

SP-Mylonites: Origin of Some Mylonites by Superplastic Flow

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Abstract. Superplasticity in fine-grained materials is characterized by extensive grain boundary sliding. This phenomenon can take place only in special conditions. Six criteria are thus defined to determine when superplasticity has been active. Applications of these criteria to several examples of mylonites are discussed and we conclude that superplasticity explains some types of mylonites and the tectonic banding that they exhibit.

Introduction

Plastic flow mechanisms in ultramafic rocks have been investigated by many authors since they are of primary importance in understanding the geodynamic processes operating in the upper mantle. These studies have recently led to the discovery of a new type of plastic flow in peridotite nodules from kimberlites, exhibiting signs of intense deformation [1, 2]. The authors argued that superplasticity was responsible for the features observed in the ultramafic nodules studied. On the other hand, the textural analogy of these nodules with mylonites, suggests that superplasticity could indeed explain some types of mylonites. Consequently the present paper examines the conditions in which superplasticity can occur and the criteria which allow it to be recognized when it has been active mechanism. Those criteria have been applied to several examples of mylonites: the peridotite nodule mentioned above which has been thoroughly analysed by the authors [2], an anorthosite from Norway, an amphibolite from Portugal. The consequences of possible superplastic flow are drawn. An attempt to subdivide mylonites is given on the basis of the type of flow which has been active.

I. Conditions, Mechanisms and Criteria of Superplasticity

Conditions

"Superplasticity" describes the quasi-viscous behaviour of polycrystalline solids exhibiting an unusually large tensile deformation without necking ($\epsilon \approx 1000\%$). So far it has been observed and documented only in metals and alloys. Two types of superplasticity exist: one is transformational superplasticity, produced when the solid is just in phase change conditions (3); the second is fine-grained material superplasticity. We are concerned here with the second type. The conditions in which this type of superplasticity appears are the following:

1. High temperature ($T/T_m > 0.5$ where T_m is the melting temperature).
2. Very small grain size (less than about 10 microns). Thus most of the super-

plastic materials are two phase alloys; because one phase prevents growth in the other, the grain size remains small. Moreover, the small grains are equant.

3. Stress σ and strain rate $\dot{\epsilon}$ not too high.

This last condition implies that there is a domain of superplasticity in the $(\sigma, \dot{\epsilon})$ coordinates. If σ or $\dot{\epsilon}$ becomes too high, plastic flow is dislocation-controlled: this is the usual high temperature plastic flow in solids. Consequently, superplastic properties disappear. The limits of the superplastic domain obviously depend on the nature of the solid, and also on the grain size.

Observations of superplastic materials have also shown that:

4. Preferred orientations are destroyed when superplasticity is active, grains are not elongated.

5. Dislocation densities are moderate, no dislocation cells are formed.

6. The strain-rate sensitivity $m = (\partial \ln \sigma) / (\partial \ln \dot{\epsilon})$ is high ($m > 0.3$). This implies that the stress exponent $n = 1/m$, in the observed flow law, varies between 1 and 3:

$$\dot{\epsilon} = C' d^{\alpha} \frac{\sigma^n}{\exp\left(\frac{-E}{kT}\right)}$$

where d is the grain-size and E is an activation energy which usually corresponds to grain-boundary diffusion. The large values of m explain why a large tensile deformation (1000%) can be achieved without necking. The strain-rate $\dot{\epsilon}$ corresponding to the above equation is faster than the strain-rate of dislocation-controlled plastic flow, extrapolated into the superplastic domain.

Mechanism

All the above results show that grain-boundary sliding must be the dominant mechanism of superplasticity. Two theories have been developed in order to explain superplasticity: Hayden *et al.* [4] suggested that grain-boundary sliding was accommodated by dislocation climb within the grains; Ashby and Verall [5] suggested that grain-boundary sliding was accommodated by diffusion. Both theories account for the above results, so that it is not clear which best represents the real phenomenon.

Criteria

However the six conditions and observations listed above provide us with six criteria to determine whether or not superplasticity has been an active flow mechanism. Given that in geology it is only possible to observe the final state of deformation, it is especially important to have such observational criteria. It is on this basis that we now suggest that superplasticity explains some types of mylonites.

II. Examples of "Superplastic" Mylonites

1. Peridotite Nodule from Kimberlite

The sample is a peridotite nodule from Kao kimberlite pipe (Lesotho, South Africa), (Fig. 1). Its mosaic fluidal texture has been described [1] as representing the most highly deformed state in these nodules. A more detailed study of this

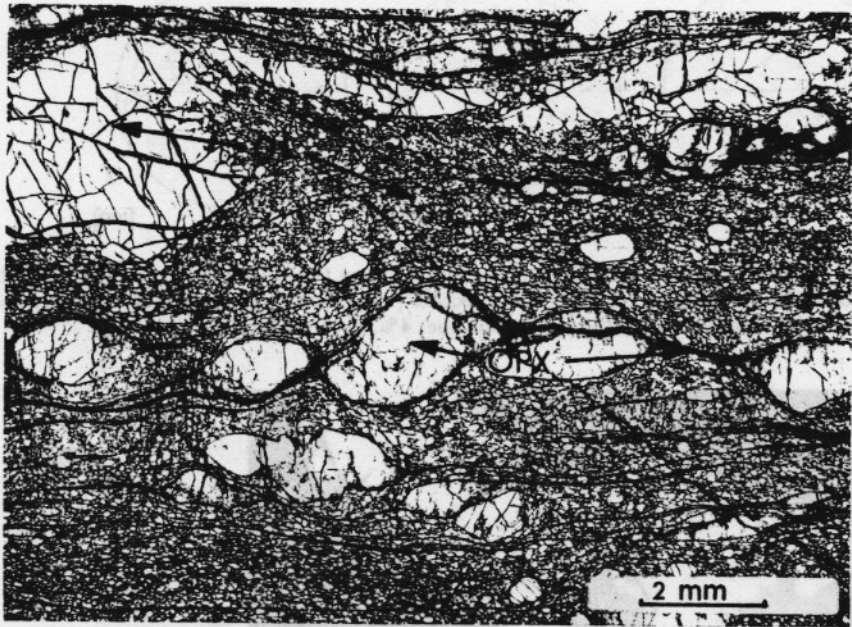


Fig. 1. Peridotite nodule from Kao (Lesotho). The stripes which go from one orthopyroxene grain to another, are made of $10\ \mu$ recrystallized orthopyroxene grains

sample has been carried out [2]. The results of our observations and of previous studies are the following, using the six criteria listed in I:

1. Geochemical results [6, 7] show that those rocks originated at a depth of 200 km and a temperature of 1400°C . That implies $T/T_m > 0.5$.

2. The rock can be regarded as a two phase assemblage since it is made of 65% olivine and 28% orthopyroxene. There is only 3.5% clinopyroxene and 3.5% garnet. Except for some porphyroclasts, olivine is almost completely recrystallized in a mosaic of small grains (0.07 mm on average). Orthopyroxene is less recrystallized, but it must be noted that orthopyroxene recrystallization is usually not observed at all in deformed peridotites [8]. The recrystallized orthopyroxene grains are very small (less than $10\ \mu$ on average) almost equant and form the stripes which can be seen in Fig. 1.

3. The $(\sigma, \dot{\epsilon})$ domain in which the deformation took place cannot be accurately determined. The moderate dislocation densities (see criterion 5) indicate that the stress could not be very high. An interpretative model [2] concludes that $\dot{\epsilon}$ was faster than $10^{-13}\ \text{s}^{-1}$, which is fast by geophysical standards but very slow by metallurgical standards. The absence of transformation of orthopyroxene into clinopyroxene shows, on the other hand, that $\dot{\epsilon} \ll 10^{-3}$ [9]. Thus we can very reasonably admit that criterion 3 is also met.

4. The fine-grained orthopyroxene grains which form the stripes have no fabric at all (Fig. 2) although the orthopyroxene porphyroclasts have a strong preferred orientation. The olivine porphyroclasts have the preferred orientation

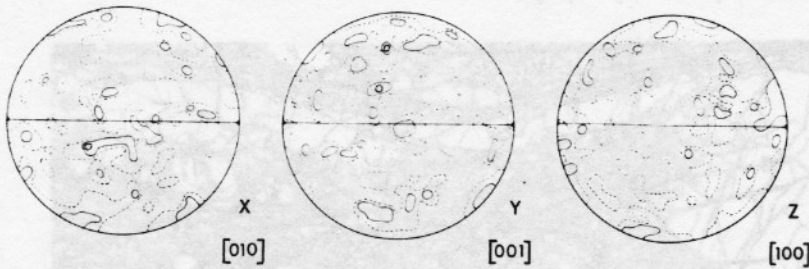


Fig. 2. Fabric of the $10\ \mu$ orthopyroxene grains forming the stripes in Fig. 1. The fabric has been optically determined on a very thin section ($10\ \mu$), using a U-stage. 100 measurements. Contours: 1%, dashed line; 2%, continuous line; 4%, decorated area

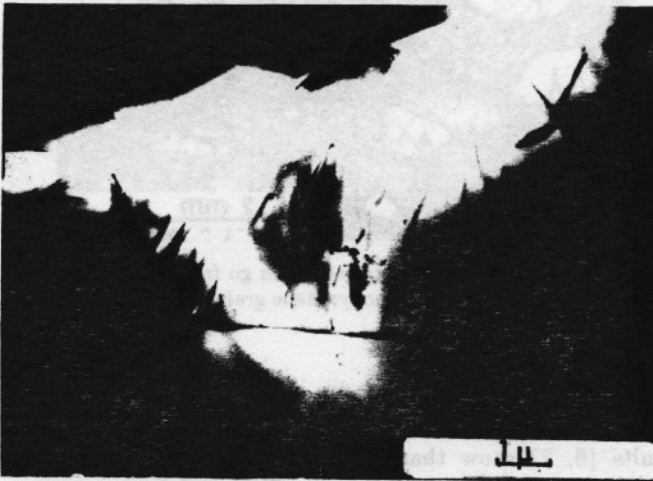


Fig. 3. Microphotograph of a $10\ \mu$ orthopyroxene grain (TEM at 100 kV) showing dislocations and stacking faults without any cell structure

usually observed in deformed peridotites [8]. The recrystallized olivine has the same fabric locally as the porphyroclasts (see Table 1).

5. The small orthopyroxene grains present no dislocation cells and their dislocation density is moderate (Fig. 3). This has been shown by Transmission Electron Microscopy at 100 kV and 1000 kV (Table 1).

6. The average percentage of deformation calculated as explained in Fig. 4 by using orthopyroxene as a marker is $\epsilon = (L' - L)/L = 840\%$ ¹. Moreover, as mentioned in 3 the strain rate was fast by geological standards. Strain-rate sensitivity and activation energy are unknown.

To the six results the following important observation may be added: the orthopyroxene stripes are prolonged within the olivine matrix by fracture lines (Fig. 5). This implies that the deformation was controlled by the small orthopyroxene grains and that olivine could not keep up with it. It therefore responded by frac-

¹ Which correspond to a rational deformation of $\ln L'/L = 220\%$.

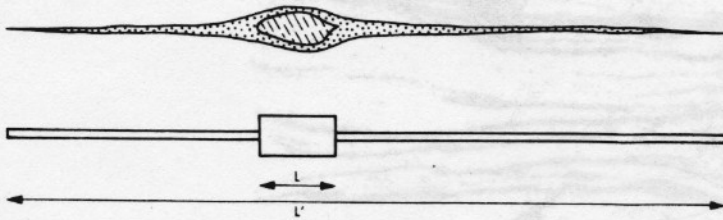


Fig. 4. Schematic evaluation of the total strain: $\epsilon = (L' - L)/L$

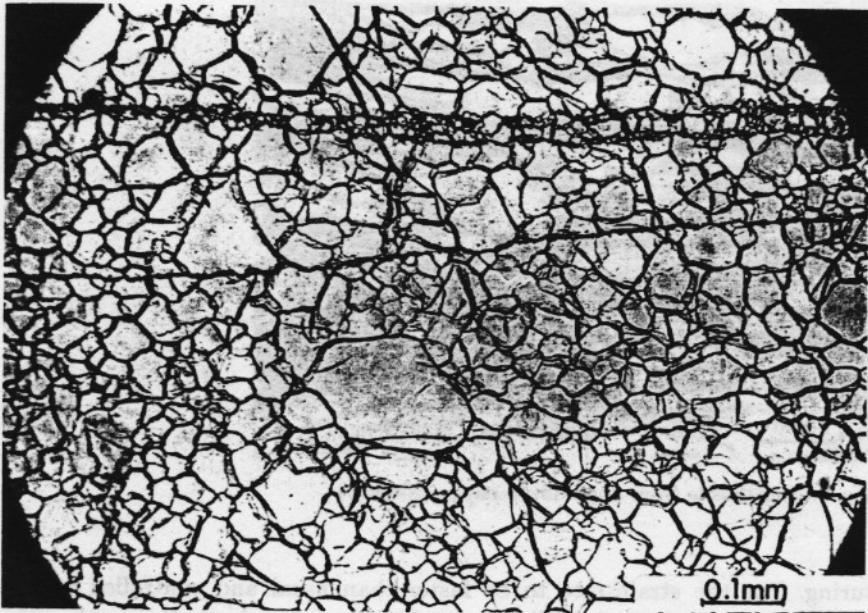


Fig. 5. Fracture through the olivine mosaic. These fractures are the prolongations of the stripes shown in Fig. 1

Table 1

	Olivine		Orthopyroxene	
	Porphyroclasts	Mosaic	Porphyroclasts	Mosaic
Dislocation density (cm^{-2})	10^9 ^a	10^7	10^8	$5 \cdot 10^7$
Microstructure	Cells formed ^a	Cells formed	Cells incompletely formed	No cells (Fig. 3)
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 (Fig. 2)

^a Green and Boullier, in preparation.

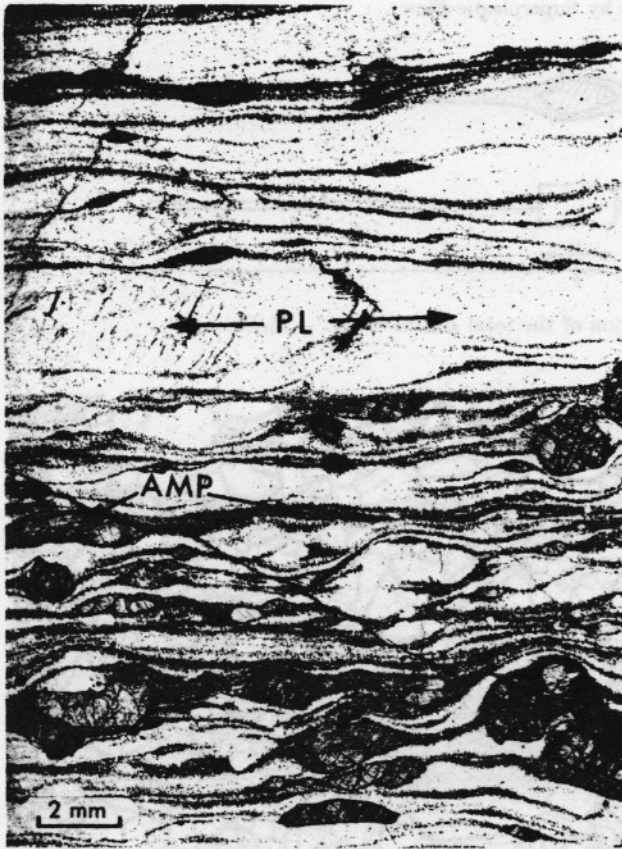


Fig. 6. Anorthosite from Sogn-Jotun nappe (Norway)

turing. For the strain-rate to be faster than usual and controlled by the less ductile mineral, given that olivine is ordinarily more plastic than orthopyroxene, a completely different flow mechanism has to be operative. This, together with the fact that the six criteria listed in I are met for the small orthopyroxene grains, strongly suggests that the mylonitic texture of this rock is the result of superplastic flow in orthopyroxene. The small orthopyroxene grains act as a "lubricating layer" within the olivine matrix. This hypothesis is confirmed by recent results on superplasticity in α/β brass [10]. Finally this analysis fits the model advanced in [11] to explain the origin of the nodules, as shown in [2].

2. Anorthosite from Norway

The anorthosite sample (Fig. 6) belongs to the anorthosites from Sogn Jotun nappe [12, 13]. It has a fluidal aspect and shows a well defined foliation determined by the flattened porphyroclasts of amphibole, plagioclase and garnet. A strong lineation is defined by the elongation of the same porphyroclasts and of mineral aggregates. Referring to the six criteria of I, it can be determined that:

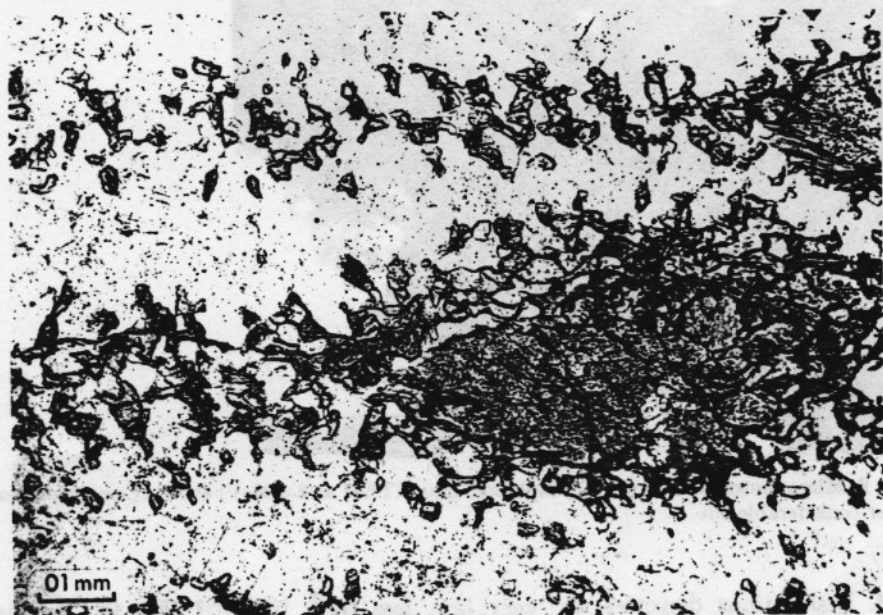


Fig. 7. Anorthosite from Norway. The dark stripes are made of $10\ \mu$ recrystallized amphibole grains. Bar 0.1 mm

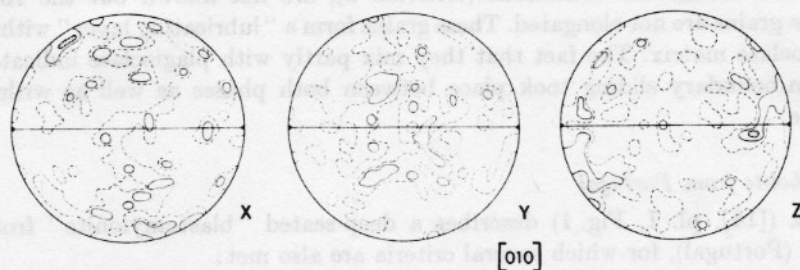


Fig. 8. Fabric of the $10\ \mu$ amphibole grains. 100 measurements. Contours: 1%, dashed line; 2%, continuous line; 4%, decorated area

1. The conditions were close to those of granulite facies [13], i.e., temperature about 600°C . Thus deformation took place at a high temperature relative to the amphibole breakdown temperature ($900\text{--}1000^\circ\text{C}$).

2. The rock is essentially made of plagioclase (55%) amphibole (35%) and garnet (10%). The total average grain-size is $25\ \mu$: plagioclase is almost completely recrystallized into an equant mosaic of small grains ($50\ \mu$), amphibole recrystallizes into very small grains ($10\ \mu$) forming a band in which they become mixed with plagioclase (Figs. 6 and 7).

4. The $10\ \mu$ amphibole grains which form the dark layers have almost no distinct fabric (Fig. 8).

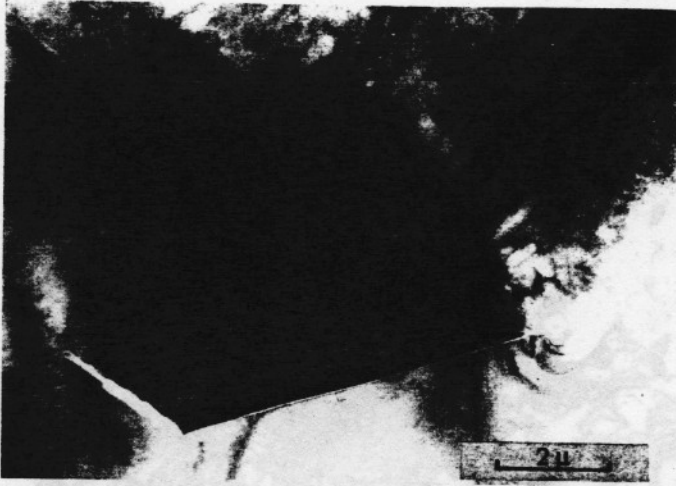


Fig. 9. Microphotograph of a $10\ \mu$ amphibole grain (TEM at 2.5 MeV) showing no dislocation after considerable tilt

5. Dislocations densities are very low, less than $10^6\ \text{cm}^{-2}$ (Fig. 9). No dislocation cell is formed.

6. The average percentage of deformation, calculated as explained in Fig. 4 by using amphibole as a marker, is larger than 1000%.

The stress, strain-rate conditions (criterion 3), are not known but the $10\ \mu$ amphibole grains are not elongated. These grains form a "lubricating layer" within the plagioclase matrix. The fact that they mix partly with plagioclase indicates that grain-boundary sliding took place between both phases as well as within amphibole.

3. Amphibolite from Portugal

Anthonioz ([14], pl. I, Fig. 1) describes a deep-seated "blastomylonite" from Bragança (Portugal), for which several criteria are also met:

1. The deformation took place at 500°C [14] which is relatively high considering the breakdown temperature of amphibole ($900\text{--}1000^\circ\text{C}$).

2. The rock is made of several minerals: dark layers (hornblende) appear within a matrix of quartz and plagioclase feldspar. The average grain-size in the matrix is 0.1 mm but there are some plagioclase porphyroclasts left. Hornblende porphyroclasts (a few millimeters in diameter) are recrystallized on their edges into very fine grains ($10\ \mu$) which form the dark layers.

The other criteria could not be studied except that from the pictures shown in [14]—the total strain was at least a few 100%. We suggest that fine-grained hornblende stripes form a "lubricating layer" like orthopyroxene and amphibole in the two other examples studied.

Other layered mylonites, such as those described in [15] have textures which are very similar to those described above. No possible conclusions can be drawn due to the absence of information on temperature, stress, strain-rate and grain-size.

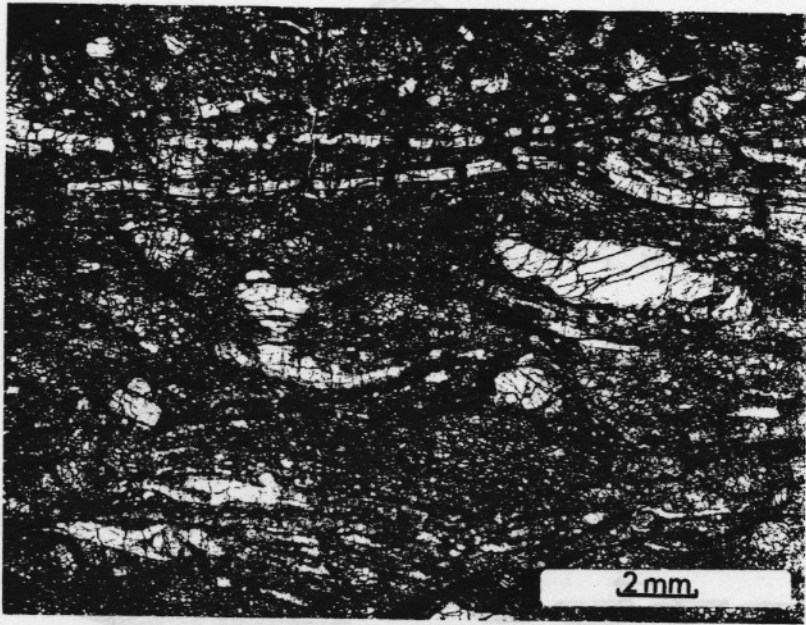


Fig. 10. Peridotite from Lanzo massif [18]. Orthopyroxene grains are very elongated and show some boudinage

III. Nature of Flow in Mylonites: One Origin for Tectonic Banding

Now we propose a possible subdivision of mylonites without any glassy phase, based on the type of flow which has been active. Mylonites are defined as crystalline rocks which have undergone a considerable grain-size reduction, subsequent to a strong deformation [16]—i.e., they are rocks for which the total strain ϵ is large (commonly more than 1000%). This does not imply a very high stress but a large strain-rate and/or a long deformation.

Mylonites made of several minerals can be subdivided into two classes according to the regime of flow which existed during the deformation.

a) Class I. The first class corresponds to a low temperature (relative to T_m), high stress deformation. Layering is developed in the following manner: the mineral in which recovery and recrystallization are the most effective recrystallizes first, after an intragranular gliding stage (olivine in peridotites, Fig. 10; feldspar in anorthosite); the mineral in which these processes are the least effective may remain as large augen or deform by intragranular gliding to become very elongated. This elongation ultimately leads to a boudinage or necking (orthopyroxene, Fig. 10). This explanation of the layering resembles Schmidt's hypothesis [17], in that it is a mechanical explanation, but here the elongated minerals are not the most ductile. This is illustrated in Fig. 10 which represents a mylonite from the peridotite massif of Lanzo (Italian Alps) [18]. Mylonites exist in Lanzo only along the edges of the massif, where the deformation has been particularly intense. Recent analysis indicates that the temperature was about 850–900°C during the deformation of this mylonite [19], i.e., it was a low temperature deformation

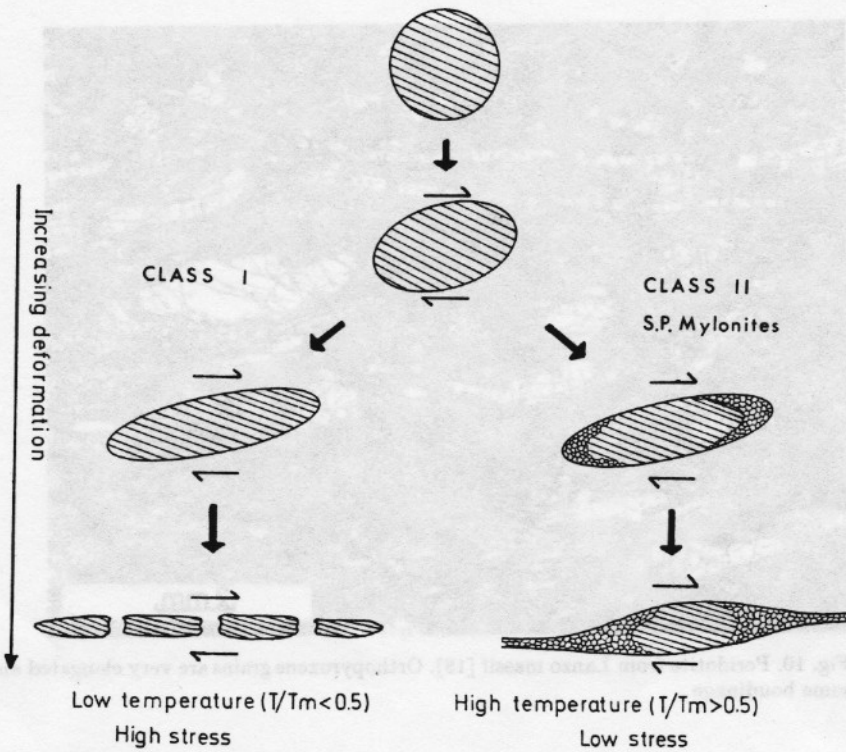


Fig. 11. Schematic representation of class I mylonites and class II mylonites. Deformation of the less ductile mineral

since the melting points of orthopyroxene and olivine are respectively about 1550°C and 1800°C . Orthopyroxene, which is less ductile than olivine, is extremely elongated but even so it has probably undergone less finite strain than olivine.

b) Class II. SP-Mylonites. The second class corresponds to a high temperature, low stress regime of deformation. As in the first class, the mineral which recrystallizes the most easily is the first to recrystallize but now the layering is developed in a completely different manner: given the high temperature, the second mineral, present in augen, begins to recrystallize also in very small grains ($10\ \mu$). When large quantities of such grains have been formed, superplastic flow takes place by grain-boundary sliding between these grains, producing the observed banding. All the examples discussed in section II belong to this type of mylonite.

The difference between class I and class II are schematised on Fig. 11. In the first case, the mylonite is crudely layered by plastic flow and in the second one, it is well layered by superplastic flow.

The differences in efficiency of the recovery processes in different minerals of a given rock have led to the above analysis. At relatively low temperatures, one of the minerals cannot recrystallize at all, so, if it participates in plastic flow,

it becomes very elongated. At relatively high temperatures, it begins to recrystallize in tiny grains and superplasticity appears. A more detailed analysis provides an explanation of this fact: in the examples given in II, orthopyroxene and amphibole are the minerals which have difficulty in recrystallizing. Both are known to deform not only by dislocations, but also by stacking faults [20, 21] whilst olivine and feldspars deform by dislocations only [20, 22]. The inefficiency of the recovery processes is also known in alloys with low-energy stacking faults, so that the presence of stacking faults is a likely explanation. This, together with the fact that several phases are present, may also explain why the grain-size of the new grains remains very small. Contrary to alloys, for which the major controlling factor impeding grain-growth is the presence of a second phase, it may be that in silicates the major factor is the inherent difficulty to recrystallize, resulting from the presence of stacking faults. It is interesting to note that development of superplasticity after an initial stage of plastic flow—as suggested above for some mylonites—has also been documented in alloys [23].

Conclusion

We suggest that superplasticity explains certain mylonites. Restrictive conditions are required for superplasticity to occur and six criteria should be looked for to determine whether or not it has taken place. However, when it has, some important consequences are:

1. The strain-rate is faster than for usual plastic flow (extrapolated into the superplastic domain) with the same moderate stress: this means that an important deformation can be achieved in much less time.

2. In a given rock, the mineral which usually controls the deformation—for instance olivine in peridotite—may become passive, if superplasticity is the result of the recrystallization of the other mineral into very small grains (orthopyroxene in peridotite). Consequently the presence of several different mineral species in a rock has important bearings on its plastic properties: in different (σ , T) conditions the controlling mineral may be different in the same rock.

3. Superplasticity is a very effective process for developing a fine scale, sharp mineral layering.

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