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CLASSIFICATION OF TEXTURES AND FABRICS OF PERIDOTITE XENOLITHS FROM SOUTH AFRICAN KIMBERLITES

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ABSTRACT

A previous classification of textures and fabrics in peridotite xenoliths from kimberlites is summarized and extended by addition of two new types: the secondary tabular type which results from recrystallization following an intense flowage; the fluidal mosaic type, with distinctive tectonic stripes which could involve superplasticity. The coarse granular and tabular types, previously defined, are strongly recrystallized and recovered; they could represent a mantle that is rigid or deforming at slow strain rates. The porphyroclastic and mosaic types would correspond to peridotites flowing with a faster strain rate at the time they were extracted by the kimberlite magma. The textures and fabrics of these two highly deformed types have been generated by plastic flow; olivine recrystallization has been minor in the former type and complete in the latter. These data and interpretations argue for a non-steady-state origin for the kink in the pyroxene geotherm proposed by other authors.

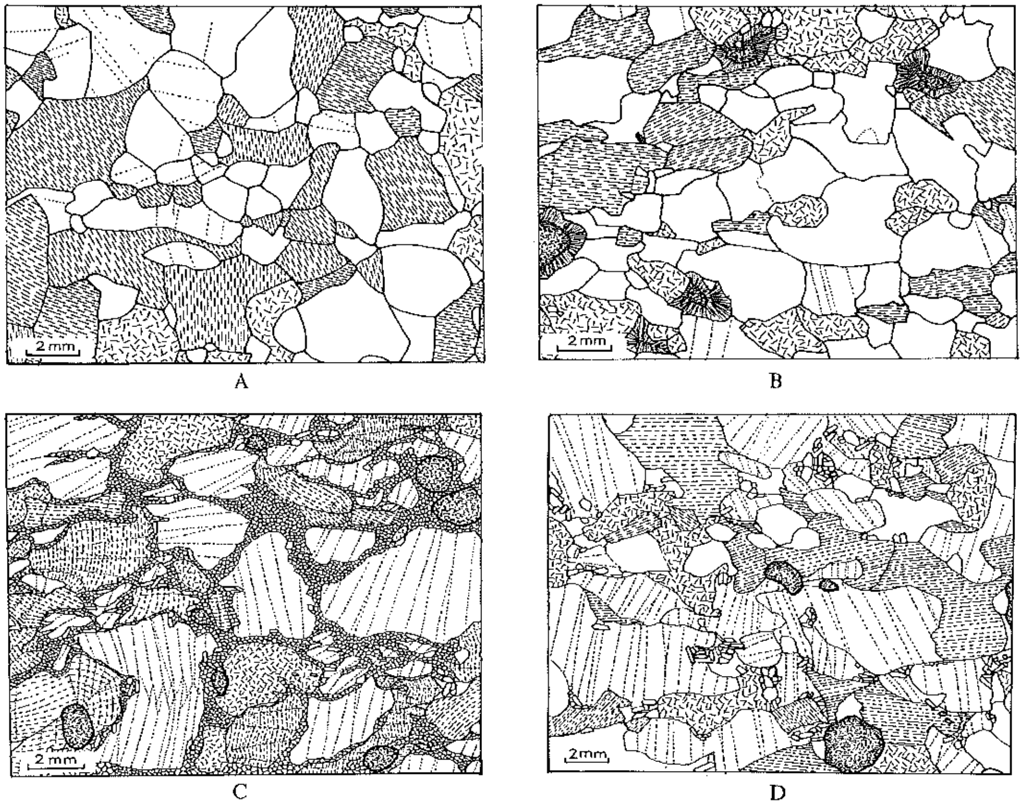
INTRODUCTION

Assuming thermodynamic equilibrium, it is now possible to assign a position in a P, T diagram to the peridotite xenoliths from kimberlites by a study of the chemistry of their pyroxenes. This has led Boyd and Nixon (1973) and MacGregor (in press) to discover that, when plotted in a P, T diagram, these peridotite xenoliths lie on a curved line that has a pronounced kink. They also observed that texturally the xenoliths were different on each side of the kink. The "granular" xenoliths plot along a curve interpreted as the continental geotherm in the lithosphere below South Africa in the Cretaceous when the kimberlite brought up the xenoliths. The "sheared" xenoliths plot below the kink in this curve with a steeper slope interpreted as the geotherm in the upper asthenosphere modified by shear heating. When our classification of textures and fabrics in peridotite xenoliths from Lesotho became available (Boullier and Nicolas, 1973a), representative samples of each group were also plotted on the P, T diagram. The points aligned according to increasing deformation and helped to define what has been considered as a transition between rigid lithosphere and flowing asthenosphere (Boyd and Nixon, 1973).

Though our classification is still provisional, this remarkable coincidence between conditions of equilibration and textures has created some need for a paper with the following objectives: (1) to recall the definitions of the different textural types and to illustrate them; the fabrics typical of these textural types will not be described here (see Boullier and Nicolas, 1973a and b) except for two new types which were not presented previously; (2) to compare briefly the textural types in peridotites from kimberlites with their counterparts in basalts and in large Alpine-type massifs; (3) to derive conclusions about the environmental conditions prevailing in the mantle when the textures and fabrics developed; and from that (4) to discuss the general model of Boyd and Nixon (1973) and MacGregor (in press).

MAIN TEXTURES

Table 1 summarizes the principal data on the different structural types met in peridotite xenoliths from South African kimberlites.



Figs. 1 and 2. Drawings after micrographs of the typical textures and of some intermediate ones; the foliation, if any, is E.W. The micrographs and the fabrics of the typical textures have already been published (Boullier and Nicolas, 1973a). Olivine: blank, except for the KBB represented by lines of small dots; orthopyroxene: aligned dashes parallel to the (100) plane when visible, otherwise random dashes; clinopyroxene: largely spaced dots; garnet: closely spaced dots, thick contours with occasional kelyphite-rims.

Fig. 1. Scale bars = 2 mm. A. Coarse granular texture (harzburgite 69 Ki 26, Kimberley). B. Coarse tabular texture (garnet and spinel lherzolite PHN 1595, Thaba Putsoa). See KBB details on Fig. 3B. C. Porphyroclastic texture (garnet harzburgite, DB2, De Beers Mine). The recrystallization of the olivine porphyroclasts in small neoblasts is important. Only a few euhedral tablets are present. D. Texture probably transitional between the coarse tabular and the porphyroclastic ones (garnet harzburgite, K7, Kamfersdam). The porphyroclasts are less deformed and recrystallized than in a typical porphyroclastic texture. Affinities in textures and fabrics with the coarse tabular texture argue for such an origin. Starting with a nearly random fabric as in the coarse granular texture, it seems improbable that the moderate deformation evidenced in the rock could be responsible for its strong preferred orientation.

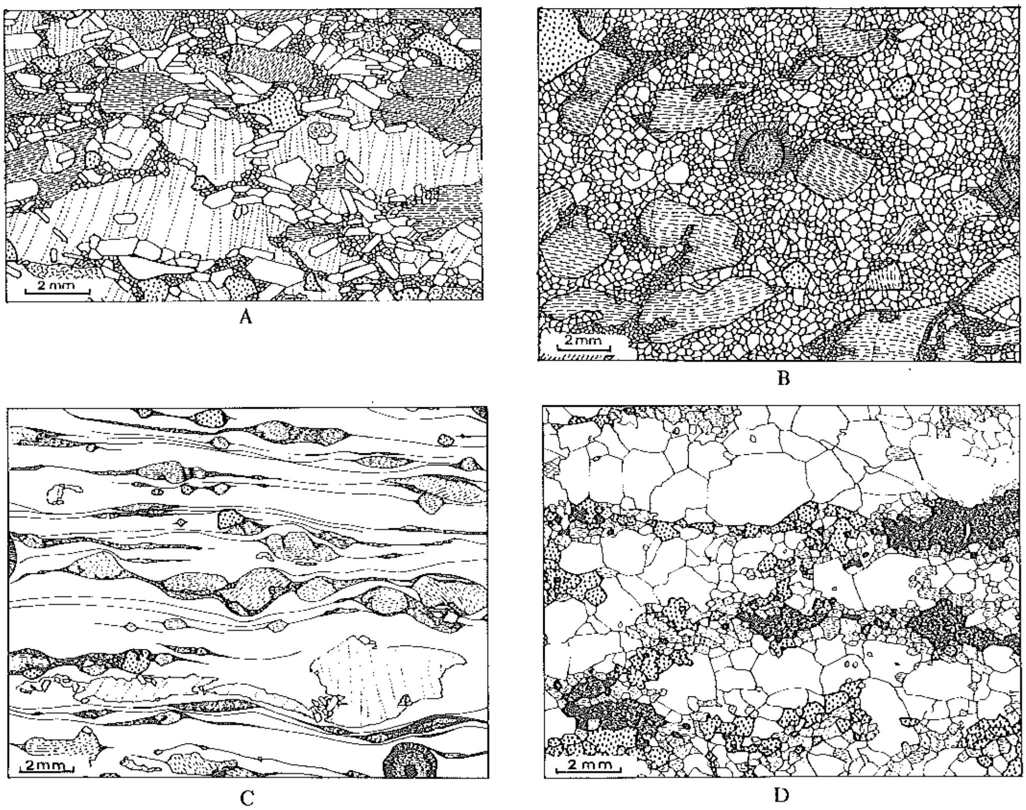


FIG. 2. Scale bars = 2 mm. A. Porphyroclastic texture (garnet lherzolite 69 Ki 14, Kimberley). Mineral lineation E.W. Note the three kinds of olivine grains: the large deformed porphyroclasts, the small neoblasts and the euhedral tablets postdating the deformation. B. Mosaic texture (garnet lherzolite PHN 1925, Mothae). Mineral lineation E.W. The olivine is entirely recrystallized while the enstatite displays porphyroclasts partly recrystallized in tiny neoblasts. C. Fluidal mosaic texture (garnet lherzolite, KAO2, Kao). Mineral lineation E.W. A large and unique olivine porphyroclast proves that the mosaic texture derived from a porphyroclastic one. The fluidal character is superimposed on the mosaic texture. See Fig. 3A. D. Secondary tabular texture (garnet lherzolite, PHN 1654, Matsoku). Mineral lineation E.W. The olivine tends to be segregated in bands where it has a tabular shape with some inclusions; these bands contrast with those where the other minerals dominate in small and scattered grains. For the fabric, see Fig. 4.

The main textures and fabrics have been described in detail in previous papers (BOULLIER and NICOLAS, 1973a and b). They were based at that time on the study of only twenty-five xenoliths. We have now examined 120 xenoliths. This larger basis verifies that all transitions exist between the types, as had been predicted from a comparable study of peridotite xenoliths from basalts (MERCIER, 1972; MERCIER and NICOLAS, in press). As in the case of basaltic xenoliths, the provisional names were assigned considering only olivine, although the investigation on textures and fabrics has also included enstatite which is the other major mineral of peridotites. For example, a texture with olivine porphyroclasts (Fig. 2A) is called "porphyroclastic"; another with the olivine entirely as small polygonal grains (Fig. 2B) is called "mosaic", whether or not the enstatite constitutes porphyroclasts. We propose here to modify (1) the former provisional name of "coarse grained" into "coarse granular" which seems more appropriate and suggests a comparison with the protogranular texture described in basaltic xenoliths (see below); (2) the former provisional name of "tabular olivine and enstatite" into "coarse tabular" because it is as coarse (sometimes coarser) than the coarse granular type and suggests between the two types an association which is verified in the position in the P, T diagram and in the petrology (see Table 1).

Estimations of the relative abundance of the different types would require a systematic study. Our only attempt in this direction is a field count of 133 xenoliths made with M. G. WILSHIRE and M. PRINZ on the Jagersfontein dumps. It is reported in Table 1 together with the proportions measured in our collection which does not claim to be representative.

Two other modifications of our earlier, tentative classification appear in Table 1. The non-penetrative deformation already described (BOULLIER and NICOLAS, 1973a, p. 65) is commonly superimposed on the mosaic texture and is therefore worthy of being distinguished as a subtype—"the fluidal mosaic texture" of the mosaic texture. It is characterized by narrow stripes (0.01–0.03 mm) that are intensely deformed and parallel to the foliation in the mosaic groundmass (Fig. 2C and Fig. 3A). They originate in the recrystallized boundaries of enstatite porphyroclasts where the neoblasts are evenly grained and tiny (0.01 mm). From there the neoblasts of enstatite, and not of olivine as previously thought, are scattered along the stripes which connect several enstatite porphyroclasts or end in the olivine mosaic

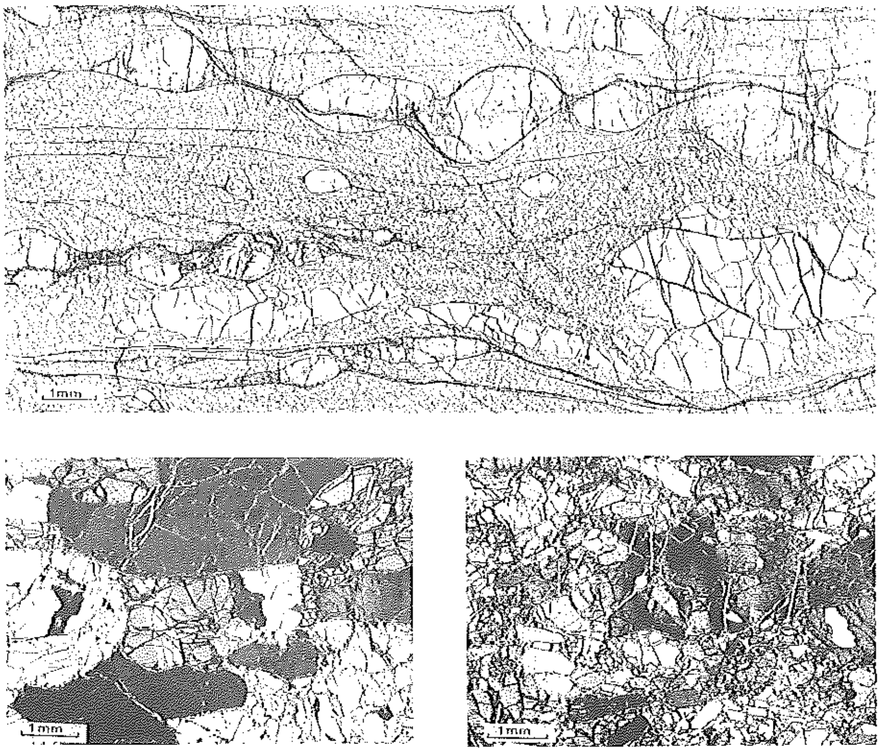


FIG. 3. Scale bars = 1 mm. Photomicrograph of the fluidal mosaic texture (detail of the drawing Fig. 2C). The narrow stripes are superimposed on a mosaic texture. They connect beads of enstatite porphyroclasts, originating in their recrystallized rims and carrying away the 0.01 mm neoblasts. They end up as microfaults in the olivine mosaic matrix. B. Photomicrograph (crossed polarizers) of a detailed area in the coarse tabular texture of Fig. 1B. The kink bands in olivine are highly recovered with sharply cut kink band boundaries. C. Photomicrograph (crossed polarizers) of a detailed area in the porphyroclastic texture of Fig. 2A. The wavy kink bands evidence a weak recovery.

where they sharply cut through the crystals as microfaults (Fig. 3A). The extremely fine grain size has made it impossible to measure the fabric in the stripes so far.

The other modification is the introduction of a new textural type, the "secondary tabular" texture to account for the special textures described by Cox *et al.* (1973) in the Matsoku pipe (Table 1, Fig. 2D). Observation on these samples shows that the peridotite has been intensely deformed with development of strong foliation and lineation, underlined by the scattering of the garnet in trails of small grains. One sample 20 cm thick shows a beautiful deformation gradient from flattened garnets to garnets scattered as described a few millimeters across, some richer in olivine, some in the other phases where enstatite, diopside and garnet are in somewhat comparable proportions. In these bands, the minerals are recrystallized but remain in small grains (0.3 mm). By contrast, in the olivine-rich bands, the recrystallization has resulted in larger tabular crystals (2 × 1 mm) which commonly include small crystals of the other phases[*]. The number of inclusions in tabular olivine grains is greater than in the coarse tabular texture. This is a first criterion to distinguish these two textures (the coarse tabular and the secondary tabular). Better ones are provided

(1) by the shape of the orthopyroxene which is small and irregular in the secondary tabular texture, and large and tabular in the coarse tabular texture;

(2) by the comparison of structures in the sample: strongly foliated and lineated in the secondary texture, and mildly foliated and non-lineated in the primary texture.

The fabric is orthorhombic for the tabular olivine grains with diffuse point maxima: Xol normal to the foliation, Yol and Zol in the foliation, the latter being parallel to the mineral lineation. The enstatite orientations are inconsistent (Fig. 4).

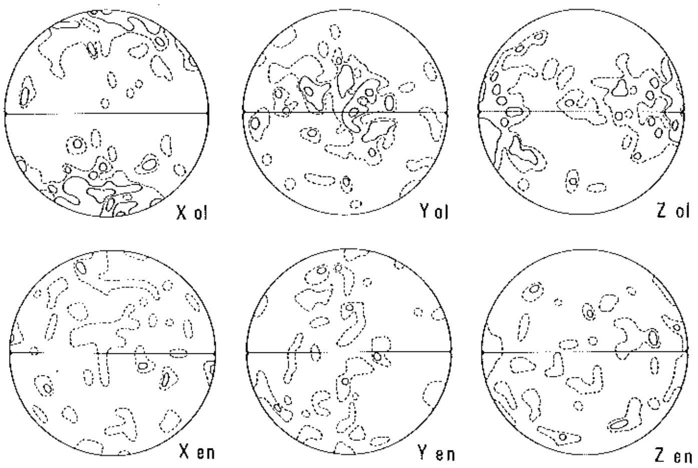


FIG. 4. Olivine (ol) and enstatite (en) fabrics in the secondary tabular texture of Fig. 2D. Equal area projections on the lower hemisphere. Contours: 1, 2, 4%; 100 olivine grains, 200 enstatite grains. Foliation horizontal, mineral lineation E.W.

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[*] It is commonly observed in peridotites which are recrystallized that the grain size is smaller when the number of phases present in the rock is larger. In similar environments dunites can be formed by olivine grains of a few centimeters across, harzburgites by grains of 5 to 10 mm, and lherzolites by grains of 3 to 5 mm. Assuming that recrystallization takes place by grain boundary migration, with some highly mobile boundaries favoring the growth of given grains, these observations can be explained by comparing the possibilities of boundary migration in the cases of an olivine rich and of a mixed band. In the first case the growth is impeded only when highly mobile olivine boundaries meet together and compete; in the other case it is soon impeded when each boundary of a given phase comes in contact with grains of different stable phases.

COMPARISON WITH PERIDOTITES FROM BASALTIC XENOLITHS AND MASSIFS

An extensive study of textures and fabrics in peridotite xenoliths in basalts from different environments has resulted in a new classification (MERCIER, 1972; MERCIER and NICOLAS, in press), which has a wider basis and correlated the fabric more closely with the textures than the earlier classification of BROTHERS and RODGERS (1969). The different types are also compared with textures and fabrics observed in peridotites from massifs. Their origin is investigated in the light of recent work on the problem of flow and orienting mechanisms in peridotites (AVE'LALLEMANT and CARTER, 1970; NICOLAS *et al.*, 1971, 1973).

The protogranular type is the oldest one recorded in peridotite xenoliths from basalts; it can be identified in some peridotite massifs despite the modification of textures and fabrics imposed by the plastic flow occurring during their intrusion. In many aspects it can be compared with the coarse granular type from kimberlite described here. In the basaltic xenoliths, every transitional stage is observed between the protogranular and the porphyroclastic type; this second type differs from the one in kimberlite xenoliths mainly on its larger amount of recovery (see below). Again, through transitions, one grades into the equigranular types; the equant subtype compares with the mosaic type described here except for the enstatite habit. In the basaltic xenoliths, the enstatite is recrystallized in the same fashion as the olivine while in the kimberlite xenoliths, it is not. In the kimberlite xenoliths, no equivalent of the equigranular tabular subtype has yet been observed. Conversely, the coarse tabular type and the fluidal mosaic subtype of kimberlite peridotite are unknown in basaltic xenoliths. Finally the secondary textures, exemplified in kimberlites by the Matsoku series, are well represented in basaltic xenoliths where a secondary cycle is initiated by formation through an annealing process of secondary protogranular types. The interpretation is the same as the one proposed by HARTE *et al.* (1973), i.e. a secondary recrystallization, post-dating a deformation cycle, which builds up a new texture and fabric in many ways comparable to the primary one. This has been documented in basaltic xenoliths using as a strain marker the progressive scattering of spinel–clinopyroxene–orthopyroxene clusters characterizing the protogranular texture. Thus it has been demonstrated that the sequence of our description of basaltic types corresponds to increasing deformation. Though the evidence is more tenuous in xenoliths from kimberlites it is believed to be also true for them (Figs. 1 and 2).

The peridotites from alpine-type massifs commonly show the porphyroclastic textures with different intensity of recovery and recrystallization (NICOLAS *et al.*, 1972); this can ultimately lead to the equigranular equant type comparable to our mosaic one. It is mainly restricted to peridotite massifs incorporated in granulitic terranes like in the Ivrea Zone of northern Italy (LENSCH, 1971).

INTERPRETATION OF THE TEXTURES AND FABRICS

Many more accurate studies need to be carried on, using, for instance, the electron-microscope techniques (GREEN and BOULLIER, in preparation) before those textures and fabrics are clearly understood. We will restrict ourselves to a few general points.

The coarse granular and coarse tabular types (like the protogranular one in basaltic xenoliths) have been recrystallized with a strong tendency toward the minimization of grain-boundary energy (Kretz, 1966). The only evidence of plastic deformation is given by the rare kink bands (Fig. 3B). They indicate that a strong recovery taking place at the same time as boundary migration minimizes the grain-boundary energy, as shown by convergence of grain boundaries with triple points at 120°.

It is not known whether these textures were developed during flow or in a static state. The lack of any orientation in the coarse granular type would indicate a static environment. The foliation and definite fabrics of the coarse tabular type could be due to some deformation but the process would have to be distinct from plastic flow because neither the shape of the grains nor the enstatite fabric are compatible with it. A stress-controlled recrystallization might explain it (Carter *et al.*, 1972), but we do not wish to exclude the possibility of an origin by a cumulate or other magmatic process, followed by some recrystallization. Harte *et al.* (1973) consider the possibility that the coarse-grained textures can be regenerated from fine-grained and deformed ones by recrystallization. This is suggested by the recrystallization, subsequent to a deformation, in xenoliths from the Matsoku pipe. The differences between such a secondary type and the coarse granular or tabular types has been stressed (p. 3); they would certainly be attenuated by prolonged annealing which cannot be ruled out as an alternative hypothesis. However it seems improbable because, in basaltic xenoliths where this recrystallization is better documented (Mercier and Nicolas, in press), the minor phases, spinel, diopside and enstatite, which have been scattered in the olivine matrix during flow, do not concentrate again significantly and are often present as inclusions in olivine. Considering the relatively low temperature of equilibration of these types (1000°, Boyd and Nixon, 1972; MacGregor, in press) and the textural features described above, we assume that the corresponding peridotites were probably static in the mantle or deforming at a slow strain rate compared to the ones displaying the other types.

The interpretation of the porphyroclastic and mosaic types has already been presented (Boullier and Nicolas, 1973a). The former type was attributed to plastic flow with minor recrystallization and the second with complete recrystallization in olivine, whereas the less ductile enstatite was still in the porphyroclastic stage. This recrystallization is not considered as stress guided (Ave'Lallemant and Carter, 1970) but as "strain guided", that is belonging to the general recovery processes due to the generation and movement of dislocations in crystals (plastic flow). There is a striking contrast between the amount of strain and paucity of recovery in the porphyroclasts on the one hand, and the total absence of any optically visible strain in the euhedral tablets on the other hand (Fig. 3C). Small tablets are also observed in the similar type in basaltic xenoliths but they are not euhedral and are often slightly strained. This special shape can tentatively be explained by a growth in the presence of a liquid film between the growing tablet and the consumed porphyroclast or, as suggested by H. W. Green (oral communication), by growth in a porphyroclast with such a high density of dislocations that it behaves as an isotropic matrix with regard to the growing tablet. It is also remarkable that those xenoliths which were deformed at higher temperatures than the coarse granular and tabular ones (up to 1400° for the mosaic ones; Boyd and Nixon, 1972; MacGregor, in press) show far less recovery in their porphyroclasts (Fig. 3B and C). Basalt xenoliths showing primary textural types, were deformed at comparable temperatures and they show the same recovery as the coarse granular and tabular xenoliths. More instructive is the case of the Lanzo massif in the Alps in which also the peridotites show a strong recovery and recrystallization. It was intruded in connection with the plate movements responsible for the alpine orogeny (Nicolas *et al.*, 1972). Therefore we assume that the mean strain rate is in the range of 10^{-14}/sec which is compatible with plate movements. The plastic flow occurred at 1200° when the peridotites were in the 7kbar range (BOUDIER and NICOLAS, 1972).

All this strongly suggests that the porphyroclastic and mosaic textured peridotites were deformed at *strain rates larger than the plate movements ones* and that *they were flowing at the time they were extracted* and brought up in the kimberlites. Otherwise, taking into account their high temperature, they would rapidly recover and probably recrystallize. GREEN and RADCLIFFE (1972) have argued similarly for a basaltic xenolith from Lunar Crater, Nevada. The absence of visible strain in the tablets cutting through the porphyroclasts suggests that they grew after the deformation, that is after the rock was incorporated into the kimberlite. The available fluids would favor their rapid growth and possibly explain their euhedral habit. On the other hand, the coarse granular and tabular textured rocks may come from areas in the mantle which are not flowing or are flowing (by a process distinct of plastic flow) at much smaller strain rates, and possibly due to plate movements.

A minor but interesting problem is raised by the fluidal mosaic texture. The scattering of tiny grains of orthopyroxene along non-penetrative planes suggests that they may have been deforming in the superplasticity field (HAYDEN *et al*., 1972). The flow which can be considerable takes place mainly by intergranular slip. The peripheral recrystallization of the porphyroclasts of enstatite into the tiny grains would necessarily precede and prepare this new stage by creating grains small enough to be able to deform by this process. This hypothesis is under investigation.

DISCUSSION OF THE RECENT MODELS OF THE UPPER MANTLE BELOW SOUTH AFRICA

We have already discussed (BOULLIER and NICOLAS, 1973a) the point regarding the composition of the minerals used by BOYD and NIXON (1972) and MACGREGOR (in press) to construct their geotherms. The strain in their sheared nodules is probably sufficient to mechanically mix layers of different compositions to form a homogeneous lherzolite as has been observed in comparable rocks from peridotite massifs. Therefore, it is not certain that the minerals which have been analyzed originally belonged to these sheared peridotites. This is not critical if it can be proved than they are now chemically equilibrated with the deforming peridotite.

The interpretation recently proposed by BOYD and NIXON (1973) and MACGREGOR (in press) mentioned above must be modified in the light of the conclusions reached in the preceding section. Two possibilities are envisaged. Either

(1) The general model is correct; the porphyroclastic and mosaic textured xenoliths represent the top of the moving asthenosphere. In this case, we think that the plate movement responsible for the development of porphyroclastic and mosaic textures is not continuous; it is a "staccato" movement as SHAW (1973) has implied for the plate movement below Hawaii with consequent basalt generation by shear heating. A comparable relationship should be expected with kimberlite generation, since we have argued that the xenoliths had to be extracted from the mantle during their deformation; or

(2) A diapiric intrusion is responsible for the distribution of xenoliths in the P, T diagram as proposed by GREEN and GUEGUEN (in press). The xenoliths above the kink of the normal geotherm belong to the diapir which, originating at a greater depth,

is hotter than the surrounding rocks at a given level in the mantle. The xenoliths coming from its margins can be deforming at any strain rate depending on the total velocity and the velocity gradient in the diapir. The generation of kimberlite is connected with the intrusion and the xenoliths can be incorporated in this fluid at any time during their deformation. This model fits better with our general constraints as well as with details like the observation of a sharp deformational gradient in a xenolith.

ACKNOWLEDGEMENTS

We thank I. D. MacGregor and P. H. Nixon who provided most of our samples and H. W. Green who critically reviewed the manuscript.

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TABLE 1

Textures	Coarse granular (Fig. 1A)	Coarse tabular (Fig. 1B)	Porphyroclastic (Figs. 1C,D; Fig. 2A)	MOSAIC		Secondary tabular (Fig. 2D)
				Normal (Fig. 2B)	Fluidal (Fig. 2C) descriptions restricted to non-penetrative stripes	
Former and other terminologies	Coarse grained (BOULLIER and NICOLAS, 1973)	Tabular olivine and enstatite (BOULLIER and NICOLAS, 1973)				
	GRANULAR			SHEARED (BOYD and NIXON, 1972)		
Number of different generations of olivine (ol.) and enstatite (en.)	1 ol. 1 en.	1 ol. 1 en.	2 or 3 ol. 1 or 2 en.	1 ol. 2 en.	1 en.	1 or 2 ol. 1 en.
Grain shape and size	isometric 6 mm	tabular 5 × 2 mm	ol. and en. porphyroclasts: elongated, ol.: 5 × 2 mm; en.: 3 × 1 mm neoblasts: isometric ol.: 0.2 mm en.: 0.02 mm ol. tablets: tabular 1 × 0.3 mm	en. porphyroclast: elongated, 4 × 2 mm neoblasts: isometric ol.: 0.3 mm en.: 0.02 mm	en. grains, isometric 0.01 mm concentrated in stripes 0.03 to 0.01 mm thick	ol. tabular: 2 × 1 mm and irregular: 2 mm en. isometric: 0.3 mm
Grain boundaries	ol./ol. straight or curved 120° triple points ol./en. curved	ol./ol. straight or curved 120° triple points ol./en. curved or straight when parallel to foliation	ol. and en. porphyroclasts: irregular, invaded by neoblasts ol. and en. neoblasts: straight or rounded ol. tablets: straight rational faces	en. porphyroclasts: irregular, invaded by neoblasts ol. and en. neoblasts: straight, 120° triple points	en., straight or rounded	straight and embayed
Deformation in crystals (KB = kink band; KBB = kink band boundary)	almost none; largely spaced and clear KB, sharp KBB converging in triple points with grain boundaries	almost none; largely spaced and clear KB, sharp KBB converging in triple points with grain boundaries	porphyroclasts: intense; closely spaced and wavy KB, blurred KBB neoblasts: invisible tablets: absolutely none	en. porphyroclasts: intense distortion in lattices neoblasts: ol., almost none en., invisible	en., invisible	almost none, wavy KB
Structures in the nodule (foliation S = plane of mineral flattening; lineation L = mineral elongation in S)	no foliation no lineation	good foliation weak lineation	good foliation good lineation	good foliation excellent lineation	excellent non-penetrative "foliation" excellent lineation	excellent foliation excellent lineation
Fabrics olivine and enstatite preferred orientations (⊥ = perpendicular; // = parallel)	ol.: weakly orthorhombic X ol. ⊥ S if any en.: almost random	ol.: good X ol. ⊥ S; Y ol. and Z ol., girdles in S weak maxima en.: X en. ⊥ S or girdle ⊥ S	porphyroclasts: strong X ol. ⊥ S, Z ol. // L; X en. girdle ⊥ S Z en. // L neoblasts: X ol. ⊥ S weak Z ol. // L tablets: strong X ol. ⊥ S, Z ol. // L	ol. neoblasts: almost random, weak Z ol. // L strong local ol. subfabrics	unknown	tabular olivine: X ol. ⊥ S, Z ol. // L en: random
Dominant petrographic type. See restrictions p. 100. * Jagersfontein field count	garnet- and spinel-poor harzburgite 72 %*	garnet- and spinel-poor harzburgite	garnet lherzolite	garnet lherzolite 83 %*		garnet lherzolite and harzburgite
Numerical importance. See restrictions p. 100. * Jagersfontein field count	50 % 66 %*	29 % coarse tabular	13 % and porphyroclastic 11 %*	8 % 22 %*		