# ORIGIN OF THE LHERZOLITE NODULES IN THE KIMBERLITES OF NORTHERN LESOTHO

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Estimates of equilibration temperatures and pressures for lherzolite nodules from kimberlites can be made through consideration of experimentally determined phase studies and mineral compositions determined by electron microprobe analysis. It is necessary that a sample have equilibrated with the assemblage Ca-rich pyroxene+Ca-poor pyroxene+garnet for the equilibration conditions to be estimated. At present, it is also necessary that these phases be poor in FeO. The diopside solvus (Davis and Boyd, 1966) is used to estimate the equilibration temperature. Once this temperature is known, the equilibration pressure can be estimated from the $Al_2O_3$ content of enstatite using the data of MacGregor (1973). This procedure is discussed in more detail by Boyd (1973).

Figure 1 shows plots of estimated equilibration temperatures and depths for a group of lherzolite nodules from northern Lesotho. These estimates are subject to substantial uncertainties, but it appears likely that the broad stratigraphic relations will not be changed by subsequent refinement. In Fig. 1 the "raw" percentages of $Al_2O_3$ in the enstatites were used to estimate the equilibration pressures. These data appear to define an inflected geotherm in which the points on the shallow limb plot close to the predicted geotherm of Clark and Ringwood (1964). In Fig. 2 the estimated equilibration pressures have been corrected for the presence of minor amounts of FeO in the natural enstatites and garnets using a method developed by Wood and Banno (in press). This correction shifts the points to more shallow depths. Corrections can also be applied for sodium, assuming that all the Na in the natural enstatite is present as jadeite ($NaAlSi_2O_6$), or combining Al and Cr before subtracting Na. Such corrections shift the points on the inflected limb of the geotherm to somewhat greater depths but do not appreciably affect the points on the shallow limb. Nevertheless, regardless of the correction made, the overall form of the geotherm and the order of points remain the same.

The lherzolites from the kimberlites of northern Lesotho form two groups that differ markedly in texture, mineralogy, bulk composition, and mineral chemistry. A group whose equilibration points fall on the shallow limb of the geotherm (Fig. 1) is characterized by a coarse-grained (2-4 mm) granular texture. A second group, whose equilibration points fall on the inflected limb of the geotherm, is intensely sheared. Lherzolites in the second group contain coarse porphyroblasts of garnet and diopside in a fine-grained, granulated groundmass of olivine and enstatite. Some of the granular lherzolites contain accessory phlogopite, chromite, and rare graphite, but these minerals have not been found in the sheared lherzolites.

It is unlikely that the geotherm illustrated in Fig. 1 describes a steady-state situation. For a steady-state geotherm to have such an inflection would require that the rocks above and below the inflection have markedly different thermal properties. There are compositional and textural differences between the sheared lherzolites on the inflected limb of the geotherm and the granular lherzolites on the shallower limb, but it seems unlikely that these differences would affect the thermal properties to a significant degree. It appears more likely that the geotherm in Fig. 1 was perturbed. In other words, it appears that in a period prior to the eruption of the kimberlites a steady-state geotherm was established in the mantle beneath Lesotho with a slope rather like the "shield geotherm" of Clark and Ringwood (1964). This primitive geotherm was then perturbed by an event that caused major heating in the depth range 150-200 km. Possibly the postulated heating was related to the intense shearing of the lherzolites that define the inflected limb of the geotherm and possibly that shearing resulted from the plate movements that occurred during the break-up and dispersal of Gondwanaland.

Briden (1967) has compiled paleomagnetic data for the southern hemisphere and found evidence for four episodes of drift since the Cambrian separated by quasi-static intervals. The principal episode of drift occurred when Gondwanaland broke up in Late Triassic and Jurassic time after a quasi-static interval lasting for approximately 200 m.y. Smith and Hallam (1970) concluded that the initial rifting of Gondwanaland began in the Late Jurassic and Early Cretaceous, but that much of the dispersal occurred in Late Cretaceous and Tertiary times. Most of the kimberlites in Lesotho and South Africa are believed to have been erupted in the Late Cretaceous (e.g., Wagner, 1914; although there are as yet few radiometric dates. Dr. T. E. Krogh (personal communication) has obtained an age of 90-110 m.y. for a crystal of zircon from one of the pipes in the Kimberley area. Thus the African plate was in motion after a long quasi-static period when the kimberlites wer erupted. The data in Fig. 1 suggest that the sheared lherzolites of deepest origin may have been stress-heated by as much as 300°C above their ambient, preshearing temperature.

Phlogopite is commonly found in the granular lherzolites, but no phlogopite has been found in any of the sheared lherzolites of deep origin (Fig. 2). Sample 1582, a sheared dunite from Thaba Putsoa, has the highest equilibration temperature of any of the phlogopite-bearing nodules--it is estimated to have crystallized at 1115°C. This temperature is well below the melting curve found for pure phlogopite in the presence of enstatite by Modreski (Fig. 2). However, the natural phlogopites contain substantial amounts of FeO and $TiO_2$, which would be expected to reduce their stability at high temperatures.

The occurrence of phlogopite in these lherzolites is complicated because it is possible that some of the phlogopite has been introduced at a late stage in their eruption. For example, phlogopite is often found mantling the kelyphite rims on the garnet in the granular lherzolites. Nevertheless it is possible that some of the phlogopite was introduced at depth in the mantle, prior to the incorporation of the nodules in kimberlite. Lambert and Wyllie (1968) have suggested that $H_2O$ is largely stored in hydrous minerals in the lithosphere, whereas in the upper part of the asthenosphere it is dissolved in small amounts of interstitial silicate liquids. Possibly the occurrence of phlogopite in these nodules reflects such a relationship.

Experimental studies of the solidi of peridotites at high pressures show that $H_2O$ produces an extremely large decrease in the temperature range for the beginning of melting. The data of Mysen and Boettcher (1972) suggest that small amounts of melting would be expected in the depth range from which the sheared lherzolites have come, provided small amounts of $H_2O$ were present. Nevertheless, there would be no melting in the absence of $H_2O$.

Various lines of evidence suggest that the point of inflection in the geotherm (Fig. 1) might have been the top of the low-velocity zone in Late Cretaceous time. The sheared lherzolites have probably been erupted intact because they were dry. Most of the sheared lherzolites show some degree of depletion relative to pyrolite. Thus they may have undergone small degrees of partial fusion, and the liquids with dissolved $H_2O$ may have been kneaded out by the shearing process. Weertman (1972) has emphasized the importance of shearing stresses in causing the coalescence of dispersed liquids in mantle rocks.

## References

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## Figure Legends

Fig. 1: Temperature-depth points for lherzolite nodules from northern Lesotho compared with the shield geotherm (Clark and Ringwood, 1964). Open points are granular lherzolites and solid points are sheared lherzolites. Equilibration pressures calculated by "raw $Al_2O_3$" method.

Fig. 2: Temperature-depth points for lherzolite nodules from northern Lesotho compared with the graphite ⇄ diamond curve and the curve for the melting of pure phlogopite + enstatite (Modreski, 1972). Equilibration pressures calculated by the Wood-Banno method.

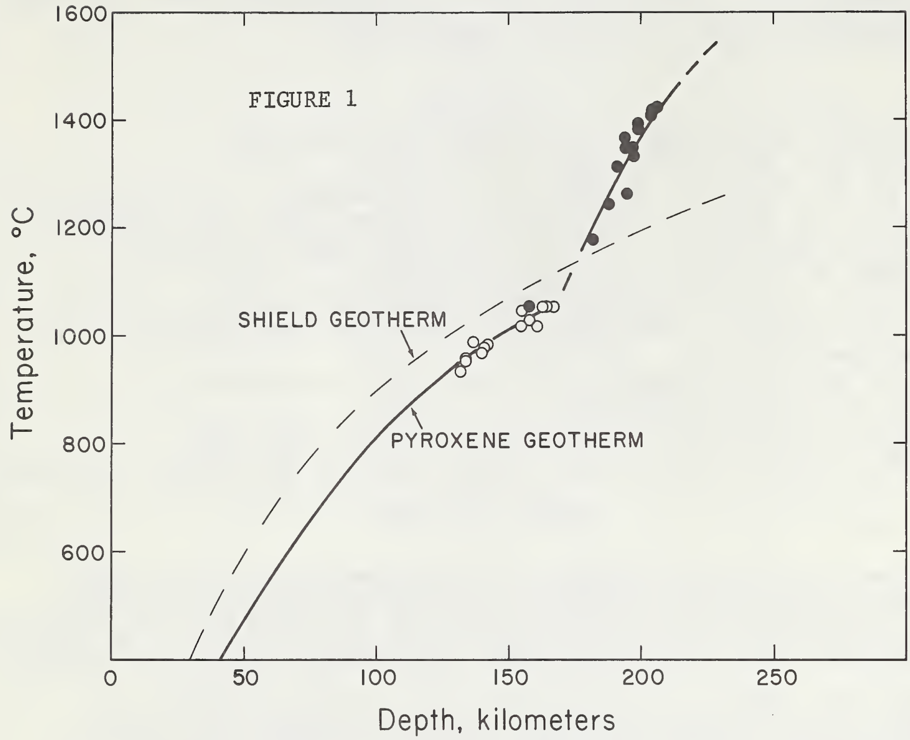
FIGURE 1
SHIELD GEOTHERM
PYROXENE GEOTHERM
Temperature, °C
1600
1400
1200
1000
800
600
0
50
100
150
200
250
Depth, kilometers

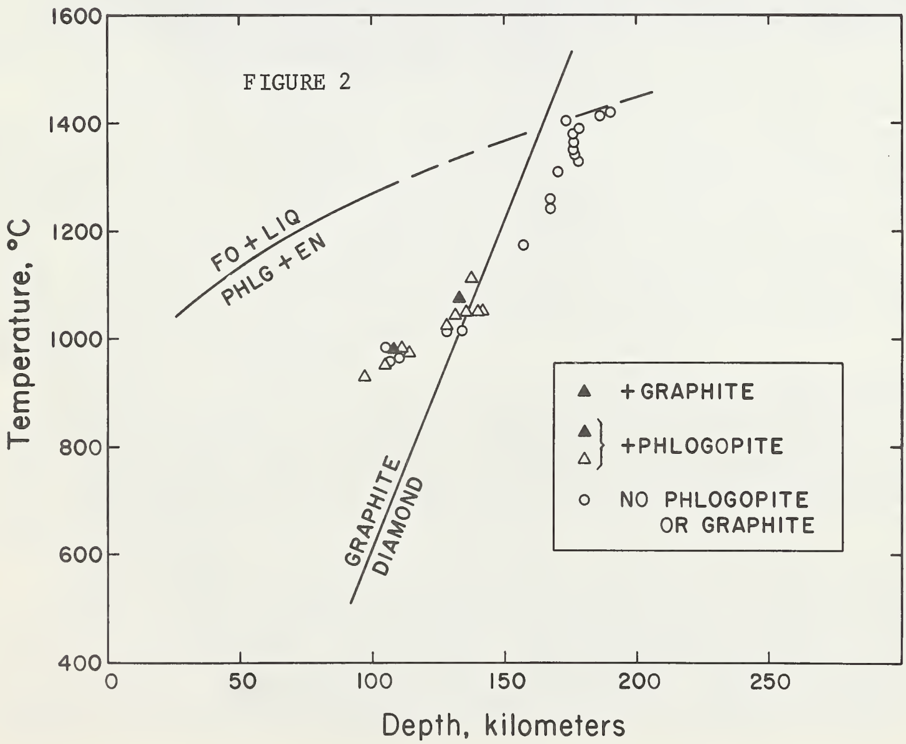
FIGURE 2
FO + LIQ
PHLG + EN
GRAPHITE
DIAMOND
+GRAPHITE
+PHLOGOPITE
NO PHLOGOPITE OR GRAPHITE
Temperature, °C
1600
1400
1200
1000
800
600
400
0
50
100
150
200
250
Depth, kilometers