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Evidence of Superplasticity in Mantle Peridotites

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1 INTRODUCTION

The peridotite nodules from kimberlites are divided into four main textural groups principally on the basis of the texture and the preferred orientation of olivine and also that of enstatite in some cases, (Boullier and Nicolas, 1973, 1975): the coarse granular and coarse tabular ones represent the granular type of Boyd and Nixon (1972) and are undeformed; the porphyroclastic and mosaic ones represent the sheared type of the same authors and show an increasing deformation. Finally, one mosaic fluidal subtype is defined and is the subject of this paper.

The geochemical studies of Boyd and Nixon (1973) and MacGregor (1975) show that the nodules of this subtype are the deepest ones: they originated at a depth of 200 km and a temperature of 1400 °C.

Boullier and Nicolas (1973) first attributed the fluidal texture to an intensive and nonpenetrative shearing superimposed on an older mosaic texture. In a later paper, the same authors (Boullier and Nicolas, 1975) proposed that this deformation took place in the superplastic field on the basis of analogy with superplastic textures in metals. The present paper is intended to show from observations at optical and electron microscope scales, that all the criteria required for superplasticity are present here and that this superplastic process is the last stage of the tectonic evolution of the kimberlites.

2 OBSERVATIONS

2.1 The Sample

The nodule is a garnet–lherzolite made of 65 per cent olivine, 28 per cent orthopyroxene, 3.5 per cent clinopyroxene and 3.5 per cent garnet. The contribution to flow of the last two minerals can be neglected and the rock considered as a two-phase sample. The nodule shows a well developed foliation defined by mineral flattening. However, the lineation is weak in this plane.

2.2 The Thin Section

The observation with the optical polarizing microscope was made on a section cut perpendicular to the foliation and parallel to the lineation. Olivine forms an equant mosaic of small grains (0.07 mm) (see Figure 1). However, as observed in many peridotites from nodules of basalts and from massifs, some elongated porphyroclasts remain (Figure 2), but the size of their subgrains is the same as the mosaic one. Some euhedral and undeformed tablets of olivine also appear at the edges of the porphyroclasts or inside them. The preferred orientation of the porphyroclasts is the one usually observed in highly deformed peridotites: [100] parallel to the lineation and [010] perpendicular to the foliation. The orientation of the olivine grains forming the mosaic has been studied (Boullier and Nicolas, 1973). It shows that local domains

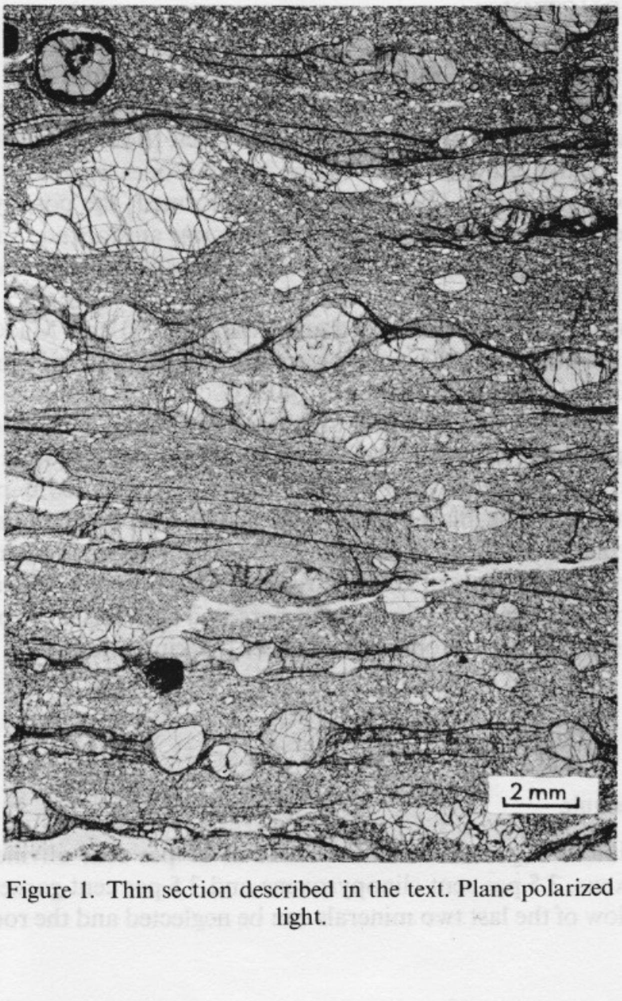

Figure 1. Thin section described in the text. Plane polarized light.

Figure 2. Olivine porphyroclast recrystallizing. Crossed Nicols.

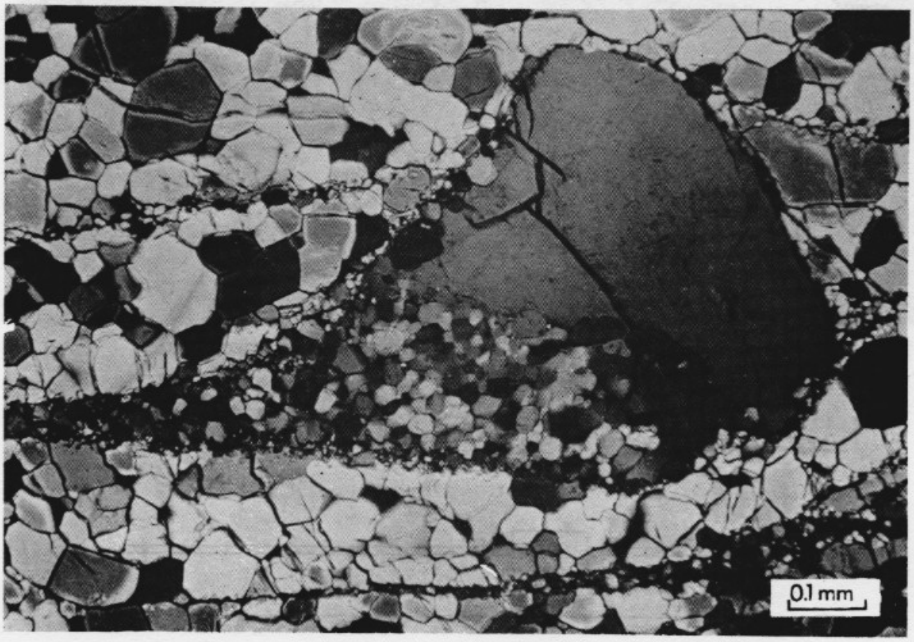

Figure 3. Orthopyroxene porphyroclast recrystallizing in fine grains forming stripes. Crossed Nicols.

have a strong preferred orientation differing one from the other. The total preferred orientation is weak. This suggests that the domains are derived from porphyroclasts which have recrystallized by the increasing misorientation process (Poirier and Nicolas, in preparation), transforming subgrains into grains beyond 10–15 per cent of rotation. This process could also explain the similarity in size of porphyroclast subgrains and grains forming the mosaic.

Orthopyroxene porphyroclasts are deformed and have an undulatory extinction. They are recrystallized on their edges in very fine grains (Figure 3) which also form stripes 0.3 to 0.01 mm thick, through the olivine mosaic, giving a fluidal aspect to the rock. The structure of the fine-grained equiaxed orthopyroxenes in the stripes is also a mosaic one with triple junctions at 120° (see Figure 3). The average size of those grains is about 10 μm. The stripes are

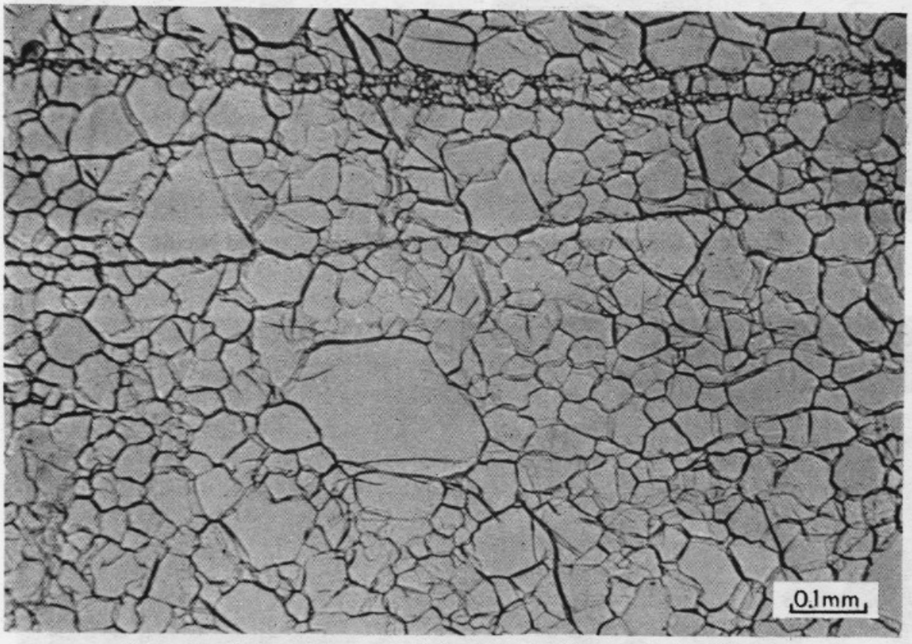

Figure 4. Fracture through olivine mosaic. Plane polarized light.

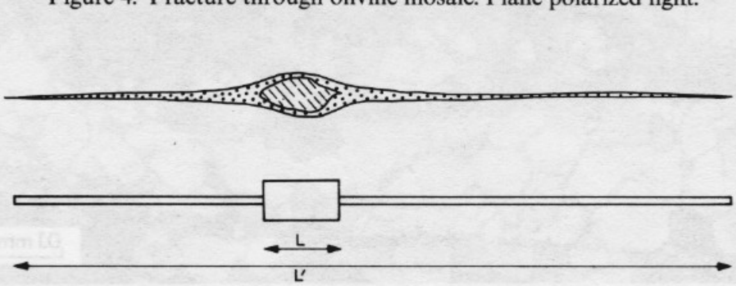

Figure 5. Percentage of deformation in orthopyroxene: $\varepsilon = \frac{L' - L}{L}$

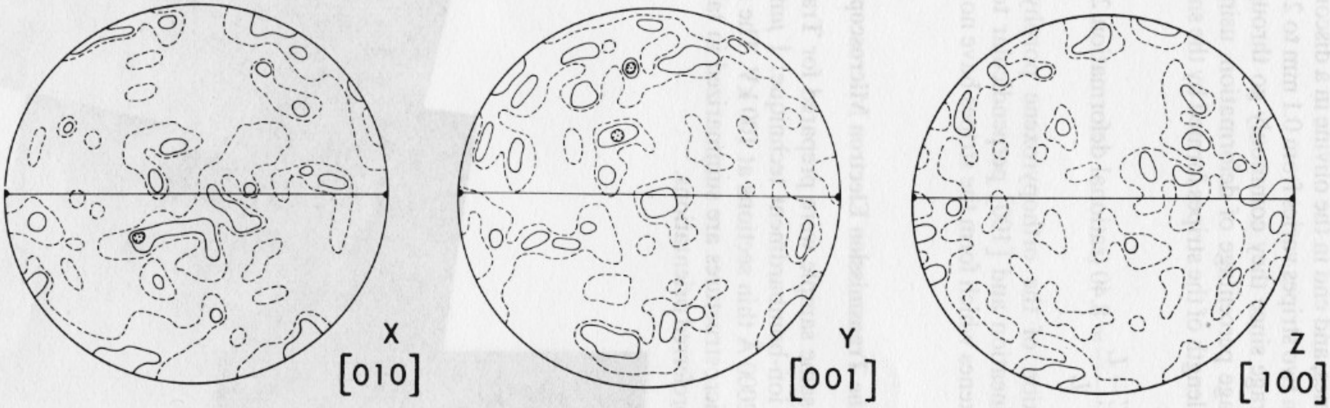

Figure 6. Fine grained orthopyroxenes preferred orientation (100 grains).

parallel to the porphyroclasts elongation, pass round the obstacles such as garnets or other pyroxenes, and end in the olivine in a discontinuity line (Figure 4). The distance between two stripes varies from 0.1 mm to 2 mm. Their length is at least 25 mm on average since they commonly go through the thin section. We calculated an average percentage of deformation, using the length of the porphyroclasts and the length of the stripes formed by the small orthopyroxenes (Figure 5). The result is:

$$\varepsilon = \frac{L' - L}{L} = 8.40 \text{ (rational deformation 2.20)}$$

The preferred orientation of the orthopyroxene porphyroclasts is strong: [001] parallel to the lineation and [100] perpendicular to the foliation. The fine grained orthopyroxenes which form the stripes have no fabric at all (Figure 6).

2.3 Observations with the Transmission Electron Microscope

Thin sections of the same sample were prepared for Transmission Electron Microscopy, using the ion-bombardment technique: 1 μm thin sections were studied at 1 MeV and 2000 Å thin sections at 100 kV. The results on the dislocation densities and microstructures are summarized in table I, as well as the results concerning the preferred orientations.

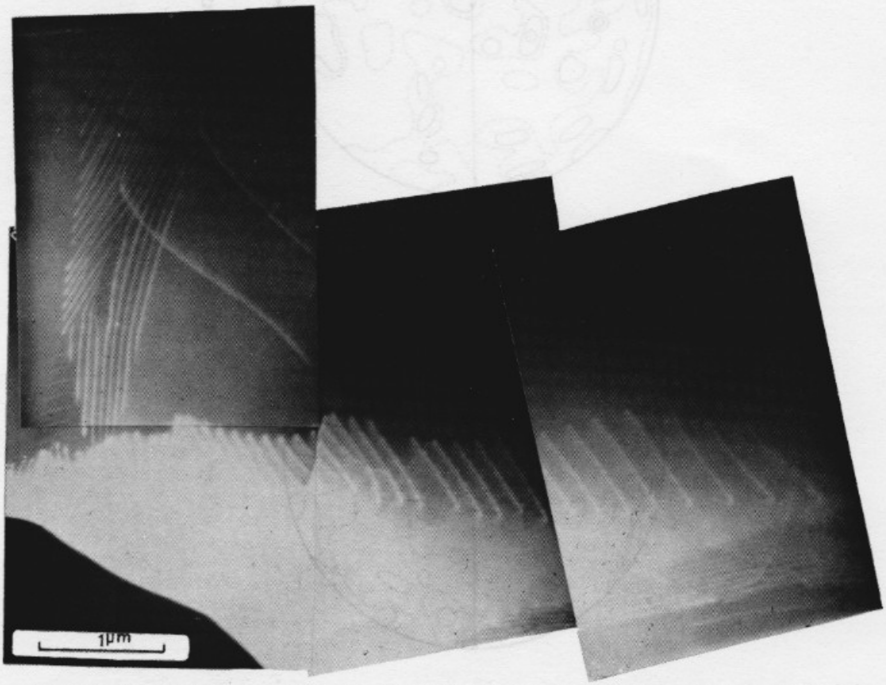

Figure 7. Dislocations in an olivine grain from the olivine mosaic (1MeV). Dark field.

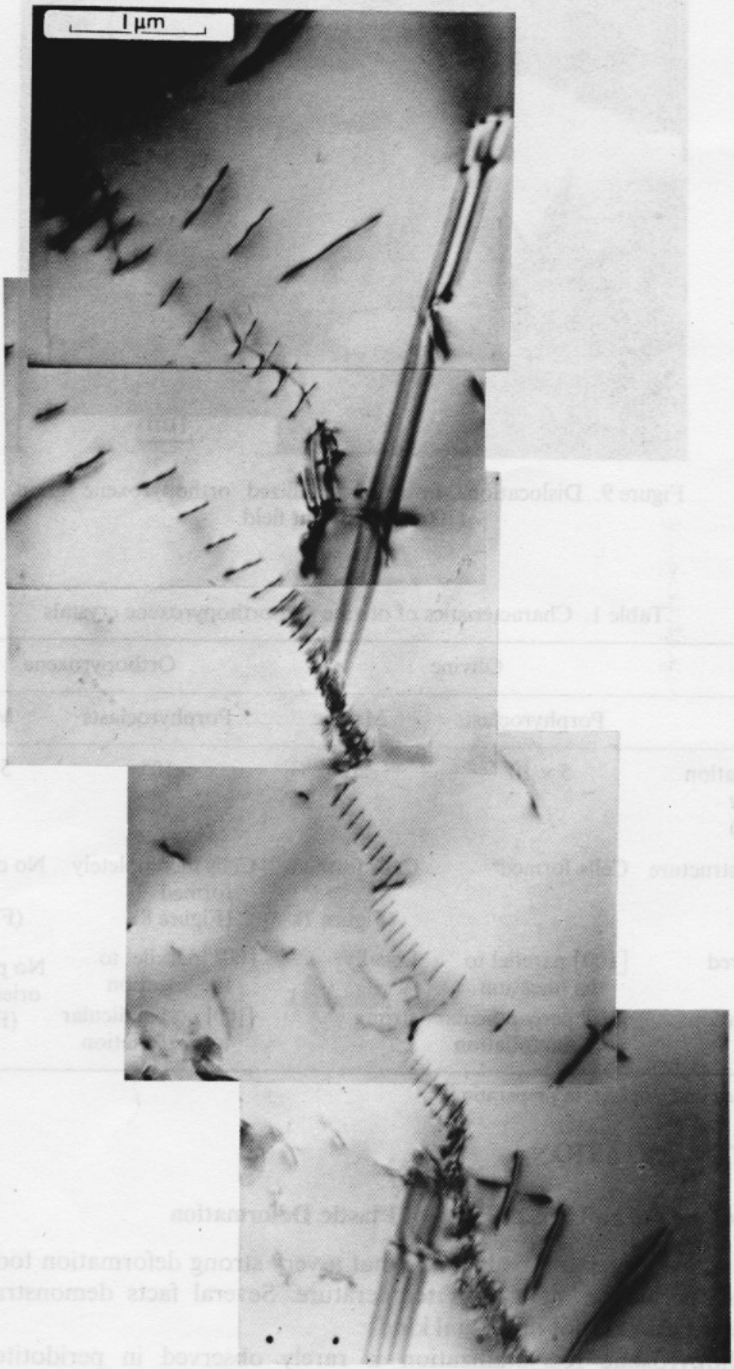

Figure 8. Dislocations and stacking faults in orthopyroxene porphyroclast (100 keV). Bright field.

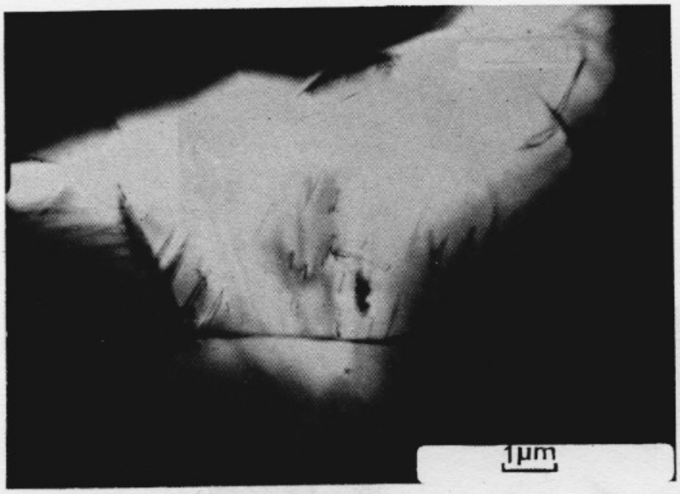

Figure 9. Dislocations in a recrystallized orthopyroxene grain (100 keV). Bright field.

Table 1. Characteristics of olivine and orthopyroxene crystals

	Olivine		Orthopyroxene	
	Porphyroclasts	Mosaic	Porphyroclasts	Mosaic
Dislocation density (cm^{-2})	5×10^7 [a]	10^7	10^8	5×10^7
Microstructure	Cells formed[a]	Cells formed (Figure 7)	Cells incompletely formed (Figure 8)	No cells (Figure 9)
Preferred orientations	[100] parallel to the lineation [010] perpendicular to the foliation	Locally strong	[001]parallel to the lineation [100] perpendicular to the foliation	No preferred orientation (Figure 6)

[a]Gueguen and Boullier, in preparation

3 INTERPRETATION

3.1 Evidence of an Unusual Type of Plastic Deformation

The above observations indicate that a very strong deformation took place in these peridotites at a high temperature. Several facts demonstrate that this deformation is not of a usual kind:

—Orthopyroxene recrystallization is rarely observed in peridotites from nodules as well as from massifs. Annealing experiments (Goetze and

Kohlstedt, 1973) demonstrate that defects are not mobile in orthopyroxene even at 1350 °C. Since recrystallization can occur only when defects are mobile, and since their mobility increases with T/T_m we conclude that in orthopyroxene, it requires an unusually high value of T/T_m.

—The large percentage (Figure 5 above) of deformation observed in orthopyroxene suggests that the strain-rate was faster than the average plate tectonics strain-rate 10^{-14} s^{-1}.

—However the stress was not very large, if we consider the moderate dislocation density ($\rho = 10^7$ cm^{-2}) in olivine mosaic. Unfortunately it does not seem possible to define its quantitative value with accuracy. There are two possible ways of evaluating it, but neither is satisfactory. The first is to use the dislocation density which is related to the internal stress:

$$\sigma_i \sim \mu \mathbf{b} \rho^{1/2}$$

where μ is the shear modulus, $\mathbf{b}$ is the Burgers vector, and ρ is the free dislocation density. Not only is ρ_i not exactly equal to the applied stress, but the dislocation density, after deformation, is no longer the same as during deformation. An undetermined amount of post-deformation recovery takes place in natural deformations as well as in experimental ones. It is obviously very difficult to quantify this recovery. The second way to evaluate the stress is to use the subgrain size-stress relationship:

$$\frac{\sigma}{\mu} = \frac{L_0}{L}$$

where L is the subgrain size and L_0 a constant. We then have to assume that the subgrains observed on a much smaller scale in high voltage electron microscopy (cells) have a completely different behaviour from the optical visible subgrains considered here, as pointed out by Green and Radcliffe (1972). If this hypothesis is right, knowing L_0 and L provides us with an indirect measure of σ. But L, in a given rock, always varies by a factor of ten. In the studied sample the average value of L is 0.07 mm. L_0 is not accurately known. Weertmann (1970) used $L_0 = 5 \times 10^{-5}$ mm but two data points from experimental deformation of olivine (Raleigh and Kirby, 1970) suggest that $L_0 = 4 \times 10^{-4}$ mm. There are clearly not enough data to get a representative value for L_0. So it does not seem possible to give any significant value for σ. The deformation is controlled by orthopyroxene since enstatite stripes end in fractures through the olivine mosaic (Figure 4 above). This means that olivine could not keep up with the deformation and that it responded by fracturing. However it is well known that orthopyroxene is much less ductile than olivine.

It is difficult to account for all these facts by any usual plastic flow mechanism. It is especially difficult to understand how the strain rate can be (geologically) fast when deformation is controlled by the less ductile mineral. So a completely different flow mechanism is required. We suggest that superplasticity could be this mechanism.

3.2 Characteristics of Superplasticity

Superplasticity is characterized by an unusual tensile extensibility: $\varepsilon \simeq 1000$ per cent. Two kinds of superplasticity must be distinguished. One occurs when P.T. conditions correspond to a phase change, the other occurs when polycrystals are fine-grained. We are concerned here with the second kind of superplasticity. So far it has been studied only in alloys: two phases are required in order to keep the grain-size very small (a few microns). A detailed review of these studies is given in Suery (1974). Superplastic behaviour can appear above 0.3 T_m for stresses below a certain limit: for instance $\sigma < 10^{-3}\ \mu$ in lead (Ashby and Verall, 1973), where μ is the shear modulus. Correspondingly the strain-rate must not exceed a certain limit either: for instance $\dot{\varepsilon} < 10^{-4}$ in lead. These limits depend on the grain size: the larger the grain-size is, the smaller the limit. Above this limit, deformation is controlled by dislocation climb. During superplastic flow, grain-boundary sliding is dominant. Consequently, dislocation density is not high, no cells are formed and the fabric is destroyed by grain-rotation. All of these are observed here in the orthopyroxene grains as shown by the comparison of Table 1 and Table 2.

Two theoretical models which explain superplasticity have been advanced:

(a) Hayden *et al.* (1972) suggested that grain-boundary sliding was dominant but that the rate-controlling effect was dislocation climb within the grains. Their result shows that the strain-rate $\dot{\varepsilon}$ is:

$$\dot{\varepsilon}_1 = \frac{K}{d}\dot{\varepsilon}_{\text{d.c.}} \qquad (1)$$

where $\dot{\varepsilon}_{\text{d.c.}}$ stands for the strain-rate produced by the usual high temperature dislocation creep, d is the grain-size and K is a constant. They found $(K/d) \simeq 50$, so that the superplastic strain-rate is fifty times the plastic strain-rate. They have shown that, in some cases, superplasticity can take place in structures where the grain-size is not small, but where grains are very elongated. The thickness of the grains may then be almost equal to the size of the cells and recrystallization takes place at the edges of the elongated grains, the subgrains being transformed into grains. The new grains thus produced are very small since their size is that of the cells. So as soon as they are produced, they display a superplastic behaviour. The strain-rate is then:

$$\dot{\varepsilon}_2 \simeq \left(\frac{K}{d} + 1\right)\dot{\varepsilon}_{\text{d.c.}} \qquad (2)$$

In this case, the superplastic flow is controlled by the production rate of small grains.

(b) A different model is given by Ashby and Verall (1973). Grain-boundary sliding is the dominant mechanism, but it is diffusion-accommodated. Their model is consistent with equiaxed grains, no cell formation, destruction of fabric and low values of strain-rate. The result is:

Table 2. Comparison of plastic and superplastic flow

	Grain-size	Preferred orientation	Dislocation microstructure	Dislocation density	$\left(\frac{T}{T_m}\right)$	Stress	Strain-rate
Plastic flow at high temperatures (dislocation creep)	No limits. Usually from a few microns to a few millimetres	Preferred orientation developed	Cells are formed	Can be as high as 10^{11} cm^{-2}	> 0.3	$\sigma \leqslant$ breakdown stress which is $10^{-3}\mu$[a] or thereabouts	Can be as high as 10^{-1}
Superplastic flow	$d < 10$ microns	No preferred orientation. The fabric is destroyed by grain rotation	No Cells	Moderate ($\leqslant 10^8$ cm^{-2})	> 0.3	$\sigma \leqslant$ limit depending on $\frac{T}{T_m}$ and d In lead at 0.5 T_m this limit is $10^{-4}\ \mu$ if $d = 8$ microns[b]	$\dot{\varepsilon} <$ limit depending on $\frac{T}{T_m}$ and d In lead at 0.5 T_m this limit is 10^{-8} if $d = 8$ microns[b]

[a] Stocker and Ashby (1973)
[b] Ashby and Verall (1973)

$$\dot{\varepsilon}_3 \simeq 100\frac{\Omega}{kTd^2}\,\sigma D \qquad (3)$$

where Ω is the atomic volume, k the Boltzmann constant, σ the stress, D a self-diffusion coefficient, d the grain-size, and T the temperature (K). In this case, the strain-rate is proportional to the stress, which means that the medium is Newtonian.

3.3 Superplasticity as the Third Stage of the Tectonic History of these Nodules

Using our observations and the above theoretical and experimental results it is possible to reconstruct the following schematic development of the deformation undergone by these nodules (figure 10).

(1) The rock was flowing in the mantle. The flow was controlled as usual by the more ductile mineral, olivine. The strain-rate $\dot{\varepsilon}$ was

$$\dot{\varepsilon}_4 = \frac{\sqrt{3^{n+1}}}{2}\,AD\,\frac{\mu \mathbf{b}}{kT}\left(\frac{\sigma}{\mu}\right)^n \qquad (4)$$

where A and n are the Dorn constants: $A = 1.2 \times 10^4$ and $n = 4.2$ for olivine (Stocker and Ashby, 1973). D is a self-diffusion coefficient for

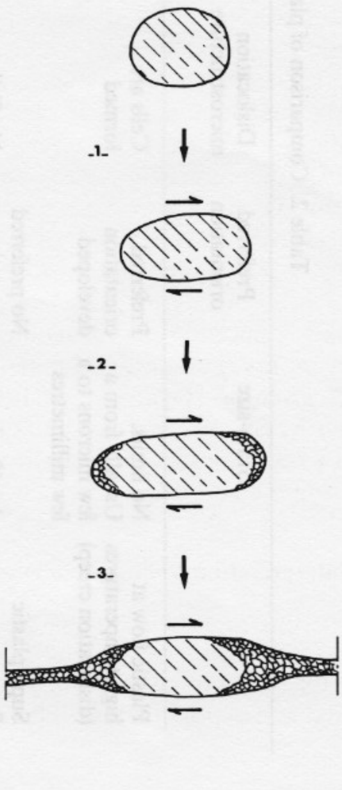

Figure 10. Interpretation of the deformation process in an orthopyroxene grain.

olivine: $D = 3 \times 10^4 \exp - (135 \text{ kcal mole}^{-1}/kT) \text{ cm}^2 \text{ s}^{-1}$ (Goetze and Kohlstedt, 1973) **b** is the Burgers vector, and the other symbols have the same meaning as above.

(2) For some reason, T/T_m increased and recrystallization took place in orthopyroxene. Cells were formed (figure 8 above) and became new small grains (figure 9 above). At this stage, olivine was already almost completely recrystallized. The flow was controlled either by olivine (Equation (4)), or by the small orthopyroxene grains produced (Equation (2)). The lack of data on diffusion and creep in orthopyroxene prevent us from comparing (2) and (4) quantitatively. But since the strain-rate is usually slower in orthopyroxene than in olivine, and since here, in equation (2). there is an 'amplification factor' K/d, we suggest that both $\dot{\varepsilon}_2$ and $\dot{\varepsilon}_4$ could well have the same magnitude. Since $\dot{\varepsilon}_2$ is relative to orthopyroxene and $\dot{\varepsilon}_4$ to olivine, $\dot{\varepsilon}$ would be about the same in both. The existence of this second stage is demonstrated by the fact that deformation of the fine-grained orthopyroxene stripes could take place only when some orthopyroxene recrystallization had occurred. If the stripes had been produced first by elongation and then by recrystallization, they would have displayed a fabric, but they do not. However the stripes were not formed right at the beginning of orthopyroxene recrystallization. If they were, then the small grains would have gone into the stripes as soon as they were produced and there would be none left around the orthopyroxene porphyroclasts, which is not the case. If, as suggested, $\dot{\varepsilon}_2 \simeq \dot{\varepsilon}_4$ during the second transition stage, the flow is not truly superplastic but many small orthopyroxene grains are produced.

(3) When the numer of these grains was large enough, grain-boundary sliding within them was no longer controlled by the production of these grains (Equation (2)) but by the diffusion in them, according to the Ashby–Verall model (Equation (3)). Then $\dot{\varepsilon} \simeq \dot{\varepsilon}_3$ and the flow is truly superplastic. Stripes were formed and fractures appeared in olivine which could not keep up with the deformation. During the second stage $\dot{\varepsilon} \simeq \dot{\varepsilon}_2 \simeq \dot{\varepsilon}_4$ but during the third one $\dot{\varepsilon} \simeq \dot{\varepsilon}_3 \gg \dot{\varepsilon}_2$ or $\dot{\varepsilon}_4$. We can compare $\dot{\varepsilon}_3$ and $\dot{\varepsilon}_2$ since the unknown diffusion coefficient in orthopyroxene which appears in (2) and (3) is eliminated in this calculation. Using the value of K given by Hayden *et al.* (1972) and the values of Dorn parameters given by Stocker and Ashby (1973) the result is $\dot{\varepsilon}_2 \ll \dot{\varepsilon}_3$ if $\sigma \ll 10^{-4}\ \mu$, that is $\dot{\varepsilon} \simeq \dot{\varepsilon}_3$ for stresses lower than 80 bars. The process was then interrupted and the nodule was brought up to the surface.

3.4 The Interpretation Related to a Diapiric Origin

The above interpretation explains all the observations made on these nodules. It is also in agreement with the model developed by Green and Gueguen (1974) to explain the origin of kimberlites. These authors suggested that an upwelling was initiated at a depth of about 300 km. Then a diapir formed and rose up to the point where the solidus was reached. At this point a magma was produced which then brought the nodules up to the surface. In this model, the plastic deformation took place in the diapir, during the upwelling. The nodule described is located at the top of the paleogeotherm, that is at the point where T/T_m is maximum. Thus that stage (2) in this model corresponds to the beginning of the upwelling. Since T/T_m is much higher than usual, recrystallization can take place in orthopyroxenes. This stage (2) leads naturally into stage (3). The stresses are in agreement with the condition stated above, $\sigma \ll 10^{-4}\,\mu$, since in this diapir model, the stresses would be in the region of 100 bars. Finally this model can provide us with a lower limit of the strain-rate which is geologically fast as expected: the strain $\varepsilon = 220$ per cent was developed in less than 3 million years since this is the time upwelling takes according to the Green–Gueguen model. Then $\dot{\varepsilon} > 2.20/3$m.y that is $\dot{\varepsilon} > 2 \times 10^{-14}$. Thus even with a moderate stress, the strain-rate was geologically fast (but metallurgically slow).

4. CONCLUSION

Superplasticity occurs in peridotites only in special conditions. It seems that these conditions, present in the case of some nodules from kimberlites, are exceptional in the mantle. Superplasticity has never been described in nodules from basalts (Mercier and Nicolas, 1975) and even in the case of nodules from kimberlites, it has been described only for some nodules, located at the top of the paleogeotherms (Boullier and Nicolas, 1973, 1975).

However the appearance of superplasticity has important consequences, the first being that the usual situation is reversed: the generally more plastic olivine does not control the plastic flow in this case. This emphasizes how important it is from a plasticity point of view to consider that the mantle is not made of a continuum of olivine, but, at a first approach, of two phases which are olivine and orthopyroxene.

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