* | 1359 | 4.6 | | 1313 | |
| LB-53 | 1298 | 4.7 | | 1257 | |
| LB-53* | 1297 | 4.7 | | | |
| GL4201 | 1260 | 3.9 | | 1186 | |
| GL4201 | | | 1381 (4.5) | 1539 | gt breakdown |
| GL4202 | 1270 | 4.6 | | 1332 | |
| GL4202 | | | 1363 (4.5) | 1407 | gt breakdown |
| GL4203 | | | | 1330 | |
| GL4206 | 1350 | 4.9 | | 1329 | |
| GL4206 | | | 1330 (4.5) | 1429 | gt breakdown |
| GLX1 | 1290 | 4.6 | | 1340 | |
| GLX9 | 1240 | 4.3 | | 1231 | |
| Garnet-free Peridotites | | | | | |
| LB-14 | | | 990 (4.5) | 993 | |
| LB-16 | | | 1260 (4.5) | 1100 | |
| LB-17 | | | 1070 (4.5) | 1074 | |
| LB-18 | | | 1120 (4.5) | 1107 | |
| LB-22 | | | 1200 (4.5) | 962 | |
| LB-23 | | | 1000 (4.5) | 999 | |
| LB-26 | | | 1040 (4.5) | 1044 | |
| LB-32 | | | 1060 (4.5) | 966 | |
| LB-33 | | | 1110 (4.5) | 1121 | |
| LB-39 | | | 1230 (4.5) | 919 | |
| LB-54 | | | 1200 (4.5) | 1065 | |
| LB-55 | | | 980 (4.5) | 854 | |
| LB-60 | | | 1220 (4.5) | 1036 | core |
| LB-60 | | | | 1150 | rim |
| Spinel-Facies Peridotites | | | | | |
| LB-11 | | | 990 (2.5) | 991 | |
| LB-29 | | | 990 (2.5) | 990 | |
| LB-31 | | | 1050 (2.5) | 1056 | |
| Fe-rich dunite | | | | | |
| LB-46 | | | 1150 (4.5) | 1149 | |

First two columns are for garnet-bearing samples.

Third column is T calculated for garnet-free samples; input P parenthesized.

Fourth column is temperatures calculated using Ca in orthopyroxene.

TBKN = two pyroxene thermometer of Brey and Kohler (1990).

PBKN = Al solubility in orthopyroxene coexisting with garnet barometer of Brey and Kohler (1990).

T Ca-in-Opx = CaO in orthopyroxene thermometer of Brey and Kohler (1990); input P = 4.5 GPa.

* Garnet composition using 800 V raster and 125 micrometer spot size to probe kelyphite.

Samples with GL-prefix are from Dawson *et al.* (1997).

mately with the equilibration pressure calculated for our shallowest garnet-bearing peridotite (3.7 GPa for LB 34).

5.6 Phlogopite

Phlogopite occurs in several samples as tiny lathes on grain boundaries, in veins, or in metasomatic patches of clinopyroxene and chromite (Table 2). Only in LB19, the composite xenolith, does phlogopite occur as large platy grains in textural equilibrium with the primary mineral assemblage. Phlogopite Mg# ranges from 84.0 to 93.3 for all samples. TiO₂ ranges from 3.63 to 7.89 wt. % except for LB19R (depleted portion of LB19) which has TiO₂ of 1.12 wt. %. Erlank *et al.* (1987) report that primary phlogopites from Kaapvaal garnet peridotites do not exceed 4.86 wt. % TiO₂, so most of the phlogopites reported here may be secondary.

We also analyzed the phlogopites which make up LB49, a glimmerite xenolith. These phlogopites have compositions within the range observed for the Labait phlogopites, suggesting a connection between the glimmerite and the phlogopites in Labait xenoliths.

Interestingly, two generations of phlogopite may occur within one xenolith. The texturally equilibrated phlogopites in LB19 exhibit compositional variation between the Fe-rich vein and depleted portions of the xenolith. The vein phlogopite has 3.63 wt. % TiO₂ and Mg# of 89.3, while the depleted portion has 1.12 wt. % TiO₂ and Mg# of 93.1. In LB34, phlogopites in garnet breakdown patches have higher Fe and Ti and lower Mg compared to those found as interstitial lathes in the primary groundmass.

6. MAJOR ELEMENT COMPOSITION

Whole-rock major-element compositions are presented in Table 3. For residual peridotites, Mg# is generally high (89 to 93 with most > 91) and similar to those of Kaapvaal peridotites (Mg# = 90-92; Boyd, 1989a). Garnet-bearing peridotites tend to have lower Mg# and Mg/Si than garnet-free peridotites. As

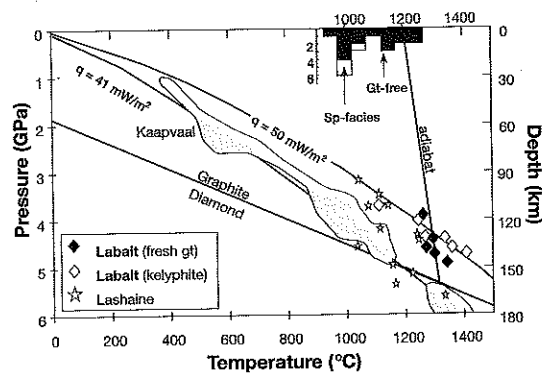


Figure 5. Pressure-temperature estimates of Labait garnet-bearing peridotites calculated from the Al-in-orthopyroxene barometer and two-pyroxene thermometer of Brey and Kohler (1990). Open diamonds represent P-T estimates determined by using the composition of fine-grained garnet kelyphites for those garnet-bearing peridotites in which fresh garnet is absent. Stars represent data from Lashaine garnet peridotites (Rudnick *et al.*, 1994; Rudnick *et al.*, unpublished). Histogram in upper left corner denotes temperature estimates for garnet-free peridotites (solid) and spinel peridotites (open). Geotherms taken from Rudnick *et al.* (1998), calculated assuming lithospheric mantle and crustal heat productions of 0.03 and 0.5 $\mu\text{W}/\text{m}^3$, respectively. Adiabatic temperature profile is for a 0.6°C/km gradient and a 1200°C potential temperature.

shown in Fig. 4a-c, Labait peridotites plot within the field of Kaapvaal garnet peridotites, but differ by having a more restricted range in compositions, which are highly refractory. The refractory character of Labait xenoliths is also reflected in the general absence of primary clinopyroxene and garnet. The spinel-facies peridotites (LB11, 29, 31) are highly refractory (Fig. 4a-c) in comparison to the average spinel peridotite reported by McDonough (1990) and more closely resemble spinel facies peridotites from Kaapvaal and Siberian cratons (Boyd, 1989a; Boyd *et al.*, 1997). Garnet-bearing peridotites are the most fertile of the residual peridotites in our collection, but are still considerably more refractory than the primitive mantle estimates. Only one sample (LB45) has a composition approaching primitive mantle.

In element-element plots, most xenoliths plot on coherent trends, which trend toward primitive mantle (Fig. 4a-c) and can therefore be explained as partial melting trends. However, some samples (KAT17, LB34, and GL4201, the latter from Dawson *et al.* (1996)) have higher FeO than primitive mantle (Fig. 4c), yet display refractory characteristics such as low CaO and Al_2O_3 ; these samples therefore plot off the trend in FeO-MgO space, but plot close to or on the trend in CaO and Al_2O_3 versus MgO space. One of these, LB 34, a garnet-bearing peridotite, has FeO of 9.28 wt. % (Mg# = 89.8) and contains a forsteritic olivine inclusion in a relict garnet (see previous sections) suggesting that this sample has been re-enriched in Fe. These observations suggest that local Fe-enrichment has been superimposed on the overall compositional trends exhibited by our xenoliths. As will be discussed below, the compositional trends correlate well with depth, so the few Fe-enriched samples represent minor perturbations to the compositional stratigraphy.

7. THERMAL STATE AND THICKNESS OF CRATONIC MANTLE

Pressures and temperatures of equilibration for garnet-bearing samples were calculated using the aluminum-in-orthopyroxene coexisting with garnet barometer (PBKN) and the two-pyroxene thermometer (TBKN) (Brey and Köhler, 1990) assuming no Fe^{3+} (Table 4, Fig. 5). Only four of our samples (KAT 17, LB 12, 24, 53) have relict garnet. Raster analyses on the fine-grained inner kelyphite assemblages were used to calculate P/T for those samples without relict garnet. The P/Ts calculated for fresh and altered garnet are indistinguishable to within error. For garnet-free samples, temperatures were calculated using TBKN and by assuming an input pressure of 4.5 GPa for most samples (2.5 GPa was assumed for spinel peridotites). Clinopyroxene-orthopyroxene temperatures were calculated only for pyroxenes believed to be in equilibrium (see Fig. 3b, Table 4).

Dawson *et al.* (1997) showed that pyroxenes in the garnet coronas record higher temperatures (reflected in high CaO and Al_2O_3), suggesting that the breakdown of garnet may have been enhanced by heating. Because the coronal clinopyroxenes were often too small to analyze, we calculated the temperature of the coronal assemblages using the amount of Ca in orthopyroxene as a thermometer, which is based on the narrowing of the pyroxene solvus with increasing temperature (Brey and Köhler, 1990). For internal consistency, we simultaneously calculated the temperatures of the groundmass orthopyroxenes by this method. Although the absolute temperatures estimated using this thermometer are uncertain, the relative temperature difference is likely to be robust. A 100-200 °C heating is implied by our calculations. The presence of higher CaO rims on some primary orthopyroxenes in Labait samples also suggests heating.

As shown in Fig. 5, cratonic mantle presently exists to depths of at least 150 km beneath Labait. The Labait peridotites plot above the 41 mW/m² geotherm denoted by Kaapvaal low temperature garnet peridotites and also appear somewhat hotter than Lashaine peridotites which show a large scatter; the Labait peridotites follow a 50 mW/m² geotherm. The Tanzanian craton is characterized by low surface heat flow (23-47 mW/m²) (Nyblade *et al.*, 1990), which is inconsistent with the elevated temperatures recorded by the Labait xenoliths. These temperatures may represent recent thermal effects due to heating from the East African Rift magmas, which are not yet reflected in the surface heat flow.

8. DISCUSSION

8.1 Comparison to Kaapvaal

Based on petrochemical studies of the Siberian and South African cratons, it is believed that cratonic mantle is highly refractory and variably enriched in silica; the latter is manifested in the orthopyroxene-rich character of Kaapvaal (Boyd, 1989a) and Udachnaya peridotites (Boyd *et al.*, 1997). Like other cratonic mantle, the Tanzanian mantle is also refractory and slightly silica-enriched (Fig. 6). The degree of Si-enrichment, however, is not as large as beneath Kaapvaal (Boyd, 1989a), and more closely resembles the enrichment seen in Siberian peridotites (Boyd *et al.*, 1997). Lashaine peridotites also show moderate silica-enrichment (Rudnick *et al.*, 1994). Interestingly, most of the Labait garnet-bearing peridotites plot closer to the "oceanic trend" and hence show no silica-enrichment. A discussion of the many models proposed to explain silica-enrichment is beyond the scope of this paper. However, we note that peridotites from Somerset Island on the Canadian craton have turned out to be orthopyroxene poor (Schmidberger and Francis, 1997) as well as peridotites from East Greenland (Bernstein *et al.*, 1998). Clearly, the pattern of silica-enrichment in cratonic mantle is complex, and Kaapvaal appears to be one end-member of a spectrum.

8.2 Compositional stratification and implications for the origin and stability of cratonic mantle

The most important finding of this study is that the Tanzanian lithosphere, at least beneath Labait, is compositionally stratified. Indices of fertility, such as FeO, CaO, Al_2O_3 , and modal clinopyroxene correlate positively with temperature (Fig. 4d-f). Ni

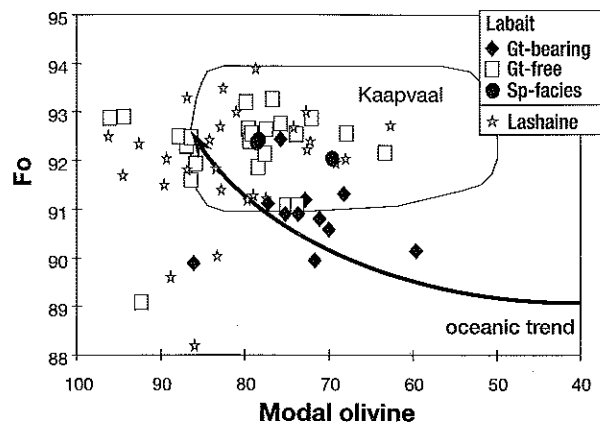


Figure 6. Forsterite content of olivine versus modal olivine. Kaapvaal field and oceanic trend taken from Boyd (1989). Lashaine data taken from Rudnick *et al.* (1994).

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(Lee and Rudnick, unpublished data), modal olivine, and Mg/Si correlate negatively with temperature. Fertility increases in a step-wise fashion with depth (Fig. 4d-f). As discussed earlier, a few samples bear evidence for Fe-enrichment; these samples represent small perturbations to the overall compositional stratigraphy of the mantle section (Fig. 4f).

The origin of this compositional stratification is unclear. If the stratification is a primary feature, then it represents a downward decrease in the degree of partial melting, as would be expected for an adiabatic melting column such as in a rising plume. If so, then the compositional trends shown in Fig. 4 are related to partial melting. We found that the model melting curves of Asimow (1998) provided the best-fit to our data (Fig. 4). These residue curves are for relatively low pressure, polybaric batch melting (assuming beginning of melting at 2.5 GPa), which approximates equilibrium porous flow (Asimow, 1998). Considerable deviation from this model, however, is seen for FeO versus MgO (Fig. 4c), which we attribute to the pressure sensitivity of FeO and to the fact that most of the Tanzanian peridotites probably formed at greater pressures than the model is calculated for. Batch melting at 7 GPa (Walter, 1998a and b) apparently depletes the residue of FeO more effectively than melting at lower pressures, which is typical of mid-ocean ridge basalt genesis. Regardless of which melting model is chosen, it is clear that our samples are ultra-refractory, having had 30 to 50 % melt extracted from them.

In a companion study (Chesley *et al.*, 1998), it was shown that spinel-facies peridotites and garnet-free peridotites record approximately the same Re depletion event (~2.8 Ga). Because the garnet-free peridotites are believed to have equilibrated at greater depths, the coincident ages suggest that the lithospheric

mantle down to depths of ~120 km beneath Labait may have formed during one melting event. However, most of the garnet-bearing peridotites, which are the deepest xenoliths, have younger Re depletion ages. This may reflect their formation from a more recent partial melting event during the Proterozoic or overprinting of the deepest lithosphere (Chesley *et al.*, 1998).

The downward increase in fertility is equivalent to an increase in intrinsic density. We calculated densities using published densities of mineral end-members, their proportions, and modes. We obtained an average density for the residual peridotites of 3.327 g/cm³ with deeper, garnet-bearing, samples having densities up to 3.350. For comparison, the average density of Kaapvaal garnet lherzolites is estimated to be 3.353 (Jordan, 1978), identical to that of the deepest portion of the Tanzanian lithosphere. This density is believed to be enough to counteract the negative buoyancy imposed by the cooler thermal state of cratonic mantle according to Jordan's isopycnic hypothesis (1978). We have illustrated this concept graphically in Fig. 7. In order to maintain stability, the density of the cratonic mantle at every level should be less than or equal to that of the surrounding asthenospheric mantle. In Fig. 7, isopycnic curves, representing neutral buoyancy, are shown with densities of residual peridotites at standard temperature and pressure conditions. These curves were calculated for different lithospheric thermal states and for an asthenosphere with a potential temperature of 1300 and 1400 °C, an adiabatic temperature gradient of 0.5 °C/km, and an intrinsic density of 3.390 g/cm³. Pressures for garnet-free samples have been inferred from equilibration temperatures and a conductive geotherm. It is clear that the residual peridotites from the Tanzanian mantle are dynamically stable at all levels, hence confirming Jordan's isopycnic hypothesis. The occurrence of Archean and Proterozoic mantle beneath Labait as deduced from Re-Os isotope studies (Chesley *et al.*, 1998) attests to the preservation of cratonic mantle despite proximity to rifting. A recent seismic tomographic study has shown that fast shear-wave anomalies extend to depths in excess of 250 km beneath the center of the Tanzanian craton and to depths of ~150-200 km beneath Labait (Ritsema *et al.*, 1998), consistent with the observation that the Tanzanian cratonic mantle persists, despite proximity to rifting.

8.3 The effects of rifting on cratonic mantle

Although this and a companion study (Chesley *et al.*, 1998) have shown that the Tanzanian lithosphere has remained intact since the Precambrian, it has not remained unmodified. Interaction with asthenospheric melts has led to an increase in density of the mantle section by local Fe-enrichment and by formation of Fe-rich dunites. Local Fe-enrichment is geochemically manifested as perturbations to the overall trend of increasing fertility with depth (Fig. 4f), and petrologically manifested in rocks that have low whole-rock Mg# but which have an otherwise depleted composition (low Ca and Al contents). Addition of Fe-rich materials is evidenced by the fact that 75% of the xenolith suite is composed of Fe-rich dunites. It is unclear whether these Fe-rich dunites are the fractional crystallization products of a melt or whether they are products of melt-rock reaction. The fact that most of these have Os and Ni contents similar to residual peridotites (Chesley *et al.*, 1998; Lee and Rudnick, unpublished data) favours the latter hypothesis. Many of the Fe-rich dunites are probably related to Cenozoic rifting, but it is possible that some are related to much older events. Future Re-Os work on Fe-rich samples will shed light on this matter.

The formation of Fe-rich dunites is likely to be the dominant mechanism for increasing the overall density at a given depth.

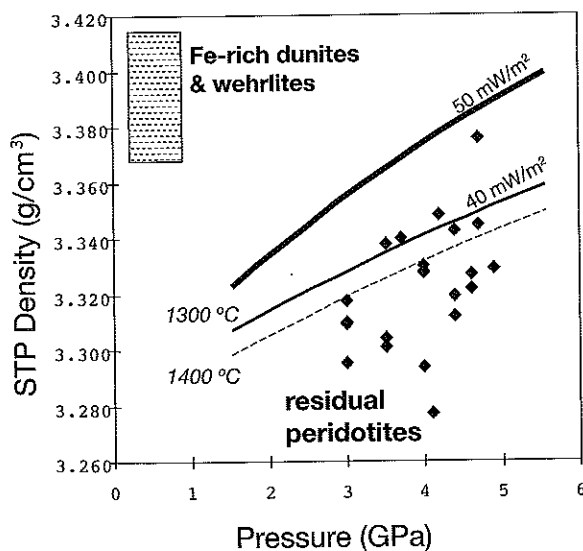


Figure 7. Densities of Labait xenoliths at standard temperature and pressure conditions. Pressures for garnet-free peridotites estimated from their equilibration temperatures and by assuming a conductive geotherm. Isopycnic curves for various lithospheric geotherms calculated using an asthenosphere with potential temperatures of 1300 °C (solid lines) and 1400 °C (dashed line), an adiabatic temperature gradient of 0.5 °C/km, a constant thermal expansivity of $2.7 \times 10^{-4}/\text{K}$, and a density of 3.390 g/cm³. Lithospheric geotherm models are from Rudnick *et al.* (1998). Densities that lie below isopycnic lines represent stable conditions. Range of densities for Fe-rich dunites and wehrlites at STP are shown by the gray bar.

Their range of densities are shown in Fig. 7. Fe-rich dunites are 0.6 to 3 % denser than residual peridotites. Given the range in densities, a minimum of 25 % addition of Fe-rich dunites via dikes or veins is required for a layer of the mantle to become negatively buoyant. Considering that Fe-rich dunites make up 75 % of the xenoliths in the field, it is possible that the above threshold will or has been met. Therefore, we speculate that as the base of the mantle section beneath Tanzania continues to interact with rift-related magmas, generating dense Fe-rich dunites, it will eventually become negatively buoyant and delaminate, aiding in the mechanical thinning of the lithosphere. The presence of low seismic shear wave velocities at depths >150 km beneath Labait suggests that the effects of rifting are currently propagating into the craton's margin (Ritsema *et al.*, 1998). These low seismic velocities may be manifestations of elevated temperatures and/or the presence of dense Fe-rich bodies.

9. SUMMARY

- 1) Tanzanian cratonic mantle extends to depths of at least 150 km beneath the Labait volcano in the Tanzanian section of the East African Rift. Re-Os systematics indicate that the upper 120 km formed during the Archean while the lowermost lithospheric section was either overprinted or formed during the Proterozoic (Chesley *et al.*, 1998).
- 2) Tanzanian cratonic mantle is compositionally stratified, with a step-wise increase in fertility with depth.
- 3) Density calculations indicate that the residual peridotites satisfy the isopycnic hypothesis and are thus dynamically stable with respect to the asthenosphere. This interpretation is supported by the preservation of Archean and Proterozoic Re-Os depletion ages beneath Labait.

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- 4) Xenoliths record elevated temperatures at depth, and some samples have experienced Fe-enrichment. Thus the mantle section has been chemically and thermally modified. Some of these modifications are due to Cenozoic rifting and some may be older.
- 5) Fe-rich peridotites make up 75% of the xenolith suite in the field, and are much denser than the residual peridotites. The contribution of Fe-rich dunites via dikes, veins, or reaction zones to layers of residual peridotite may eventually impose negative buoyancy, causing such layers to delaminate.

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