ESTIMATES OF STRESS AND RECOVERY CONDITIONS IN VARIOUS TYPES OF MANTLE PERIDOTITES.

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Structural studies in mantle peridotites have been hitherto essentially devoted to describing the geometry of the deformation and to understanding the mechanisms and kinematics of flow. A wide consensus is now obtained on the idea that the elementary mechanism is the motion of dislocation in nearly all the studied peridotites, like it is in metals. This achievement makes it possible to use for investigating the flow dynamics, after the appropriate experimental calibration, the empirical relations established in metals between the dislocation microstructure and the deviatoric stress. RALEIGH and KIRBY (1970) and GOETZE (1975) have been the first authors to apply these relations to olivine from mantle peridotites. Since, both the experimental record and the data on naturally obtained microstructures have increased and it is possible to make some comparisons between the stress-recovery histories of the various mantle peridotites, namely peridotites from kimberlite and basalt nodules and peridotites from lherzolite and harzburgite massifs. The results can also be compared with the stress estimated for asthenopheric flow by other methods. Prior to presenting these results the different kinds of "structural geopiezometers" will be critically assessed, summarizing a more complete discussion already presented (NICOLAS, in press).

The relations between dislocation microstructure and stress have been experimentally established for olivine which is the dominant mineral in peridotites, largely controlling their flowage. The empirical relations tie with the stress, the dislocation curvature and density, the subgrain size and the dynamically recrystallized grain (neoblast) size (NICOLAS and POIRIER, 1976, p.137). From the above mentioned discussion, it has been concluded that the last relation is the most reliable when estimating the stress applied during the presumably steady state flow. Three calibrations have been made :

$\sigma = 11 \times d^{-0.5}$ (GOETZE, 1975) (σ = Kb; d = μm)

$\sigma = 19 \times d^{-0.67}$ (POST, 1973)

$\sigma = 40 \times d^{-0.81}$ (MERCIER, 1976)

The subgrain size consists usually for olivine in the measurement of the (100) subboundary spacing. Here the question of the scale of observation is important. With the TEM or the decoration technique all the subgrains are deciphered whereas with the optical microscope at low magnification in crossed nicols only the subgrains misoriented by more that 1° are visible. Our preliminary studies on recovery suggest that the latter subgrains are fairly stable either to a recovery or to a stress pulse (strain $<$ 2%, DURHAM et al, in press). Therefore their (100) spacing can be used in a comparable way to the neoblast size: for instance in the Lanzo massif a good linear relation has been found between this (100) spacing and the neoblast size with $d_{(100)} = 0.44\ d_{neobl.}$ (BOUDIER and NICOLAS, in press).

With the decoration technique at a x 1000 magnification all the subboundaries are decorated. The (100) spacing is now one order of magnitude narrower than above, due to the fact that most subboundaries are misoriented by less than one degree. The relations with the stress are :

$$\sigma = 17 \times d^{-1} \quad \text{(GOETZE, 1975)} \quad (\sigma = \text{Kb};\ d = \mu m)$$

$$\sigma = 10 \times d^{-1} \quad \text{(DURHAM } \underline{\text{et al}}\text{, in press).}$$

The low angle subboundaries are thought to be very sensitive to a recovery or to a stress pulse. Therefore this piezometer can be used to decipher these phenomena from the stress operating during the steady state flow. The same conclusion applies to the stress estimated from the density of dislocations but here appears the further difficulty of obtaining a correct estimation of the dislocation density (GUEGUEN, 1977).

The first systematic data on stress oriented studies of dislocation microstructures in mantle peridotites are those by GUEGUEN (1977) for kimberlite and basalt nodules, COISY (1977) for the Massif Central basalt nodules, MERCIER (1976) for the U.S. basalt nodules and the Newfoundland ophiolite peridotites and BOUDIER and NICOLAS (in press) from the Lanzo lherzolite massif.

In the porphyroclastic and mosaic textured nodules from kimberlites, the average size of the dynamically recrystallized olivine grains (75 μm) suggests a stress in the range of 1 Kb. However, these nodules display evidence of subsequent recovery and annealing with static recrystallization of olivine in tablets and stress relaxation down to 400 bars estimated from a mean density of free dislocations of 2. 10^7 cm^{-2}. On the basis of the kinetics of growth of the olivine tablets, MERCIER (1976) has evaluated to a few hours, during the eruption, the annealing time.

In the case of basalt nodules, the stress corresponding to the main flow is comprised between 100 and 600 bars, based on the neoblast grain size and on the (100) subboundary spacing observable with crossed nicols. This is mainly valid for the protogranular and equigranular textures, with a clear tendency from the stress to be higher in the latter textures. In the porphyroclastic textures from some areas (Massif Central, Western U.S.) these structural piezometers record stresses in the range 500-1000 bars. The free dislocation density is uniformely in the range of 10^6 - 10^7 cm^{-2} suggesting during the eruption process a moderate recovery sometimes obscured by a late stress pulse.

In peridotite massifs a distinction has been made between those associated with ophiolites in which the flow structures are believed to reflect the oceanic mantle flow and others like the Lanzo lherzolite massif, which could represent mantle intrusions into the crust, at plate margins. The only extensive data concern the Lanzo massif where the stress associated with the intrusion at solidus conditions has been estimated at 200 - 400 bars (neoblast size : 500 - 700μm). Further flowage into the crust led to an heterogeneous distribution of stress and strain whose values continuously increased at the margins of the massif and inside bands dividing it. The ultimate deformation yields mylonites with stresses of a few Kb.

If the intrusion model for Lanzo is correct the flow at solidus conditions should be representative of the asthenosphere as occurring at strain rates in the 10^{-14} sec^{-1} range (BOUDIER and NICOLAS, in press). This raises the problem of the corresponding stress (200 - 400 bars) which is found to be one order of magnitude greater than that derived from models on the rheology of the mantle. Stress values in the same range have been reported above for the protogranular and equigranular textures in peridotite nodules from basalt. As discussed in a former paper (NICOLAS, in press), the discrepancy between these different stress estimates could be due to the analytical uncertainties which are still important in both approaches. Thus the flow structures observed in these peridotites and associated with apparent stresses of a few hundred bars could indeed represent the asthenopheric flow. On the other hand, the porphyroclastic and mosaic textures in kimberlite nodules and the high stress porphyroclastic textures locally observed in basalt nodules correspond to stresses and strain rates too high for an asthenospheric flow and certainly represent some local tectonic instabilities. COISY (1977) has attributed such porphyroclastic textures in basalt nodules to narrow shear zones (one kilometer thick) developing during the last stage of an asthenosphere upwelling, a situation recalling what has been described in the Lanzo massif.

REFERENCES :

BOUDIER, F. and NICOLAS, A. - Stress and strain estimates in the Lanzo Peridotite massif (Western Alps). C.N.R.S. Colloque Inter., in press.

COISY, P., 1977 - Thesis, Nantes, 115p.

DURHAM, W.B., GOETZE, C. and BLAKE, B. - Plastic flow of oriented single crystals of olivine part II : observations and interpretations of the dislocation structures. Jour. Geophys. Res., in press.

GOETZE, C., 1975 - Eos Trans. AGU, 56, 6.

GOETZE, C., 1975 - Geology, 172-173.

GUEGUEN, Y., 1977 - Tectonophysics, 39, 231-251.

MERCIER, J.C., 1976 - Ph. D., S.U.N.Y. at Stony Brook.

NICOLAS, A. - Stress estimates from structural studies in some mantle peridotites. Phil. Trans. R. Soc. Lond., in press.

NICOLAS, A. and POIRIER, J.P., 1976 - J. Wiley, London Publ., 444p.

POST, R., 1973 - Ph. D., U.C. at Los Angeles.

RALEIGH, C.B. and KIRBY, S.M., 1970 - Mineral. Soc. Amer. Spec. Pap. 3, 113-121.