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Texture and Fabric of Peridotite Nodules from Kimberlite at Mothae, Thaba Putsoa and Kimberley

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ABSTRACT

A preliminary study of 25 ultramafic xenoliths from Lesotho and South African kimberlites defined four main textures. Firstly, a "coarse grained" texture with one generation of crystals which are slightly deformed, with no foliation and a weak fabric. Secondly a "tabular olivine and enstatite" texture with one generation of crystals and a better defined fabric—by analogy with certain basalt peridotite xenolith textures, this is tentatively attributed to recrystallization with strong annealing. A third, is a "porphyroclastic" texture, with juxtaposition of large elongated and deformed crystals of olivine and enstatite, and smaller ones forming an undeformed mosaic; the former are thought to be due to deformation by intracrystalline gliding and the latter to recrystallization. A fourth is characterized by a "mosaic" texture with no olivine porphyroclasts since these have been replaced by a small crystal mosaic (depending on the intensity of deformation, orthopyroxene may or may not be affected by this process)—this texture is common in basalt peridotite xenoliths where it characterizes a very intense deformation, accompanied and followed by complete recrystallization. A non-penetrative shearing deformation can be superimposed on this.

INTRODUCTION

The present report is the result of a preliminary examination of 25 ultramafic xenoliths, brought up by the kimberlite intrusions, Thaba Putsoa and Mothae (Lesotho) and Kimberley (Republic of South Africa). The rocks studied, viz., harzburgites, garnet-harzburgites, lherzolites, garnet and/or spinel-lherzolites are often serpentinized.

The present study forms a complement to the data of Mercier (1972), Nicolas *et al.*, (1971) on the peridotite xenoliths in basalts, and on Alpine-type peridotite massifs, both of which probably originated in more superficial levels of the upper mantle.

On the basis of texture and fabric* of olivine and enstatite, the samples have been grouped and given provisional names, except when the analogy with textural types of peridotite xenoliths from basalts described by Mercier (1972) is such that it is possible to use the same name. The adopted classification will be revised when further samples have been studied. This should provide new data on the textures of the deep layers of the mantle where these xenoliths are found, and contribute to explaining their kinematics. Nevertheless an interpretation of some textural types is proposed in view of recent research in this

* The term "fabric" is not used in its general meaning, that is, comprising all spatial data in the rocks under consideration, but only the microscopic ones (shape and lattice orientations); in the same way, the large scale geometry (structure) is not considered here, but only the microscopic mutual arrangement of minerals (texture).

field (Ave Lallemant and Carter, 1970; Carter *et al.*, 1973; Nicolas *et al.*, 1971, 1972, in press; Mercier 1972).

MAIN TEXTURES

1 "*Coarse-grained*" *texture* (6 out of 25 xenoliths)

This texture is illustrated by the harzburgite *69 KI 26* (Kimberley Mine, provided by E. D. Jackson). The crystals are large (7 mm approx.) and belong to the same generation (plate 19A). They are not well enough elongated (L/W = 1,4) to define a foliation on the sample. However, a statistical flattening plane of the minerals can be defined by measurements of their anisometry in thin sections cut in discernible planes. The olivines and enstatites show kink-bands (KB) perpendicular to this flattening plane. The intergranular boundaries are regular: slightly curved between olivine and enstatite and straight between two minerals of the same type. These and the kink-band boundaries (KBB) converge in triple points. This indicates that the deformation producing these KB, precedes annealing (Nicolas *et al.*, 1971).

The olivine fabric is only slightly orthorhombic and that of the enstatite is even more blurred. X olivine is perpendicular to the flattening plane, whereas Y olivine and Z olivine lie in the plane (figure 13).

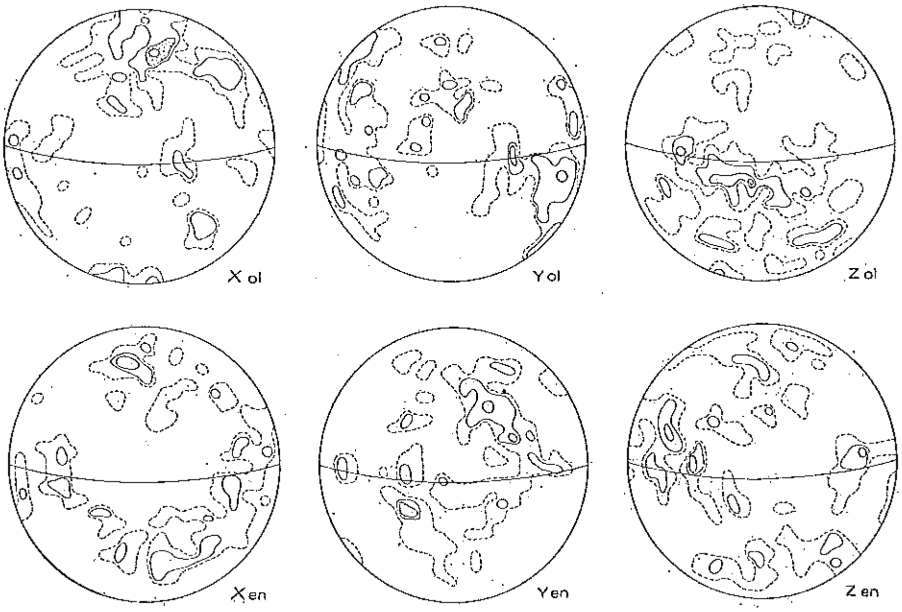

Figure 13 Olivine and enstatite fabric in the "coarse-grained" texture (specimen 69 *KI* 26) represented by equal area projections on the lower hemisphere.
Contours: 1% (dashed line); 2% (continuous line); 4 and 8% (decorated area;) measurements of 100 grains. The flattening plane has been projected on the nets.

The texture recalls the protogranular type described by Mercier (1972), but this cannot be ascertained due to the scarcity of spinel which characteristically exsolves with clinopyroxene from orthopyroxene.*

The garnet-harzburgite *H 137* (Kimberley Mine, Museum National d'Histoire Naturelle, Paris) is similar to harzburgite *69 K 126*, except for more intense deformation and the presence of garnet. This mineral, consisting of small globular grains (2–3 mm), is usually associated with orthopyroxene and surrounded by a ring of black fibrous kelyphite. The olivine and enstatite are slightly elongated and deformed. In the olivine the KB are blurred. There are two groups in enstatite (plate 19B). One consists of narrow KB with intense rotation (16°) from one band to the other, in crystals where the (100) glide plane is normal to the flattening. The other consists of blurred and wavy KB with weak rotation (8°) in crystals in which the glide plane is now parallel to the flattening. By analogy with experimental deformation (Nicolas *et al.*, in press) the former would correspond to the shortening direction and the latter to the flow direction. Small olivine crystals (0,01 mm) apparently due to recrystallization appear between the large deformed crystals. The rock is still coarse grained (olivine, enstatite = 6 mm approx.), the intergranular boundaries are regular and the texture *non-oriented* (plate 19B). This garnet harzburgite is, therfore, very similar to harzburgite *69 KI 26*, except for the presence of a second generation of olivine crystals, and the abundance of KB which results from a superimposed deformation.

Some lherzolites display a similar "coarse-grained" texture, e.g., the garnet and spinel lherzolite *1914 A* from Mothae. Here, the garnets are slightly flattened parallel to a weak foliation. They are surrounded by an undeformed reaction-rim, the outer part of which consists of non-oriented phlogopite flakes. The bright green clinopyroxene (2 mm) is smaller than the other minerals and flattened along the foliation. In thin section, this mineral tends to be encircled by the enstatite, which is grey-green and slightly elongated parallel to the foliation. The olivine has a similar habit and is deformed by distinct KB. The intergranular boundaries are regular, although some olivine crystals seem interlocked as if they had originated from one older large crystal. A few grains of rutile have been found in this rock. This is rare but has been noted by Williams (1932, p. 356) and in specimen *1654* (Matsoku) by Boyd (personal communication).

The "coarse-grained" texture group is characterized by:

A single generation of coarse-grained crystals (6 mm).

A weak deformation and insignificant elongation of the crystals; consequently there is no foliation and lineation.

Straight or curved mineral boundaries.

A weak orthorhombic olivine fabric, even weaker in enstatite.

* Editor's note: Spinel-pyroxene symplectites have been noted at Letseng-la-terae (Dawson, personal communication) and elsewhere in kimberlitic ultrabasic nodules by Frick (1970).

2 *"Tabular olivine and enstatite" texture* (7 out of 25 xenoliths)

The reference sample is a garnet lherzolite *1595*, from Thaba Putsoa, which shows a good foliation due to mineral flattening (plate 20A). Grain size is medium (olivine, enstatite: 5 × 2 mm; garnet: 2 mm; clinopyroxene: 1–2 mm; spinel: 0,2 mm). Sporadic bright green diopside and the dark brown interstitial spinel tend to be associated. The garnet is flattened parallel to the foliation, and surrounded by a black fibrous rim of kelyphite, with an outer non-deformed corona of orthopyroxene, clinopyroxene and brown spinel. It is scattered through the rock and is not associated with a specific mineral. The grey-green enstatite crystals are flattened in the foliation plane but they do not define a lineation. They can show some distinct KBB normal to the foliation. The olivine forms tablets with straight lined boundaries parallel to the foliation, but their limits normal to that plane are less straight. The olivine and enstatite tablets can partly enclose one another. As soon as KBB appear in the olivine crystals, the straight lined contours are altered and their new segments converge with KBB in triple points. The KBB are distinct; they tend to be normal to the foliation. Some crystals with a close common orientation originated from one larger olivine by fragmentation; otherwise, the minerals belong only to a single generation (plate 20A).

The olivine fabric (figure 14) shows a strong X olivine maximum, normal to the foliation and partial girdles of Y olivine and Z olivine in this plane. Relying

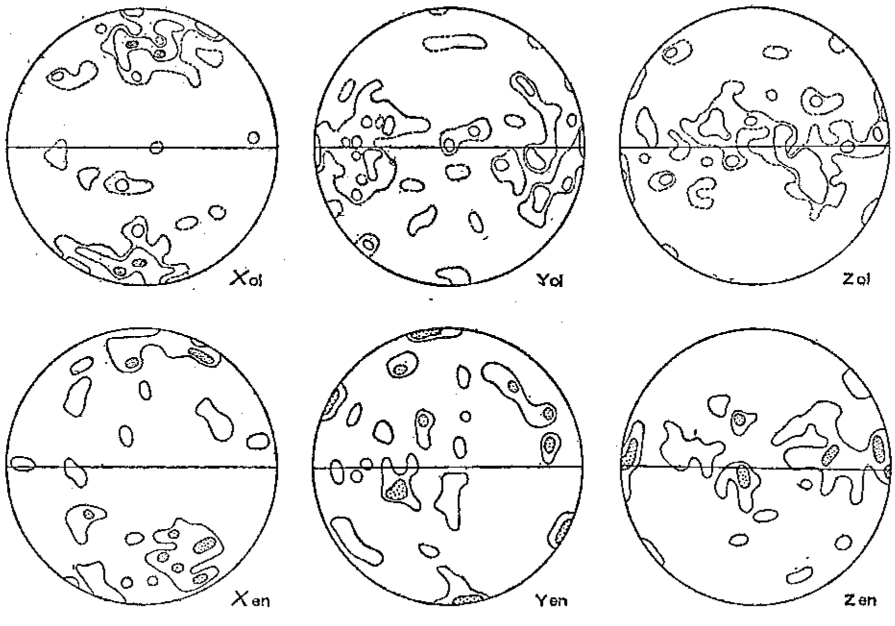

Figure 14 Olivine and enstatite fabric in specimen *1595*: "Tabular olivine and enstatite" texture. The foliation is horizontal. 70 measurements for olivine; 45 for enstatite. The same key as in figure 13.

on partial data (45 points), the enstatite fabric is clear but unusual; X enstatite tends to be normal to the foliation, with Z enstatite in this plane and Y enstatite rather scattered.

Allowing for the moderate deformation evidenced by the development of KBB in some crystals, and the modification of the tabular habit, the texture and the fabric, except for the coarser grain size (5 × 2 mm versus 1,4 × 0,5 mm), recall the equigranular tabular textural type described in basalt peridotite xenoliths (Mercier, 1972). Here, it is attributed to an annealing, following a strong deformation. It may be relevant to observe that the unusual X enstatite orientation normal to the foliation, has been experimentally produced by syntectonic recrystallization (X enstatite parallel to σ_1 and normal to the flattening plane; Carter, Baker and George, 1973).

3 *Porphyroclastic texture* (7 out of 25 xenoliths)

A typical sample *69 KI 14*, Kimberley Mine, provided by E. D. Jackson, has already been described by Mercier and Nicolas (in preparation). This is summarized here:

> "The olivine porphyroclasts are 6×2 mm – larger than the enstatite and diopside porphyroclasts. Surprisingly, their KBB are not straight as in the basalt xenoliths but wavy, disproving a strong recovery after deformation. The deformation occurred prior to the formation of the tabular grains which are not deformed although they can cut or be enclosed in the porphyroclasts (plate 20B). The tablets are 1 × 0,3 mm; they have straight lined boundaries. They seem superimposed on the fine grained (0,2 mm) and equigranular mosaic background and might represent a later recrystallization. The porphyroclastic and tabular crystals define an excellent foliation with a good mineral lineation revealed in hand specimen by a slight elongation of the garnet (5 mm).
> Explicit fabric data are given in fig. 15 for the olivine and enstatite porphyroclasts, the tabular olivine crystals and the fine-grained olivine mosaic. Their fabrics compare very well; they show an X olivine maximum normal to the foliation, and a Z olivine parallel to the observed lineation. It is strongest for the porphyroclasts where the whole orthorhombic symmetry indicates pure shear as the flow mechanism responsible for the fabric with presumably the [100] (010) system active for olivine. The good Z enstatite maximum parallel to the lineation is in agreement with this interpretation but the Y enstatite behaviour is not understood. The fabric quality decreases for the recrystallized tabular and mosaic crystals".

Sample *1915* presents a tabular texture tending toward a porphyroclastic one by a moderate plastic deformation. The straight boundaries between grains are replaced by broken lines meeting with the KBB in triple points. The olivine fabric (figure 16) tends towards that shown by plastic flow. In a typical plastic flow fabric, the position of X enstatite should be in, or close to, the foliation

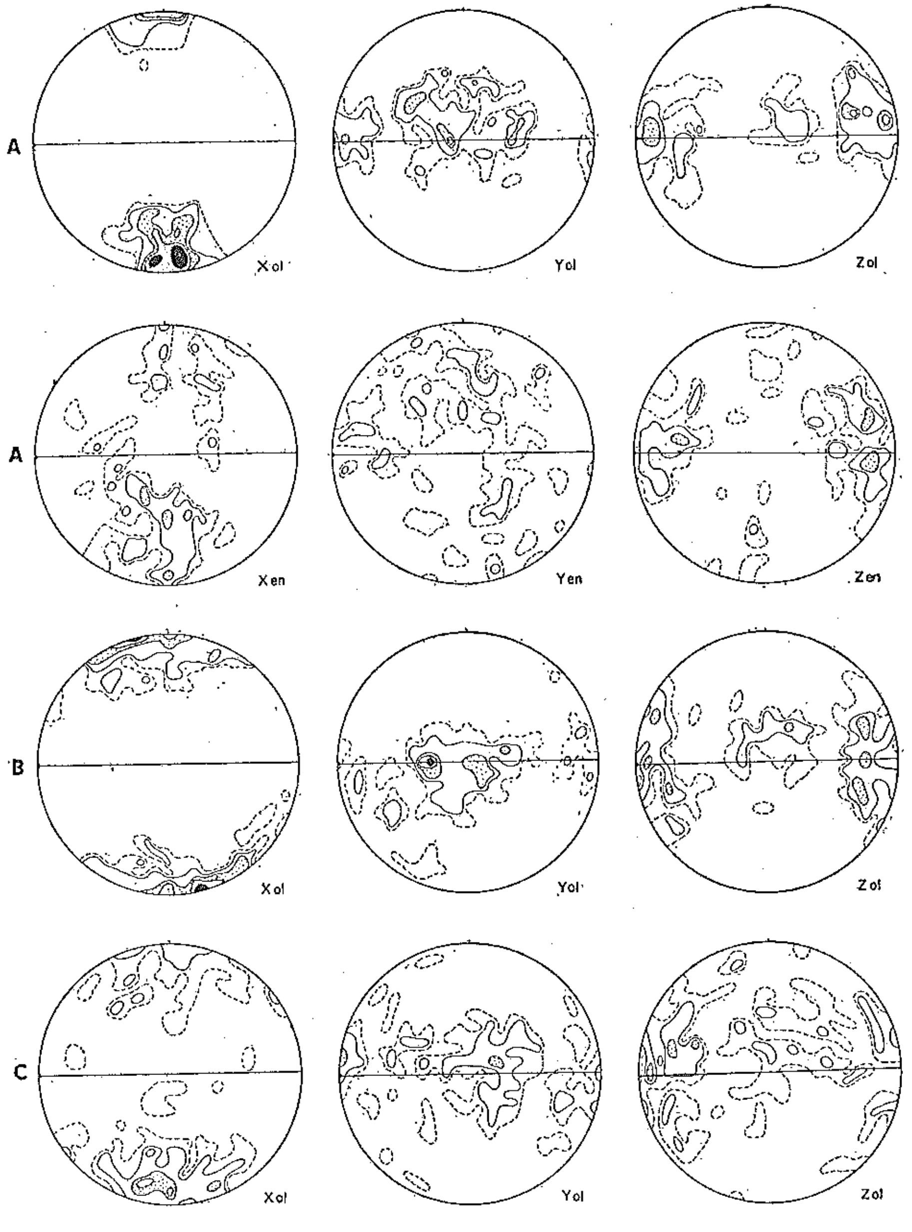

Figure 15 Olivine and enstatite fabric in the "porphyroclastic" texture (specimen *69 KI 14*); measurements of 100 grains. Foliation plane and weak mineral lineation (flow direction) have been projected on the nets. The same key as in figure 13.
A: Olivine and enstatite porphyroclasts. B: Olivine tablets. C: Olivine mosaic.

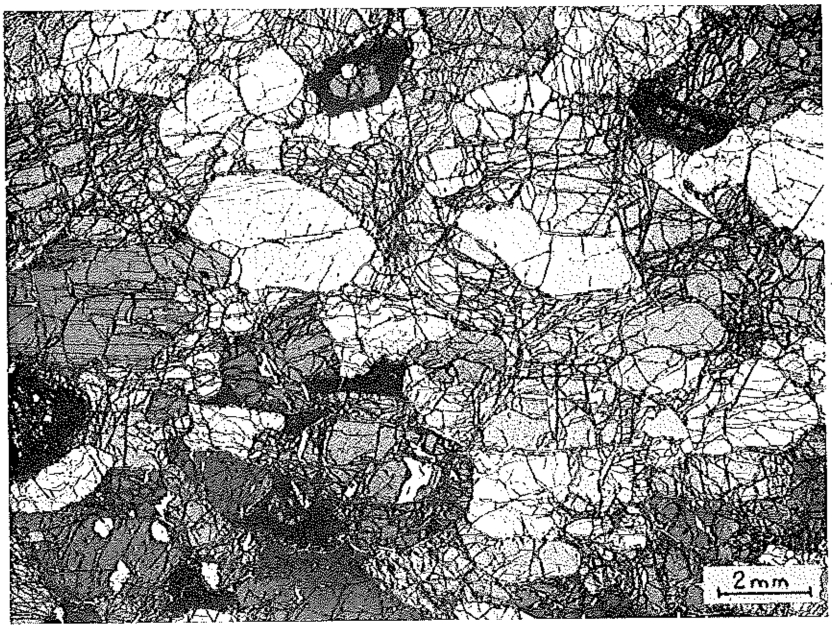

Plate 20A "Tabular olivine and enstatite" texture (garnet and spinel lherzolite *1595*). The foliation is horizontal. The grain boundaries parallel to the foliation are regular and straight. The nicols are not exactly crossed. (*Boullier and Nicolas*)

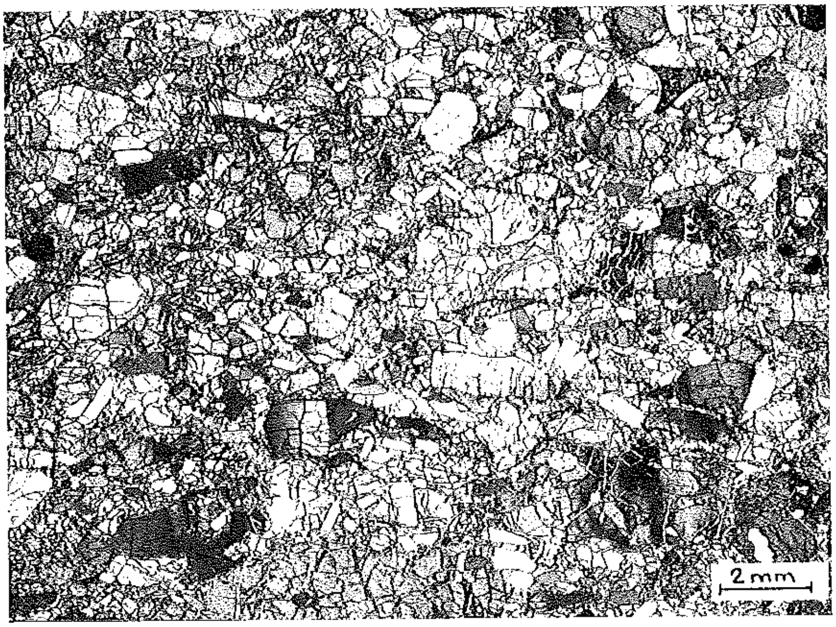

Plate 20B "Porphyroclastic" texture observed in the a–c kinematic plane; the kinematic direction is horizontal (garnet lherzolite *69 KI 14*). Three classes of olivine crystals can be distinguished: large deformed porphyroclasts, euhedral and undeformed tablets, and fine-grained mosaic. The nicols are not exactly crossed.

(*Boullier and Nicolas*)

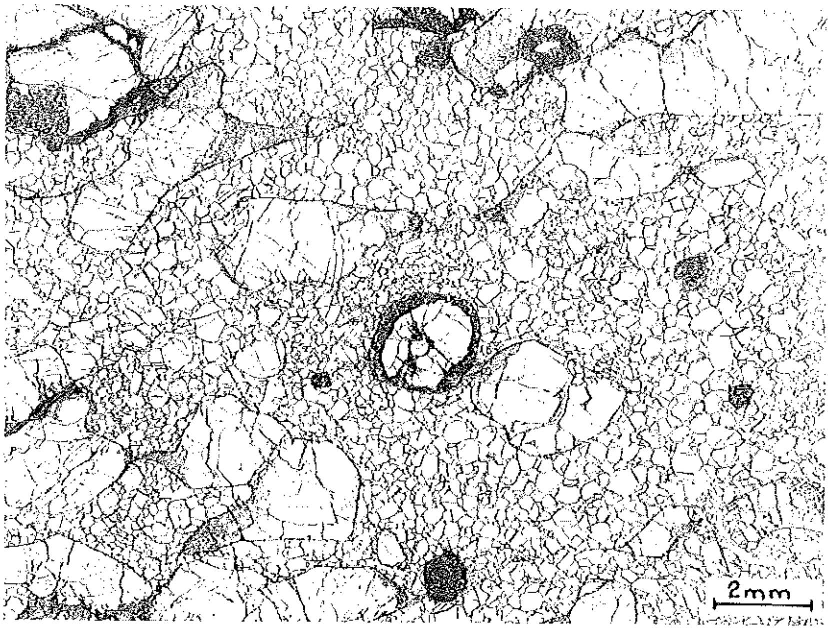

Plate 21A "Mosaic" texture (garnet lherzolite *1925*) showing porphyroclasts of garnets surrounded by kelyphite, diopsides with cloudy margins and partially recrystallized enstatites in a matrix of olivine with a mosaic texture. Plain light. (An extended portion of this section, under crossed nicols, is shown in plate 15B). (*Boullier and Nicolas*)

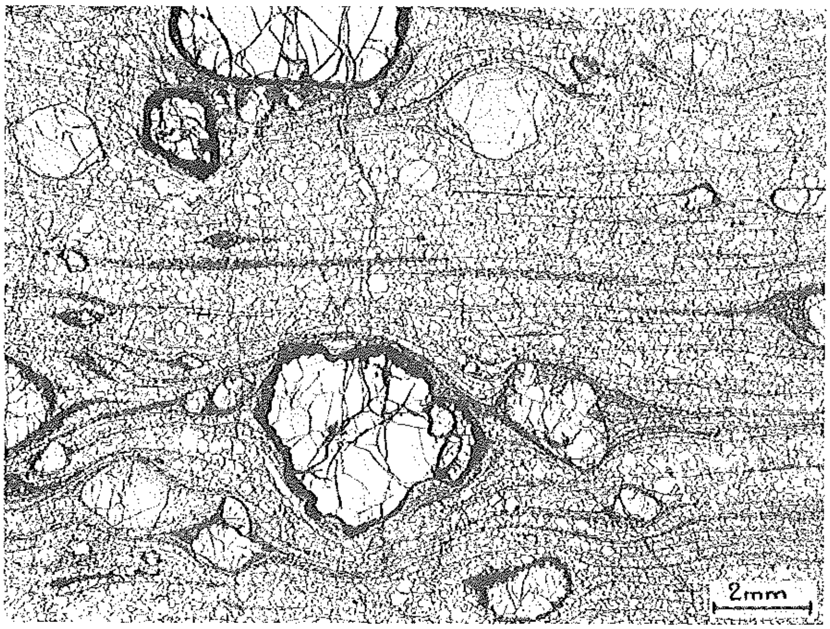

Plate 21B Non-penetrative shear deformation superimposed on a mosaic texture, *1611*. Plain light. Thin section of rock shown in plate 18B. (*Boullier and Nicolas*) the X, Y and Z olivine maxima are pronounced, but distinct from the general pattern. This indicates a common origin by recrystallization of a former large single crystal, from which the new grains have partially inherited their orientation (Ave Lallemant and Carter, 1970). In the latter case, the general fabric is poorly defined as is common in recrystallized textures.

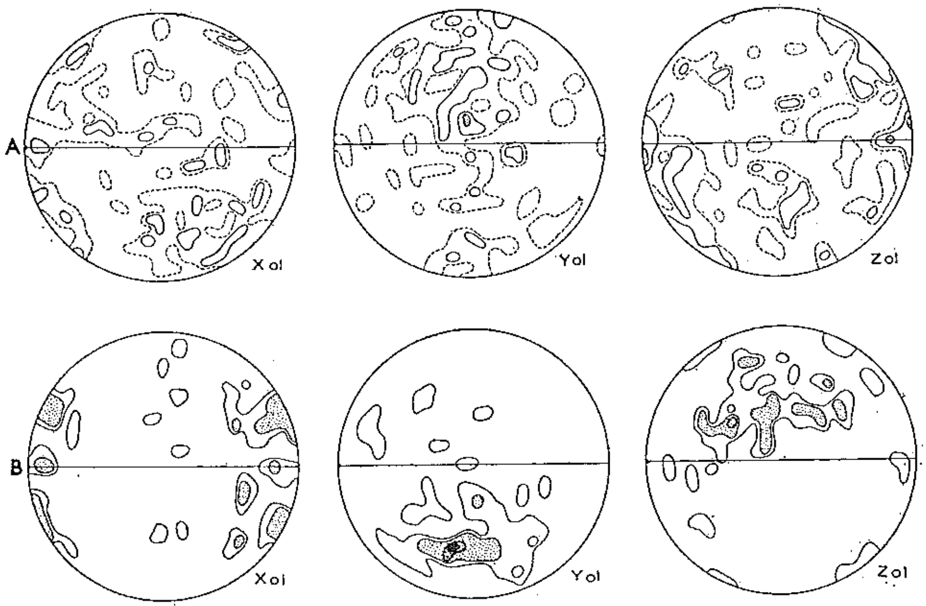

Figure 17 Olivine fabric in specimen *1925*.
A: 100 measurements scattered throughout the sample. B: 50 measurements on a single domain.
Same key as in figure 13.

During the deformation responsible for this texture, garnet, diopside and, more rarely, enstatite were passively rolled in a flowing olivine matrix. The enstatite reacts differently according to its original orientation. Either it will be passively rolled or, if the glide system is favourably oriented with (100) within a given angular domain, it will glide. If outside the domain it will be locked, before getting a retort shape by twisting and gliding, (A. Etchecopar, personal communication) and, finally, along lines of intense deformation, it recrystallizes to a fine-grained mosaic. Although indirectly proved by the oriented domains, the existence of an earlier coarse-grained texture is confirmed by relict olivine porphyroclasts, in the mosaic of specimen *1895* (Mothae). The olivine can recrystallize in equant grains (*1925*) or in small tablets parallel (*1924*) or not (*1596*) to the foliation.

This textural type is well known in peridotite xenoliths from basalts, where each transitional step has been observed between a thoroughly recrystallized texture and a porphyroclastic one (Mercier, 1972).

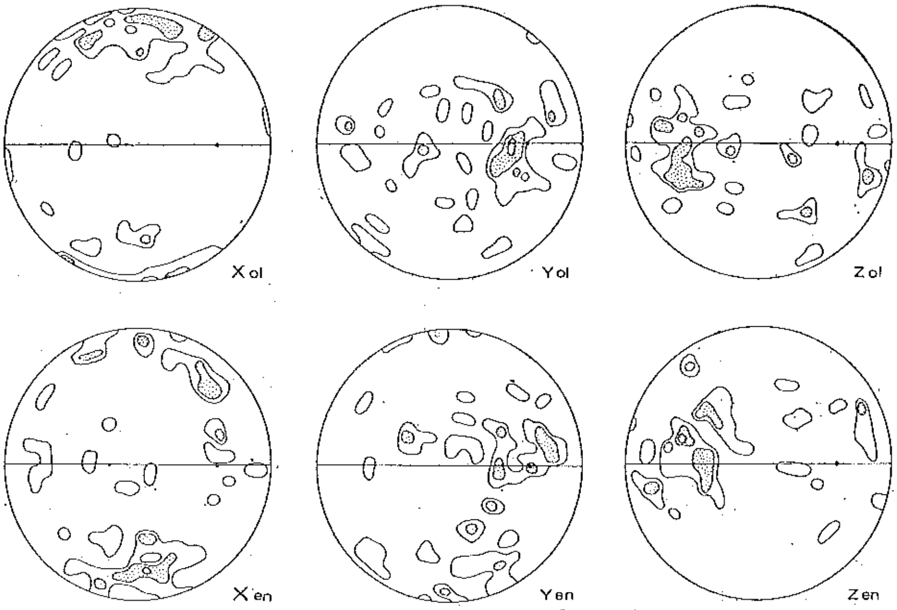

Figure 16 Olivine and enstatite fabric in specimen *1915*: texture intermediate between the "tabular" and the "porphyroclastic" types. The foliation and the lineation defined by mineral elongation are projected on the nets. 50 measurements for olivine and enstatite. Same key as in figure 13.

plane. In this sample its intermediate position between this plane, and its normal, is interpreted as due to a migration from the normal towards the plane; Y enstatite migrates in the opposite way.

4 *Mosaic texture* (5 out of 25 xenoliths)

The reference sample, *1925* from Mothae, is a garnet but spinel-free lherzolite with both an excellent foliation and lineation produced by mineral elongation. The thin section (plates 15B and 21A) was cut normal to the foliation and parallel to the lineation. There is only one olivine generation represented by an even mosaic of small and undeformed crystals (0,3 mm), the boundaries of which converge at 120° in triple points. Domains, elongated paralell to the foliation, can be defined, in which the grains present a similar orientation. The mosaic texture contains porphyroclasts of garnet (2 mm), clinopyroxene (3 mm) and enstatite (4 mm). The latter crystals are elongated, sometimes with a retort shape; they are deformed with wavy KB and blurred KBB. The fractured or severely twisted zones are scarred by a fine-grained (0,02 mm) mosaic of enstatite. Unlike olivine, the enstatite can thus be divided into two generations. The garnets are globular with an undeformed rim of orthopyroxene-clinopyroxene and spinel (plate 21A). The clinopyroxenes which have been deformed are more angular with cloudy outer parts.

The olivine fabric was measured on 50 grains from a single domain (see above), and on 100 grains scattered throughout the section (figure 17). In the former case, Specimen *1611* (from Thaba Putsoa) is a fine-grained garnet lherzolite, texturally comparable to the preceding sample, except for the presence of striking, evenly spaced (0,2 mm) shear planes, which plainly cut through the olivine mosaic (plate 21B). The fine-grained enstatite aggregates have been stretched, and garnet, clinopyroxene and orthopyroxene porphyroclasts passively rolled. Tiny olivine grains ($< 0{,}01$ mm) have recrystallized along the shear planes. The undeformed olivine mosaic possesses a statistically significant extinction between crossed nicols at a high angle to the shear planes. This indicates that the non-penetrative shearing was superimposed obliquely on an older mosaic texture, which is not modified, except along those very planes where the tiny olivine grains have recrystallized.

DISCUSSION

In this preliminary study four textural groups have been defined among 25 peridotite nodules from kimberlites: the "coarse grained", the "tabular", the "porphyroclastic" and the "mosaic". The first three correspond to the petrological "granular group" defined by Boyd and Nixon (1972) and Nixon (1972a) and the last one to their "sheared group". There is an excellent analogy between the porphyroclastic and mosaic textures in these kimberlite xenoliths, in basalt xenoliths and in Alpine-type and crustal peridotite massifs (Nicolas *et al.*, 1971; Mercier 1972). It is believed that they were formed by plastic flow (porphyroclastic texture), with an increasing amount of recrystallization (mosaic texture) due to increasing temperature, deformation and annealing. The "coarse-grained" texture could be tentatively compared to the "proto-granular" texture described in basalt xenoliths, the origin of which is unknown. The tabular texture could be due to some kind of recrystallization, perhaps under differential stress.

Based on mineral chemistry, Boyd and Nixon's (1972) results show a clear distinction between the granular nodules which equilibrated around 1 000°C, and the sheared ones which equilibrated around 1 400°C. They also point to more general chemical trends: the granular group is more refractory, and accordingly it bears a few per cent of chromite which is totally absent in the other group. From this, two interpretations can be considered:

1 The granular and the sheared nodules indeed belong to two independent stems. However, one must then explain why the high temperature and less-depleted peridotite group is sheared and does not include non-deformed peridotites.

2 Both groups are connected and the sheared group derives from the other by deformation. However, one must then explain the chemical and mineralogical differences between the two groups.

We provisionally favour the second interpretation because, as in peridotite xenoliths from basalts, there seems to be no gap between the tabular, porphyroclastic and mosaic textures, that is, between the granular and sheared groups. The latter seem to originate from the former through increasing deformation.

Thus, a transitional facies between the tabular and porphyroclastic group is suggested from the description of *1915* (see p. 61); again there are some mosaic textures with relicts of olivine porphyroclasts advocating a transition to this group (see p. 64).

The mineralogical and chemical differences are tentatively explained by a mechanical process. Supposing the peridotites with granular textures (coarse grained, tabular, porphyroclastic) were interlayered with griquaites and clino-pyroxene and garnet mono-mineralic beds, the intense deformation displayed by the sheared texture would result in a mechanical dismembering of the more competent pyroxene and garnet layers and in their intimate mixing with the flowing peridotites. This has been described at the margins of the Beni-Bouchera lherzolite massif (Kornprobst, 1966), of the Ronda massif (Darot, personal communication), of the "Bois des Feuilles" (Lasnier, 1971) and of the Lanzo massif (Nicolas *et al.*, 1972) where the shearing is comparable in intensity. In these examples, the layered lherzolites of the centre of the massifs are transformed at the margins into a homogeneous peridotite where the garnet (Beni-Bouchera, Ronda, "Bois des Feuilles") formerly restricted to pyroxenite layers, is now scattered throughout the rock.

In the present case this interpretation is supported by the general chemical similarity of clinopyroxene and garnet in griquaite, discrete (monomineralic) and sheared peridotite nodules (Boyd and Nixon, 1972). However, a mixed paragenesis with some garnets and clinopyroxenes inherited from the original peridotite should be expected to occur in the sheared nodules. This has not been chemically proved yet. In the same way one should expect to find some chromite in the sheared paragenesis since this mineral belongs to the original paragenesis, but this has not been observed. This non-appearance could be connected with the conditions prevailing during deformation, as suggested by the fact that in nodules showing porphyroclastic texture, with one exception, there is no spinel present.

Acknowledgements

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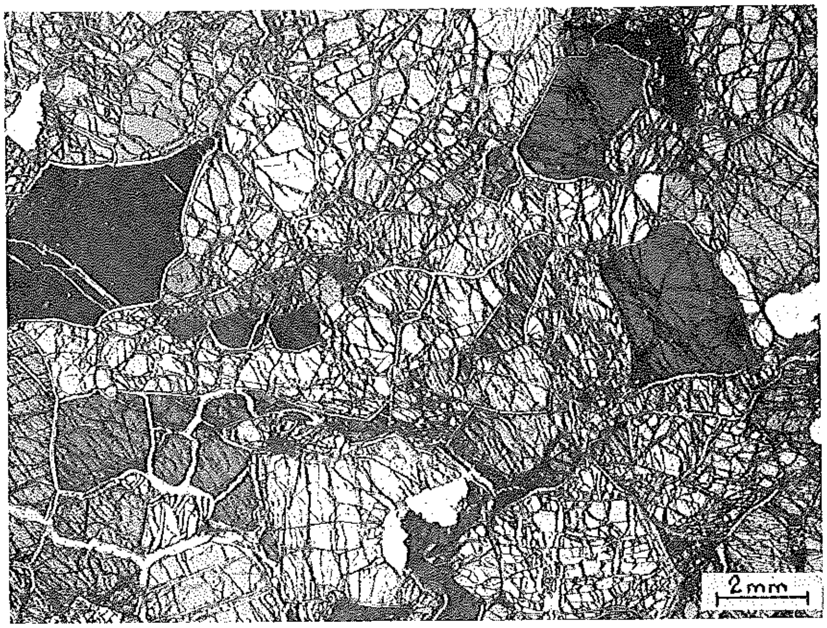

Plate 19A "Coarse grained" texture (harzburgite *69 KI 26*). The crystals are large, weakly elongated and defined by straight or curved boundaries. The nicols are not exactly crossed. (*Boullier and Nicolas*)

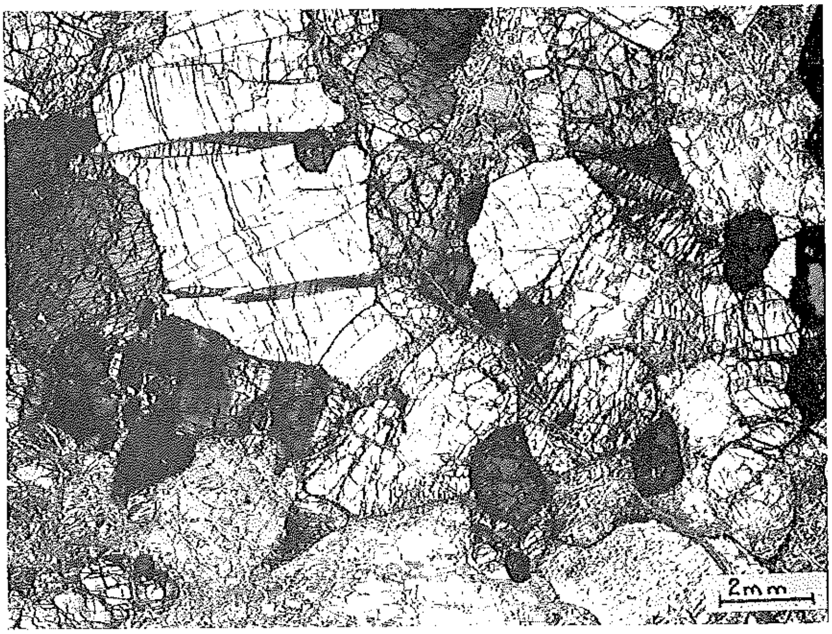

Plate 19B "Coarse grained" texture with a weak deformation superimposed (garnet harzburgite *H 137*). Note the two distinct kinds of KB (explanation in the text) and the small olivine grains recrystallized between large deformed crystals. The nicols are not exactly crossed. (*Boullier and Nicolas*)

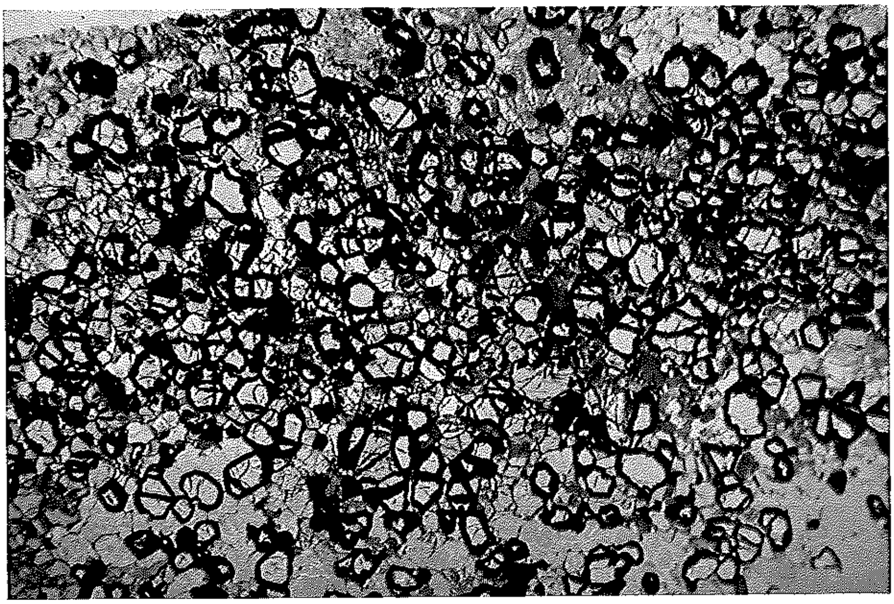

Plate 15A Photomicrograph of granulite nodule, *1919*, showing subhedral garnets with kelyphitic rinds and interstitial clinopyroxene. Plain light; width of photograph is 1,5 cm.

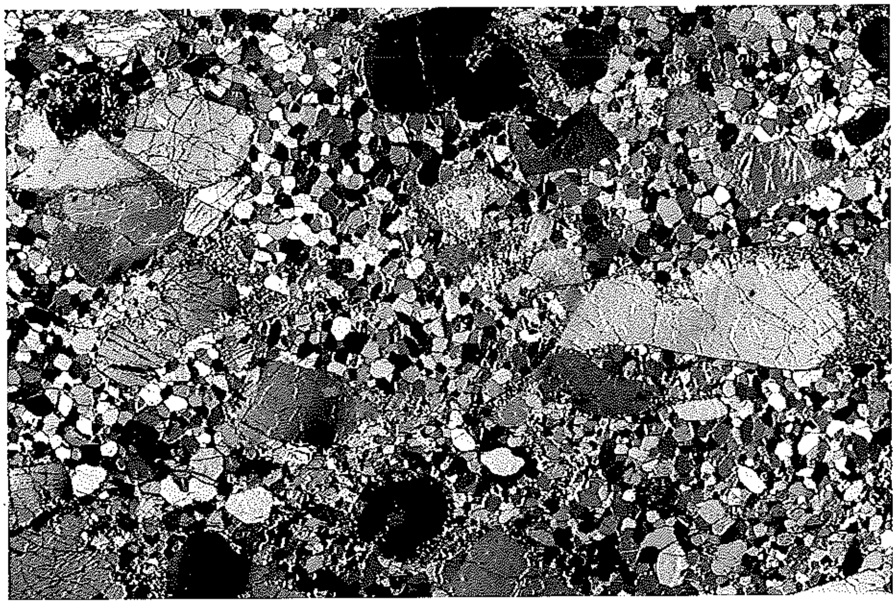

Plate 15B Photomicrograph of ultrabasic nodule *1925* showing pyroxene and garnet porphyroclasts in a matrix of olivine with mosaic texture. Crossed nicols; width of photograph is 2 cm. *(Boullier and Nicolas)*