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Microstructural features of high temperature shear zones in gabbros of the Northern Apennine Ophiolites

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Abstract—This paper presents preliminary data on the microstructural evolution of upper amphibolite facies mylonitic metagabbros from the Bracco Ophiolite Complex, Northern Apennines (Italy). High temperature deformation, possibly related to the initial stages of breakup and oceanization in the Ligurian Tethys, led to the development of three different types of fabrics in the coarse grained Mg-gabbros, the most widespread rock-type in this area. With progressive deformations, coarse-grained porphyroclastic mylonites (fabric type 1), banded (fabric type 2) and 'flinty' ultramylonites (fabric type 3) were formed. In plagioclase and clinopyroxene, the two main minerals in the studied rocks, optical microstructures and scanning electron microscopy analyses indicate crystal plasticity as the main deformation mechanism. A possible change from 'rotation'-recrystallization regime, through grain boundary migration to diffusion-assisted high temperature grain boundary sliding, is suggested for the plagioclase grains in high temperature shear zones.

GEOLOGICAL SETTING

THE Ligurian Apennines (northwestern Italy) (Fig. 1) are dominated by the exposures of the Northern Apennine Ophiolites, traditionally considered as remnants of the Jurassic Ligurian Tethys. These ophiolites occur at the top of a nappe-pile in tectonic units called Liguride Units (Elter & Pertusati 1973). The Alpine deformational history occurred at high structural levels under very low grade metamorphic conditions (prehnite–pumpellyite in metabasic rocks), so the primary features of the ophiolites could be accurately reconstructed (Abbate *et al.* 1980, and review in Cortesogno *et al.* 1987). The stratigraphy of the ophiolites shows laterally varying sequences made up of ultramafic and gabbroic bodies directly covered by a volcano-sedimentary sequence (comprising ophiolitic breccias and scarce pillow lavas) and/or by pelagic sediments represented by cherts (Callovian–Oxfordian), Calpionella Limestone (Berriasian) and Palombini Shale (Berriasian–Santonian) (Marroni 1991).

The gabbros and the ultramafics show evidence of a tectonic evolution associated with retrograde metamorphism, which started from conditions of high temperature and low pressure directly related to the uprise of the gabbros and peridotites at the ocean floor. The initial stages of this deformation are observed in the gabbros in upper amphibolite facies shear zones, which form the subject of this contribution. Cross-cutting relationships with undeformed Morb-type basaltic dykes clearly demonstrate that these shear zones are of pre-Alpine age. The overall interpretation of the geological environments for the Northern Apennine Ophiolites is still debatable; an original transform setting has been hypothesized in different studies in the last decades (Gianelli & Principi 1974, Abbate *et al.* 1980, and review in Cortesogno *et al.* 1987). According to this model, the deformation in the gabbroic rocks results from transcurrent movements during upper mantle uprise into a transform zone. However, more recent structural studies (Hoogerduijn Strating 1988, Molli work in preparation) focusing on the geometry and kinematics of the high temperature shear zones propose an extensional setting directly related to the initial stages of breakup and oceanization. This is in agreement with paleotectonic models proposed for the birth of the western Tethys by Decandia & Elter (1969), Lombardo & Pognante (1982), Lemoine *et al.* (1987), Drury *et al.* (1990), Vissers *et al.* (1991) and Piccardo *et al.* (1992).

PROTOLITH AND DEFORMATIONAL SEQUENCE IN THE SHEAR ZONES

The protolith consists of a coarse grained Mg-gabbro (Fig. 2a) with magmatic paragenesis dominated by euhedral or subhedral plagioclase ($An_{60\pm6}$), and interstitial to poikilitic clinopyroxene (Mg-rich diopside); olivine in scattered occurrences (generally less than 5%) is always transformed into chlorite+actinolite aggregates; Fe–Ti oxides complete the assemblage. The mafic minerals usually form less than 40% of the rock.

High temperature shear zones ranging in width from a few decimetres to several metres are observed in many exposures of otherwise undeformed gabbroic wall rocks. Geometrical reconstruction based on an inferred paleohorizontal surface, in combination with kinematic analysis of the shear zones (Hoogerduijn Strating 1988; this work) indicate predominantly normal displacements and generally non-coaxial deformation in these shear zones.

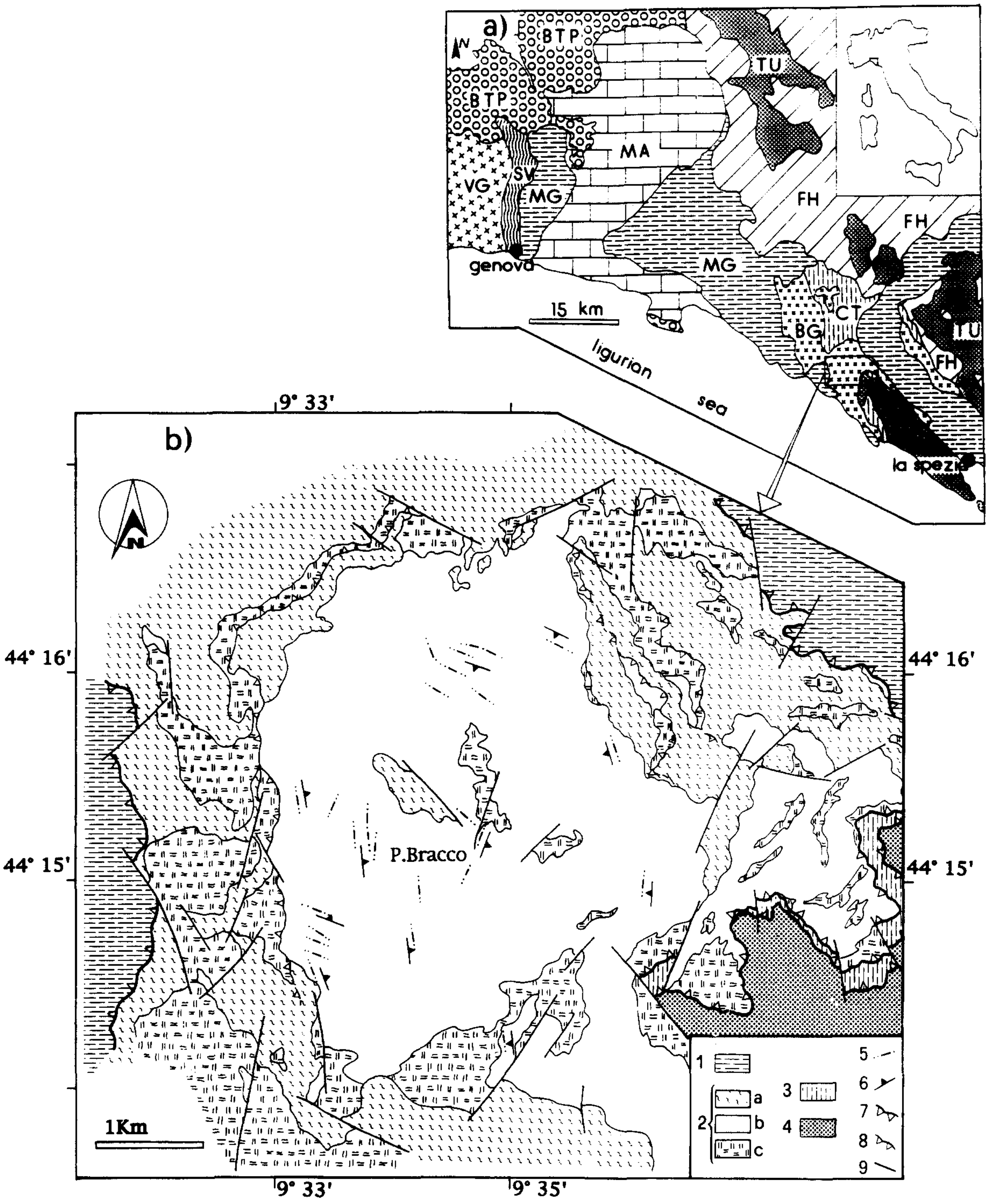

Fig. 1. (a) Tectonic map of eastern Liguria, Italy, with location of the study area. BTP—Tertiary Piemontese Basin; VG—Voltri Group; SV—Sestri-Voltaggio Units; MA—Mt. Antola Unit; MG—Mt. Gottero Unit; BG—Bracco-Val Graveglia Unit; CT—Colli/Tavarone Unit; FH—External Liguride Units; TU—Tuscan and Canetolo Units (modified after Marroni 1991). (b) Geological sketch map of the Bracco area. 1—M. Gottero Unit. 2—Bracco/Val Graveglia unit; *a*—pelagic sediment; *b*—gabbro; *c*—serpentinite. 3—Colli/Tavarone unit. 4—Tuscan unit. 5—Trace of high temperature shear zones. 6—Foliation of high temperature shear zones. 7—Major thrust. 8—Internal thrust. 9—Late normal fault.

Within the shear zones studied, the mineral assemblage is made up of Ca-plagioclase ($An_{50/55}$) + clinopyroxene (Mg-rich diopside) + scarce Ti-rich hornblende (tschermakitic to edenitic hornblende) + ilmenite. This assemblage must indicate temperatures around 660–730°C and pressures less than 400 MPa (Cortesogno & Lucchetti 1984). These data agree with experimental studies (Spear 1980) that find a similar assemblage for a basaltic composition at 100 MPa of fluid pressure and temperature 750–800°C (Mevel 1987).

Starting from virtually undeformed gabbros, three main fabric-types can be distinguished. Field relationships, as well as the microstructures, indicate a gradual transition between these main fabric types, suggesting that they could represent stages of increasing strain during progressive deformation.

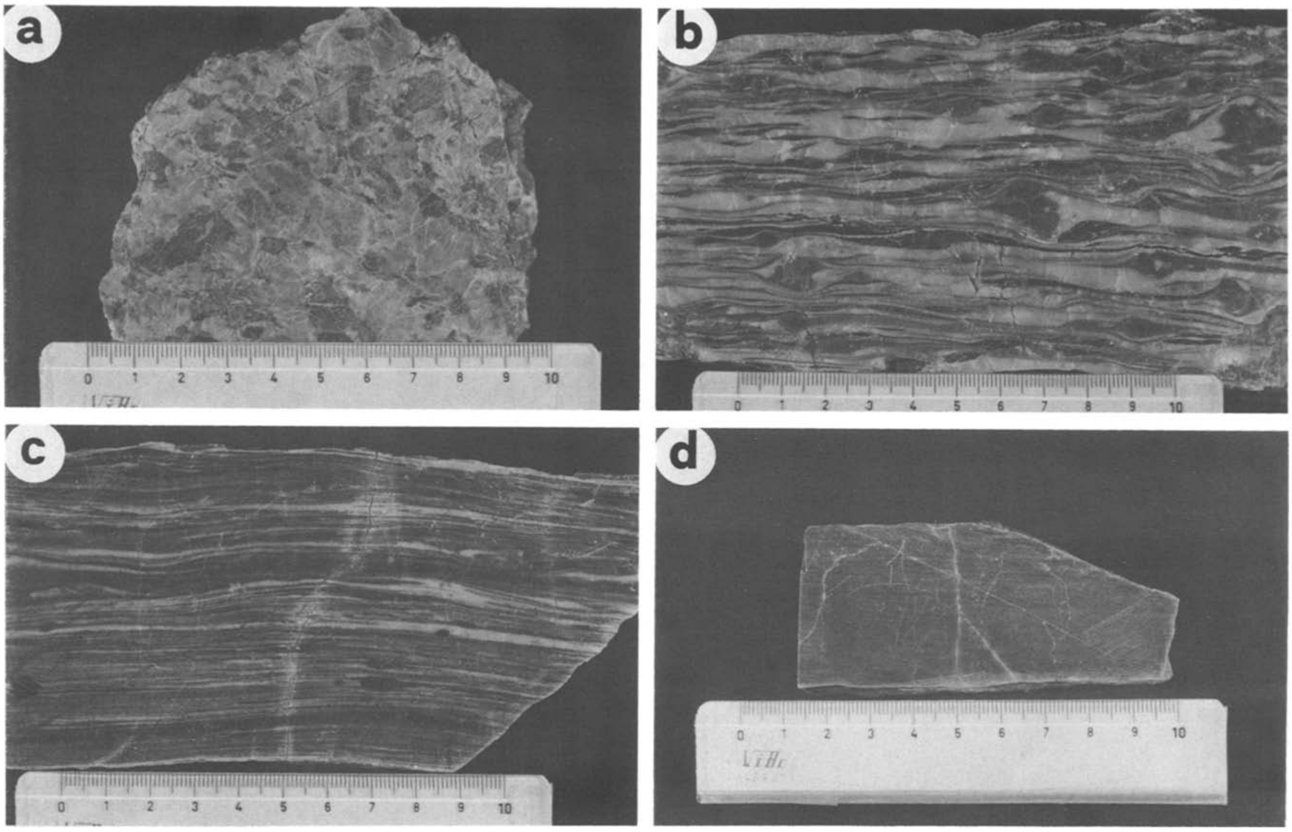

Fig. 2. (a) Undeformed coarse grained Mg-gabbro; (b) coarse-grained porphyroclastic metagabbro mylonite, fabric type 1; (c) banded metagabbro ultramylonite, fabric type 2; (d) 'flinty' ultramylonite, fabric type 3. Centimetre rule for scale.

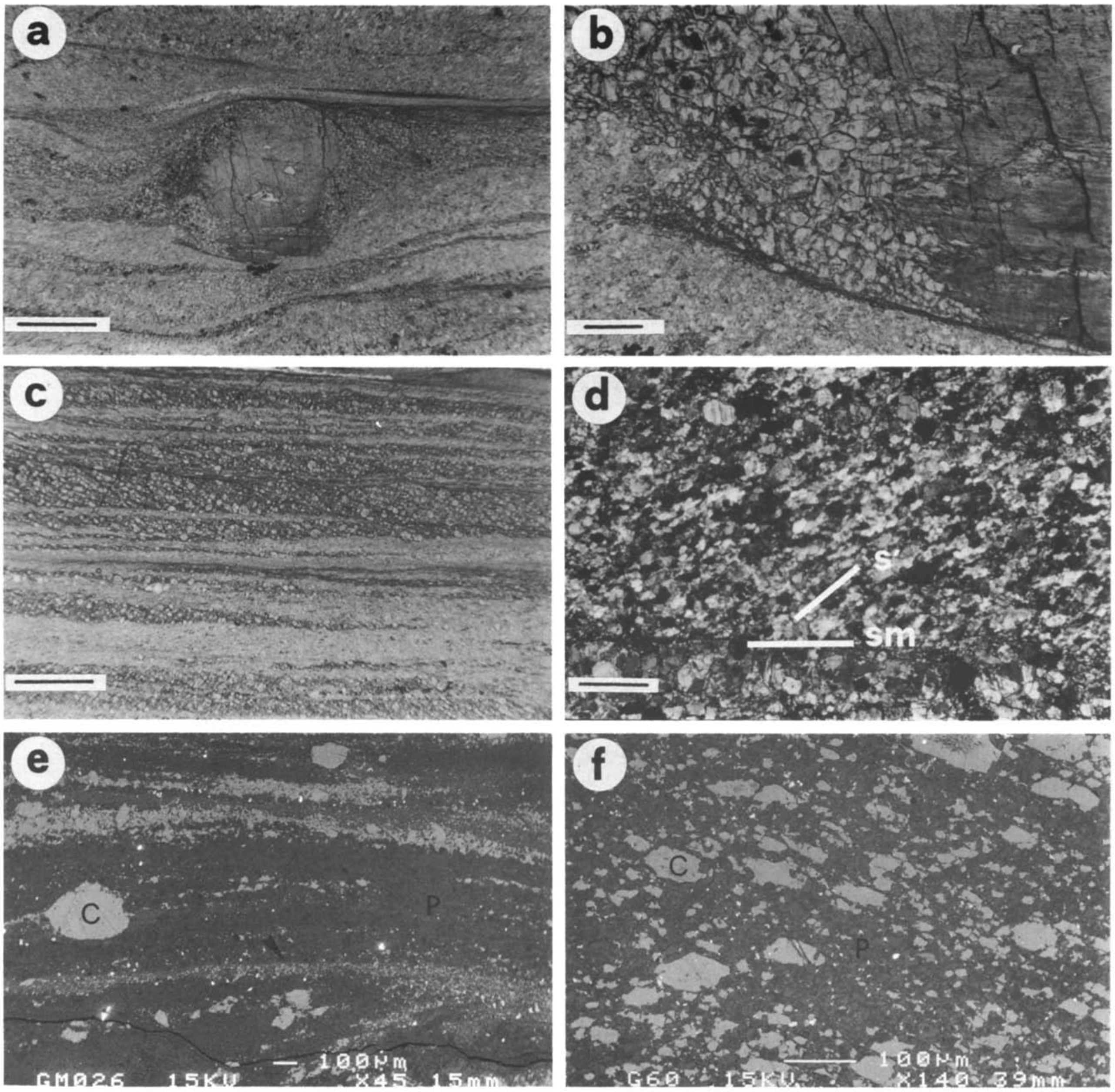

Fig. 3. (a) Microstructures of coarse-grained porphyroclastic metagabbro mylonite (fabric type 1), showing an σ-type clinopyroxene porphyroclast. Plane polarized light. Scale bar 2 mm. (b) Detail of (a) showing recrystallized diopside-rich clinopyroxenes (with interstitial Ti-rich hornblende and ilmenite) at the tail of a magmatic clinopyroxene porphyroclast. Scale bar 0.25 mm. (c) Microstructure of banded metagabbro ultramylonite (fabric type 2). Plane polarized light. Scale bar 2 mm. (d) Micrograph of plagioclase grain shape (*S'*) oblique to the mylonitic foliation (*S*m) defined by clinopyroxene grains. Crossed polarized light. Scale bar 0.5 mm. (e) Back scattered electron micrograph (B.S.I.) of fine grained bands (arrow) of fabric type 3 showing intergrown diopside-rich pyroxene (C, light contrast) and plagioclase (P, dark contrast) within a fabric type 2. (f) Back scattered electron micrograph showing detail of fabric type 3. C (light contrast) represent diopside-rich pyroxene and P (medium grey contrast) plagioclase which is locally altered to more sodic composition (dark grey contrast).

Fabric type 1

Fabric type 1, or coarse-grained porphyroclastic metagabbro mylonites (Fig. 2b), consists of augen of clinopyroxene crystals in a fine-grained plagioclase matrix. The augen are composed of an inner porphyroclast of magmatic pyroxene showing variable degrees of internal strain (undulatory extinction, kink bands and sometimes microfolding of the cleavage) surrounded by polygonal pyroxene neoblasts (grain sizes 0.2–0.1 mm) progressively smeared out to form tails (Figs. 3a & b).

Recrystallization of plagioclase occurs initially along the grain boundaries of large plagioclase crystals. Then a progressive grain size refinement is observed. The typical grain size of the plagioclase in this fabric type is around 0.1 mm. The grain boundaries are either straight or curved and subgrains of variable sizes (10–50 μm) are observed. The plagioclase grains frequently show undulatory extinction and mechanical twinning, mainly affecting the porphyroclasts but also the new grains. Microstructures consisting of 'ribbon' grains of plagioclase, with (010) cleavages sub-parallel to the foliation, aspect ratios varying from 5:1 to 50:1 and fine recrystallized grains along the margins similar to those described by Ji & Mainprice (1987), can also be recognized. Clinopyroxene and plagioclase with grain sizes strongly reduced to less than 50 μm, and forming millimetre-thick bands appear near the transition to fabric type 2.

Asymmetric pyroxene porphyroclasts of σ-type (Passchier & Simpson 1986) are the most widespread kinematic indicators (Fig. 3a). Book-shelf or domino-like structures can often be observed. They are formed by pyroxene porphyroclasts with (110) cleavages sub-parallel to the main foliation, characterized by microfaulting orientated at 35°–50° with respect to the flow plane and with a displacement antithetic to the overall shear sense deduced through other criteria. Asymmetric folds refolding the fine grained pyroxene-rich bands are frequently found, associated with flow heterogeneity due to the proximity of clinopyroxene porphyroclasts.

Fabric type 2

Fabric type 2, or banded metagabbro ultramylonites (Fig. 2c), is characterized by a millimetre scale alternation of fine-grained pyroxene-rich (~ 0.1 mm in size) and plagioclase-rich (0.08–0.05 mm) layers (Fig. 3c). On a mesoscopic scale this microstructure corresponds to a strongly banded appearance of the rocks. The original large magmatic clinopyroxene grains have almost completely disappeared, and can only rarely be observed as rounded grains of δ-type (Passchier & Simpson 1986). Ti rich-hornblende, present as interstitial phases between the refined clinopyroxene grains, is interpreted as a late phase with respect to the deformation.

The plagioclase boundaries are differently developed within the same thin section, either straight, curved or strongly irregular. They represent different degrees of recovery. Plagioclase grains with irregular grain boundaries and shape preferred orientation oblique to the main foliation are common (Fig. 3d). They are defined by the elongate shape typically orientated at 25°–40° (occasionally angles up to ~50° are observable) to the mylonitic foliation, in combination with elongate zones of related crystallographic orientation observable with the gypsum plate inserted. This microstructure, verified when possible in conjunction with asymmetric porphyroclasts, has been used as a shear sense indicator (e.g. Simpson & Schmid 1983, Lister & Snoke 1984).

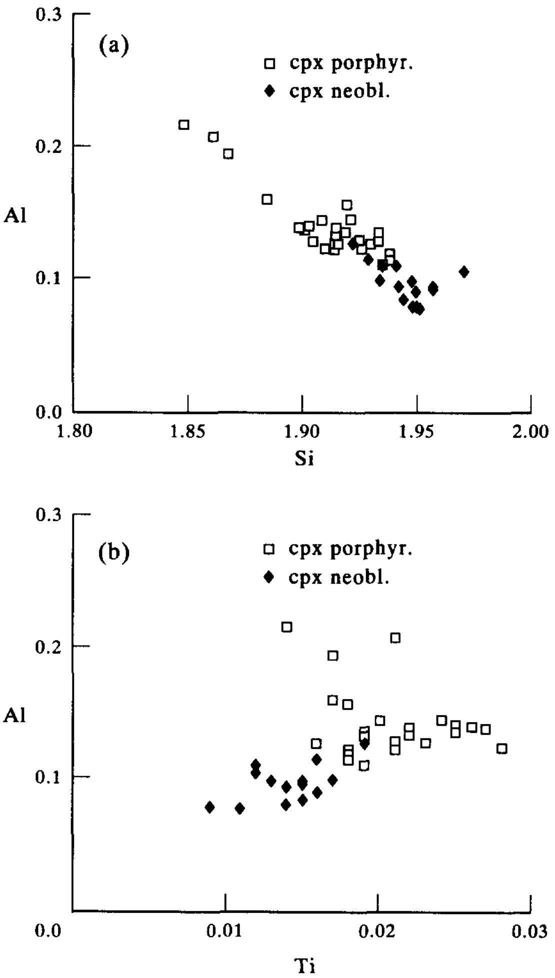

Fig. 4. (a) Al vs Si and (b) Al vs Ti diagrams of clinopyroxene showing the variation of these elements between porphyroclasts (open symbol) and recrystallized neoblasts (full symbol).

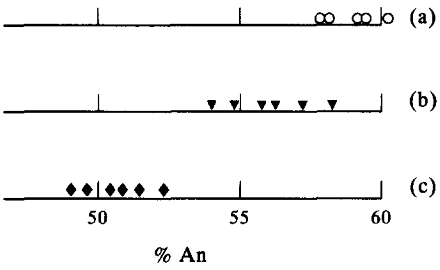

Fig. 5. Anorthite content of plagioclase. (a) Undeformed grains and relicts in fabric type 1; (b) recrystallized grains in fabric type 1; (c) recrystallized grains in fabric type 2.

The ultrafine grained submillimetric bands of intergrown clinopyroxene and plagioclase appear more frequently than in fabric type 1 (Fig. 3e).

Fabric type 3

Fabric type 3, or 'flinty' ultramylonites (Fig. 2d), is characterized by an extreme reduction in grain size, less than 0.05 mm for both plagioclase and pyroxene. A submillimetric banding, detectable at the microscopic scale only, is formed by pyroxene-rich layers alternating with pyroxene and plagioclase intergrowths. An equiaxed shape is predominant for both minerals, although the clinopyroxenes are sometimes elongated parallel to the main foliation. Isolated larger grains of clinopyroxene 0.1–0.2 mm in size, with a grain shape preferred orientation parallel to the main foliation, observed in the ultrafine grained pyroxene-rich bands, may derive from previous layers of recrystallized pyroxene (Fig. 3f). Shear bands or extensional crenulation cleavage (Platt & Vissers 1980) deforming the pyroxene-rich bands are locally observed at angles between 10° and 20° to the main foliation.

MINERAL CHEMISTRY

Samples derived from a selected, meter-scale wide shear zone have been analyzed in order to investigate the possible changes in mineral composition with increasing strain. The full spectrum of microstructural types is present in this shear zone, with fabric type 3 developed in millimetre-scale bands within planar domains showing fabric type 2.

The clinopyroxene grains show a slight but systematic decrease in Al-content between the magmatic grains (porphyroclasts) and the clinopyroxene neoblasts (Fig. 4). Among the recrystallized grains very little variation is observed with grain size or fabric type.

Plagioclase (Fig. 5) grains show a significant decrease in anorthite content from $An_{58(\pm 3)}$ in the magmatic crystals to An_{56} in the neoblasts of fabric type 1 and An_{50} in those of fabric types 2 and 3. This change in composition as a function of the fabric-type, may indicate a slight decrease in temperature, as already argued by Brodie & Rutter (1985), occurring during progressive increase and localization of strain. However, some initially different An-content in the protolith composition cannot be excluded.

DISCUSSION: DEFORMATION MECHANISMS

The mineral chemistry of the pyroxenes indicating a slight variation of the porphyroclast and neoblast composition suggests recrystallization rather than cataclastic grain size reduction followed by high temperature annealing (Brodie & Rutter 1985). The optical microstructures indicate their syn-tectonic growth. Therefore, plastic deformation of the pyroxenes and their dynamic recrystallization can be considered as the main deformation mechanism, although a subordinate contribution of the cataclasis is testified by the observation of microfaulting and domino-like features.

Mechanical twinning, undulatory extinction, 'ribbon' grain and subgrain/newgrain development in plagioclase suggest intracrystalline plasticity in conjunction with grain size reduction by dynamic recrystallization. The high temperature of the deformation might promote recovery-accommodated dislocation creep (Tullis & Yund 1985), possibly developed in fabric type 1 mainly by bulging and subgrain rotation (Bell & Johnson 1989). An increasing role of grain boundary migration in fabric type 2 with respect to fabric type 1, is suggested by the oblique plagioclase grain shapes.

Studies on quartz, Mg-alloy and olivine (Lister & Snoke 1984, Drury *et al.* 1985, Knipe & Law 1987, Van der Wal *et al.* 1992), reveal a recrystallization regime controlled by grain boundary migration. The intergrown, ultrafine clinopyroxene and plagioclase grains, forming 'flinty' ultramylonites (fabric type 3), may be the result of mechanical dispersion between grains during 'superplastic' flow (Boullier & Gueguen 1975, Kerrich *et al.* 1980) in an originally banded ultramylonite (fabric type 2). An increased role of diffusion within fabric type 3 cannot be ruled out. However, chemical analyses show no change in composition among the recrystallized pyroxene grains and the very fine grains within fabric type 3, and are therefore inconclusive. The possible switch of deformation mechanisms within the ultrafine bands (fabric type 3), from predominant dislocation creep to a grain size sensitive flow ('superplastic' flow) is suggested by the very fine grain sizes ($<50\,\mu$m), by their extensive mixing and prevalent equiaxed shapes. The lack of L.P.O. studies precludes confirmation of this hypothesis, however.

CONCLUSION

The shear zones studied in the Bracco ophiolite gabbroic complex show three main fabric types, that developed during a deformation occurring under upper amphibolite facies conditions. Progressive mylonitization is mainly characterized by grain size refinement, from the centimetre-scale of the clinopyroxenes to less than 50 μm in the highest strained bands.

The contrasted mechanical behaviours of pyroxene and plagioclase may have controlled the fabric evolution, with the plagioclase constituting the softer strain-supporting framework. The presented data confirm the inference generally made that during high temperature deformation of metabasic rocks plagioclase deforms through intracrystalline plasticity and dynamic recrystallization, in contrast to its cataclastic behaviour at lower temperatures (Brodie & Rutter 1985).

A switch in the plagioclase deformational regime from predominant 'rotation'-recrystallization in fabric type 1, through progressive increase of diffusion in migration recrystallization (fabric type 2) to high temperature grain boundary sliding in fabric type 3 is proposed.

The presence of very fine grained zones associated with fabric type 1 and fabric type 2 as well as fabric type 3 suggests that high temperature plasticity in plagioclase as the main deformational mechanism controlling the rheology of the metagabbro shear zones, was possibly accompanied by grain size sensitive flow with partitioning of the strain among the different microstructures.

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