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Strain and shape-fabric variations associated with ductile shear zones

CAROL SIMPSON

Department of Geological Sciences, Brown University, Providence, RI 02912, U.S.A.

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Abstract—The foliated and compositionally-banded granitic orthogneisses in the central core of the Maggia Nappe, a Lower Pennine basement nappe of the Central Swiss Alps, are shown to be the sheared equivalent of late-Hercynian age granitic intrusions. These ductile shear zones show mineral assemblages in amphibolite facies, are Alpine in age and form an anastomosing network enclosing remnant lozenge-shaped pods of relatively undeformed rock.

The foliation developed within the shear zones concomitantly with a change in shape of quartz grain aggregates from initially equidimensional, through 'tear-drop' shapes, to ribbon-like aggregates. These shape changes occurred by intracrystalline glide together with intercrystalline slip on deformation-induced planar surfaces.

INTRODUCTION

DUCTILE shear zones are regions of high heterogeneous strain localized in narrow planar zones (Ramsay & Graham 1970). They are recognizable in the field by the deflection of planar markers such as dykes and/or by the formation of a new foliation with increasing strain in otherwise isotropic rock, as first described by Teall (1885). The geometrical relationship between the new foliation in shear zones and the finite strain axes has been discussed by Ramsay & Graham (1970), Ramsay & Allison (1979) and Ramsay (1980). This paper presents the results of a study of microtextural changes that occur as a new foliation is observed in sheared granitic rocks of the Maggia Nappe, Central Swiss Alps.

Several authors have described microstructural variations with increasing shear strain in shear zones (e.g. Katz 1968, Bell & Etheridge 1976, Wakefield 1977, Burg & Laurent 1978, Berthé *et al.* 1979), and mineral aggregate shape changes in shear zones have also been described (e.g. Ramsay & Graham 1970, Coward 1976, Grocott 1979). In this paper a combined study of microstructural and grain-aggregate shape changes across a shear-zone boundary is used to illustrate how a foliated granitic gneiss may develop as a result of isochemical deformation of originally non-foliated rocks in ductile shear zones.

GEOLOGICAL SETTING

The Maggia Nappe is one of the Lower Pennine crystalline nappes of the Lepontine Alps in southern Switzerland. These nappes are north-closing anticlines, characterized by cores of pre-Triassic metamorphic complexes with envelopes of calcareous Mesozoic metasedimentary rocks. The two groups of rocks show polyphase penetrative Alpine deformation and metamorphism (Heim 1922, Higgins 1964, Thakur 1973, Ayrton & Ramsay 1974, Milnes 1974, Huber *et al.* 1980, Simpson 1981). In the core of the Maggia Nappe, the main lithological units are orthogneisses formed from granitic rocks of probable Hercynian age (Köppel *et al.* 1981) (Fig. 1). In the north and south regions of the Maggia Nappe core, the granitic rocks are mostly unfoliated and still retain their original intrusive relationships (Ramsay & Graham 1970, Ramsay & Allison 1979, Simpson 1981). Foliated gneiss and compositionally-banded muscovite- and biotite-rich gneisses predominate in the central portion of the nappe core.

The first discernible phase of Alpine deformation gave rise to a penetrative linear fabric, locally accompanied by a planar fabric within ductile shear zones. This deformation event was most probably associated with the main differential displacements of the crystalline rocks occurring during nappe emplacement (Ayrton & Ramsay 1974, Simpson 1981). One major phase of tight folding was followed by a locally developed phase of crenulation. A regional thermal metamorphic event (the Lepontine metamorphism) reached a maximum of lower amphibolite facies in the Maggia gneiss before the onset of a regional phase of backfolding and associated deformation (Ayrton & Ramsay 1974, Milnes 1974, Huber *et al.* 1980). Recrystallization of almost all mineral grains in the Maggia rocks, except within some late-stage ductile shear zones, suggests that the metamorphism persisted through the backfolding phase of deformation (Simpson 1981). Post-tectonic recrystallization has also been noted by workers in other localities within the Lower Pennine zone (Higgins 1964, Hall 1972, Ayrton & Ramsay 1974). A more detailed description of the lithological units and structure of the Maggia Nappe is given elsewhere (Simpson 1981, 1982).

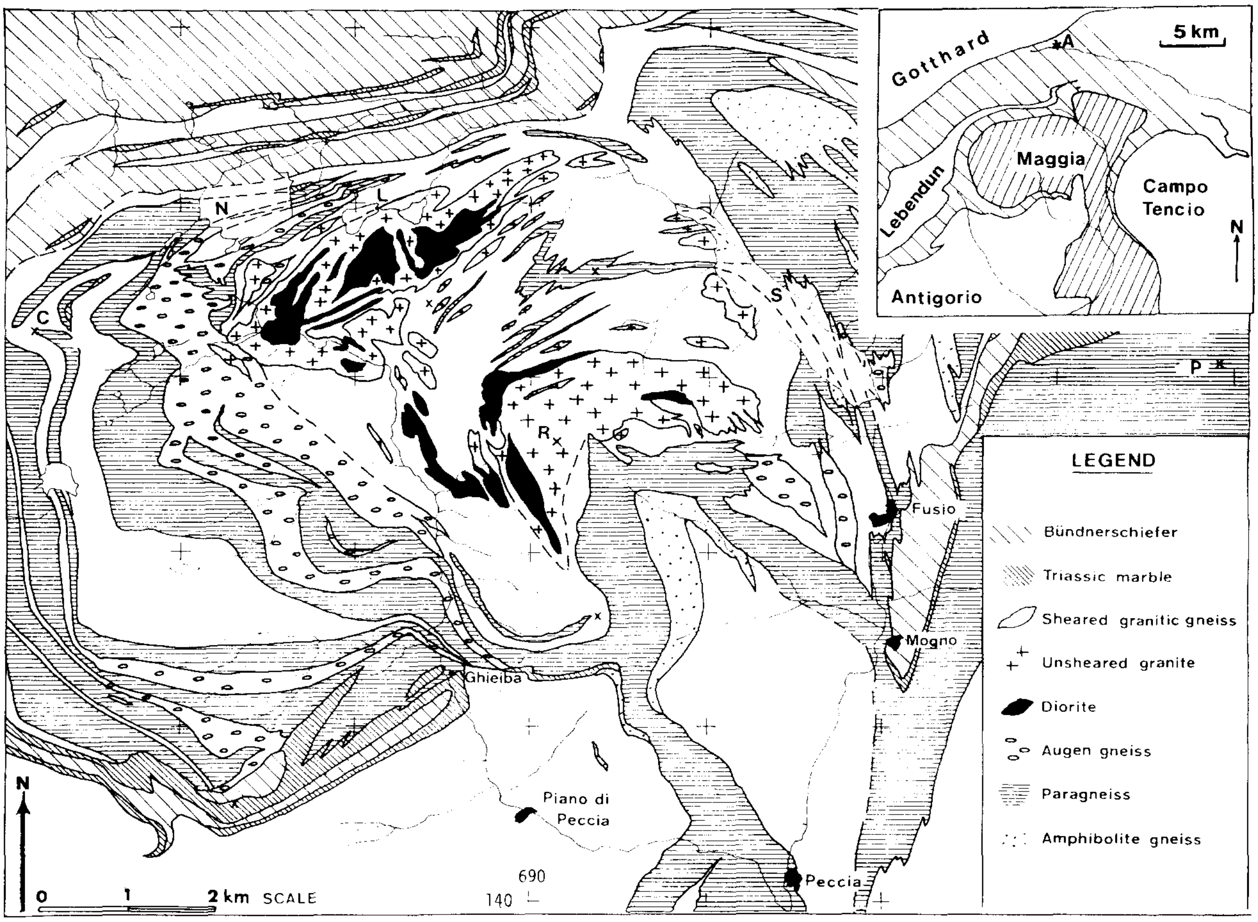

Fig. 1. Sketch map of the geology of the Northern lobe of the Maggia Nappe, Ticino, Switzerland. C = Cristallina, L = Laghetti, N = Lago Naret, P = Pizzo Campolungo, R = Pizzo di Rod, S = Lago Sambuco. Inset: schematic map of the tectonic units in the central region of the Lower Pennine Nappes, Central Swiss Alps, A = Airolo.

THE NON-FOLIATED ROCKS

The non-foliated rocks in the north and south regions of the Maggia Nappe core are granitic, tonalitic, adamellitic, granodioritic and dioritic in composition. These massive igneous rocks contain numerous basic and ultrabasic xenoliths and are cut by at least two generations of aplites as well as mafic and felsic quartz microdiorites (Ramsay & Graham 1970, Ramsay & Allison 1979). A mineral elongation lineation, parallel to the long axes of xenoliths and defined by aggregates of quartz and biotite, is almost all-pervasive throughout the igneous rocks in the region studied. Only in part of the diorite and in very small areas of the granitic rock is this linear structure absent.

The non-foliated and non-lineated granitic rock contains roughly equidimensional, 5-mm diameter lenses of quartz and biotite grains, set in a matrix of plagioclase, epidote, K feldspars and occasional muscovite and sphene. K feldspar crystals vary in size from 0.5 to 5 mm, individual quartz and biotite crystals vary in size from 0.5 to 2 mm, and the plagioclase grains of the matrix are 0.1–0.3 mm in diameter. No relict igneous textures have been observed in thin section; all quartz and plagioclase grains show evidence of annealing. Individual biotite and epidote grains have subhedral crystal outlines and show no preferred crystallographic orientation even within aggregates of these minerals. Large orthoclase grains of more than 3 mm diameter have fairly straight boundaries usually and may show weakly developed strain-shadow regions around inclusions of quartz and epidote. Rarely, myrmekitic intergrowths of quartz and feldspar occur. Small (0.1–0.3 mm) grains of feldspar, epidote and mica are randomly scattered throughout the quartz aggregates. Quartz crystals within grain aggregates only rarely show undulatory extinction or the presence of deformation bands; grain boundaries are straight and meet at 120° triple junctions.

ANASTOMOSING SHEAR ZONES

In the Maggia Nappe core, metre-scale shear zones of the same displacement sense show an anastomosing pattern with intervening remnant ‘pods’ or lenses of relatively undeformed rock (Fig. 2). Within these lenses the earlier mineral elongation lineation may be at a small or large angle to the boundary of the surrounding shear zones. There are occasional sets of paired and parallel cm-scale shear zones of the same displacement sense; a typical example is illustrated in Fig. 3. Oblique shear zones with the same sense of displacement often connect the paired shear zones, resulting in a lozenge-shaped

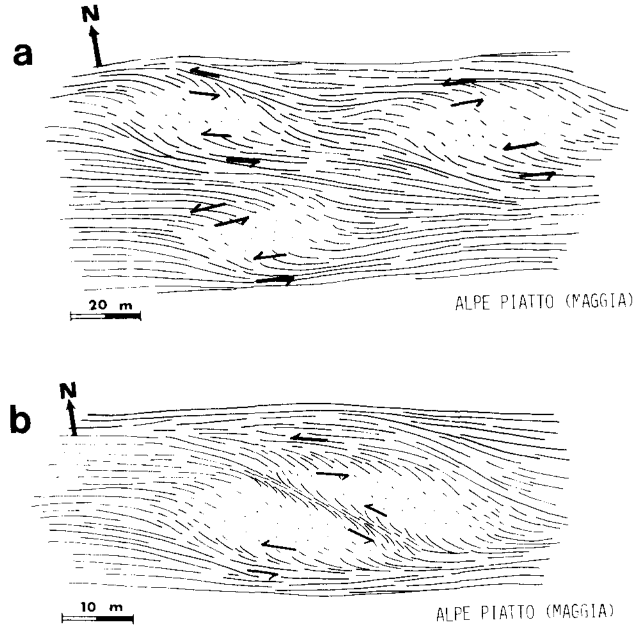

Fig. 2. Field sketches of remnant unsheared pods of granitic gneiss surrounded by sheared, foliated gneiss (central core of Maggia Nappe). (a) Shear zones with same displacement sense anastomose to surround remnant pods of relatively undeformed rock. (b) Small shear zone within relatively undeformed pod has same displacement sense as that of major shear zones surrounding the pod.

outcrop pattern (Fig. 3). A weak planar fabric is sometimes developed between the paired shear zones but is not observed beyond the outermost boundaries of the shear-zone pair.

Towards the central region of the Maggia Nappe core, the shear zones become progressively wider and subparallel to each other and the remnant pods become fewer in number and smaller with more smoothed outlines and more elongate aspect ratios. Within the pods themselves, smaller scale ductile shear zones often occur at small angles to the larger shear zones that surround the pods. With reduction in pod size, the mineral elongation lineation within the pods is rotated towards the movement direction of the surrounding shear zones. This observation suggests a penetrative ductile deformation of the wall rocks to the Maggia shear zones, as noted by Ramsay & Allison (1979).

CHEMICAL AND MINERALOGICAL VARIATIONS ACROSS THE SHEAR ZONE

Major-element and trace-element analyses of several series of specimens from amphibolite-grade shear zones of various compositions within the basement core of the Maggia Nappe have shown that the deformation approximated isochemical and isovolumetric conditions (Kerrich *et al.* 1977, Simpson 1981). Günthert (1954) and Günthert *et al.* (1976) have also made a number of whole rock analyses of specimens from the Maggia Nappe. Although these authors did not specify the deformation state of their samples, it is apparent from the petrographic descriptions that in several instances, sheared and unsheared examples of the same granitic parent rock have been taken (e.g. Günthert *et al.* 1976, fig. 14a). Günthert *et al.* (1976) also stated that there was no significant variation in major-element chemistry in their samples.

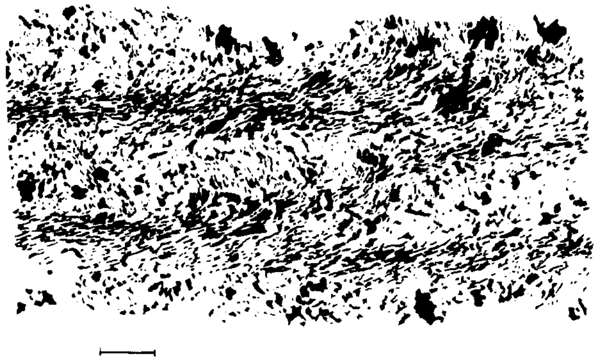

Fig. 3. Two small-scale, parallel dextral shear zones linked by a low-angle shear zone in granodiorite (Laghetti, Maggia Nappe). Tracing from photograph; biotite grain aggregates black, quartz and feldspar not illustrated. Scale bar 2.5 cm. All shear zones are dextral and this geometrical configuration results in remnant elongate lozenge-shaped pods between shear zones. A weak foliation is locally developed between the parallel shear zones at a high angle to the shear-zone boundaries.

The possibility exists that the regional amphibolite facies metamorphism may have post-dated the formation of the shear zones and thus could have caused a re-equilibration of the rather simple mineralogy in the sheared granitic rocks of the Maggia Nappe core. However, it is unlikely that any significant chemical differences between unsheared and sheared rocks at the time of deformation would be completely overprinted by a later metamorphic event. For example, a syntectonic removal of silica and addition of potassium such as reported by Beach (1973, 1976, 1980) for the amphibolite-grade shear zones in NW Scotland, or an increase in TiO, Na_2O and K_2O as reported by Brodie (1980) for sheared phlogopite peridotite in the Italian Alps, should still be detectable even after an annealing event. The lack of any detectable change in the whole-rock chemistry from unsheared to sheared rocks in the Maggia Nappe core suggests that these shear zones were indeed formed under isochemical conditions and did not act as major conduits for fluid transport (Kerrich *et al.* 1977).

In general, the mineralogy as well as the chemistry of rocks in the Maggia Nappe core remains unchanged from unsheared to sheared rock (Simpson 1981). In the mafic rocks, both unsheared and sheared, biotite grains are occasionally observed altered to chlorite and opaque minerals along the cleavage planes and are often seen replaced by blue–green hornblende or by sphene. Neither biotite nor chlorite shows any evidence of internal deformation. Any quartz grains present in the rock also show little or no internal evidence of deformation. In the more felsic rocks, both unsheared and sheared, biotite again shows alteration to chlorite and occasionally sphene, but in these rocks there is no evidence for hornblende growth. Epidote, or clinozoisite, and muscovite commonly replace feldspar grains which are themelves always completely strain free. As in the mafic rocks, the quartz grains in general show little or no evidence of internal deformation.

In a few very small-scale (cm-width) ductile shear zones within otherwise undeformed rocks in the northern region of the Maggia Nappe core, some evidence for internal deformation of the constituent minerals has been found. Some biotite flakes have bent cleavage traces and many of the quartz crystals within quartz-grain aggregates in these small shear zones exhibit deformation bands and subgrains. These observations suggest that the small shear zones formed after the peak of the amphibolite grade metamorphism. An absence of any mineralogical change across these shear zones suggests that they also underwent isochemical deformation. The number of unrecrystallized biotite grains in these late-stage shear zones is small. However, some of the quartz-grain aggregates have retained evidence of the processes by which they changed their shape; this is discussed in some detail in a later section.

BANDED AND FOLIATED GNEISS

There has been much debate in recent years over the origin of compositionally banded gneisses. The layering in a banded gneiss may be entirely tectonic in origin (Johnson 1967, Myers 1976, Vernon 1974, 1976), it may be mimetic after original sedimentary or igneous layering, or it may result from a combination of these effects, with or without metamorphic segregation of material (Bennington 1956, Carpenter 1968, Spry 1969). It is often not possible to determine which of these processes has caused the banding in highly deformed rocks. However, where the protolith is a homogeneous igneous rock, as in the core of the Maggia Nappe, the formation of compositional banding cannot generally be explained by the folding and metamorphism of an originally layered sequence. It appears that most of the compositionally banded and foliated orthogneisses in the Maggia Nappe have arisen from progressive deformation in shear zones; evidence for this is presented in the next section.

Transition from granite to foliated gneiss

A foliation defined by ribbon-like aggregates of mica, quartz and feldspar is first observed to develop at the margins of the steeply dipping shear zones (Ramsay & Allison 1979). This new foliation becomes progressively more intense with increasing strain, and in the centre of most shear zones the original intrusive relationships of aplitic veins and dykes become obliterated as all structures become subparallel to the micaceous foliation surfaces. At shear strains greater than $\gamma = 5$ the rock can be categorized as a compositionally-banded gneiss. The presence of highly strained xenoliths within these banded gneisses confirms their igneous origin. Thus, in the Maggia Nappe the deformation of an originally homogeneous granite produces a foliated gneiss, whereas a compositionally-banded gneiss is only formed where the granite originally contained dykes and/or xenoliths.

Transition from composite dykes to banded gneisses

Composite mafic/felsic dykes are often observed to cut the late-Hercynian diorite and granodiorite in the core of the Maggia Nappe. The dykes appear to have had a complex injection history; angular to rounded blocks of mafic biotite–microdiorite are completely surrounded and often invaded by felsic quartz–biotite–microgranodiorite which almost always occurs along the dyke margins with a sharp contact (Fig. 4a). The development of a compositionally banded gneiss from undeformed composite dykes is particularly well displayed in several localities within the core of the Maggia Nappe. The geometrical features indicative of originally intrusive relationships become progressively obliterated with increasing deformation, as the dykes are deflected into steeply dipping shear zones. Mafic inclusions are elongated and flattened and a planar anisotropy is observed (Fig. 4b). With increasing strain, the components of the dyke become more difficult to distinguish. Individual colour bands are relatively short at low strains (γ less than 2) but at progressively higher strains (γ between 2 and 3) the length of single colour bands increases as the mafic components become extremely elongated and thinned. At higher strains (γ greater than 5), a compositionally banded mafic/felsic gneiss is developed (Fig. 4c).

MICROSTRUCTURAL TEXTURAL CHANGES ACROSS A SHEAR ZONE BOUNDARY

Figure 5 illustrates the change in shape fabric across a typical small-scale, late-stage shear zone in granitic rock from the relatively undeformed Laghetti region of the Maggia Nappe (Fig. 1). The quartz and mica grain aggregates are approximately equidimensional in the unsheared rock. The shear zone boundary is defined as the position where the first visible foliation is observed and the initially non-planar fabric is changed into a planar fabric. With increasing shear strain the degree of planar anisotropy increases and the quartz and biotite grain aggregates become progressively more ribbon-like.

Microstructures adjacent to the shear zone boundary

Figure 7(a) illustrates randomly scattered epidote and feldspar grains within a quartz grain aggregate that has been unaffected by the shearing deformation (position A on Fig. 5). The microstructures in this unsheared rock have been described above.

In the unsheared rock immediately outside the shear zone boundary (position B on Fig. 5), no visible change could be detected in the aspect ratios of quartz, biotite or muscovite on the hand specimen scale. In thin section, the mica flakes show a very weak preferred orientation, with a tendency for their long axes to be aligned at 25–35° to the traces of the shear zone boundary. Epidote grains remain randomly oriented. Many of the large feldspar grains contain cores of 0.2 mm diameter, with equant

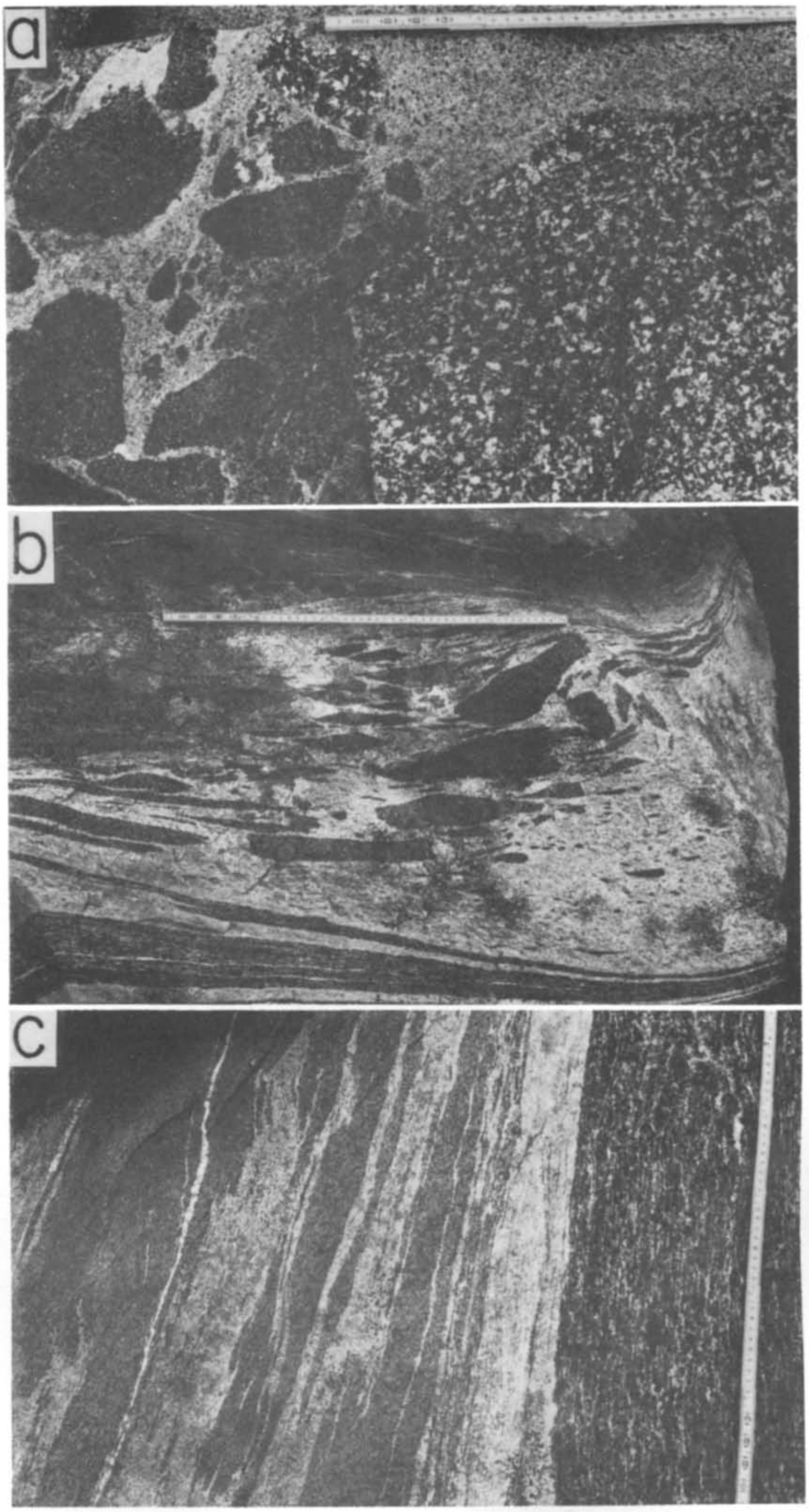

Fig. 4. Development of compositionally-banded gneiss by progressive strain of composite dyke and diorite host rock in ductile shear zones (Laghetti, Maggia Nappe). (a) Undeformed composite dyke of mafic lamprophyre and diorite blocks in felsic lamprophyre matrix, cutting undeformed diorite. (b) Deformation of composite dyke in two dextral shear zones; mafic inclusions are increasingly flattened with increasing shear strain. (c) Composite dyke in dioritic host rock (right portion of photograph) deformed in a 4-m wide shear zone; original intrusive relationships have been obliterated and the rock is a compositionally banded gneiss. Folding rule numbered in cm.

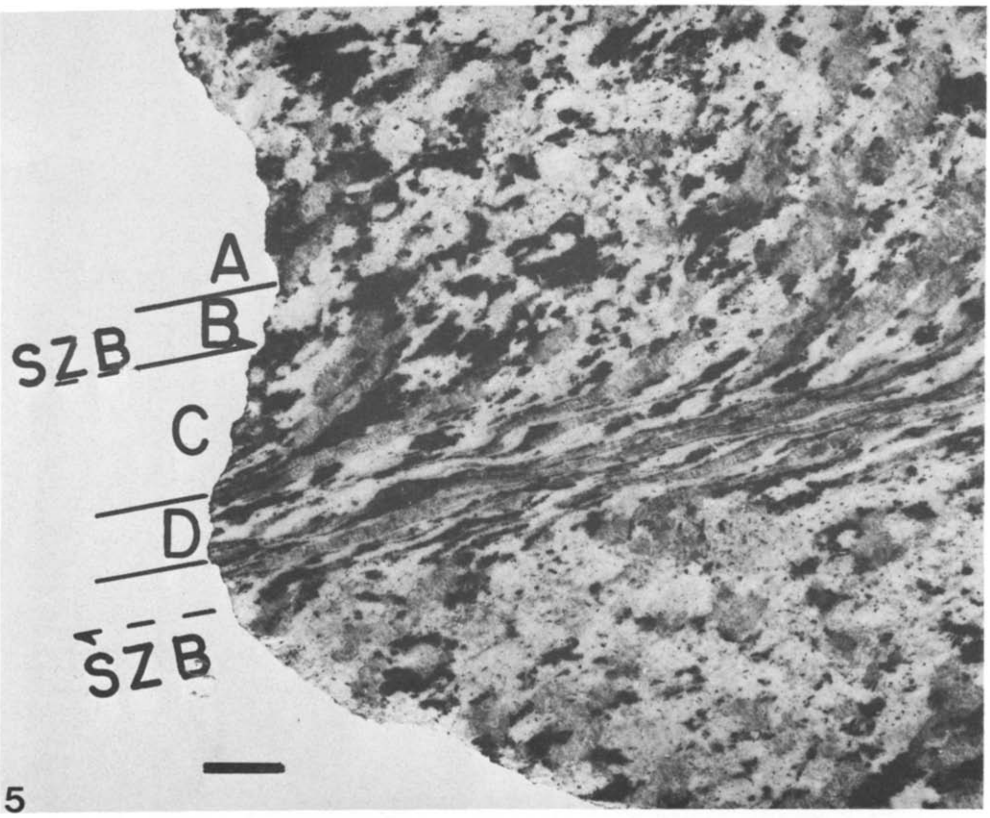

Fig. 5. Polished surface of hand specimen illustrating the change in shape fabric of quartz-grain (medium grey) and biotite-grain (black) aggregates in a feldspar matrix (pale grey) across a small dextral shear zone in Maggia granitic basement. Positions A, B, C and D are referred to in text. SZB = shear zone boundary. Scale bar 1 cm.

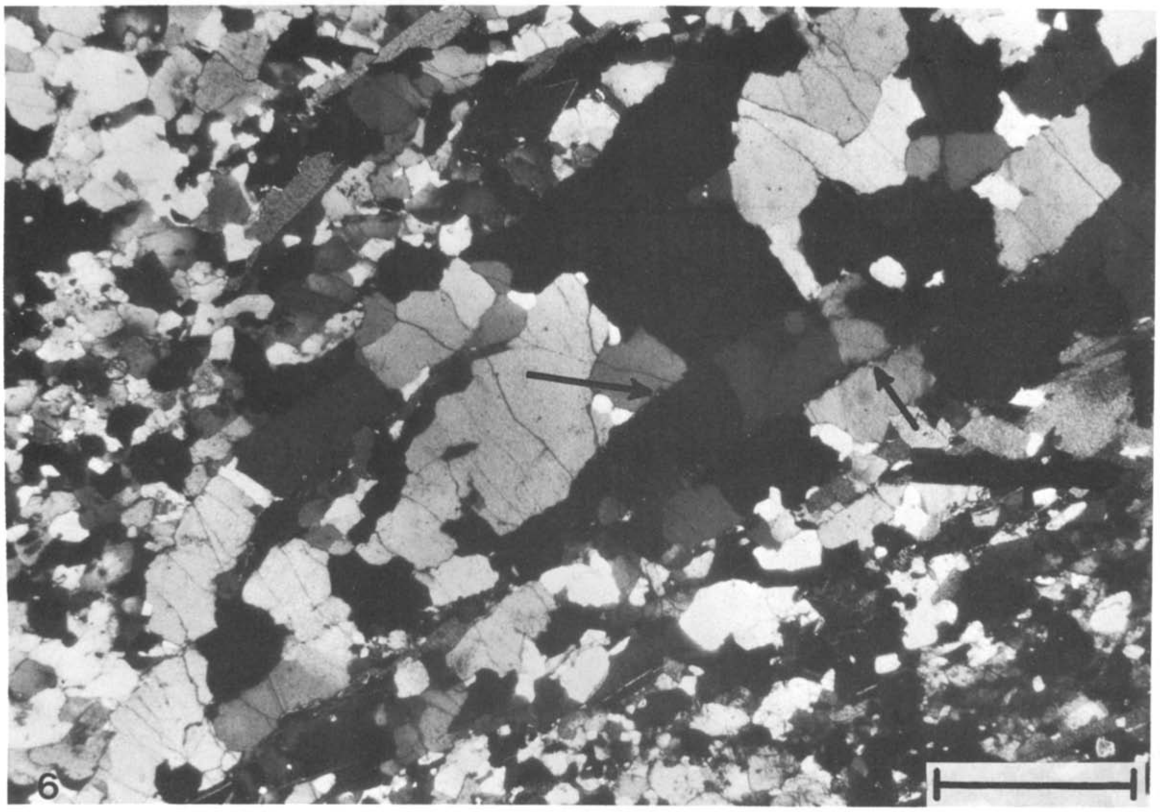

Fig. 6. Photomicrograph of part of a tear-drop shaped quartz aggregate at the boundary of the ductile shear zone in Fig. 5. Note the presence of *F* surfaces (arrowed) within the deformed aggregate. Crossed nicols, scale bar 0.5 mm.

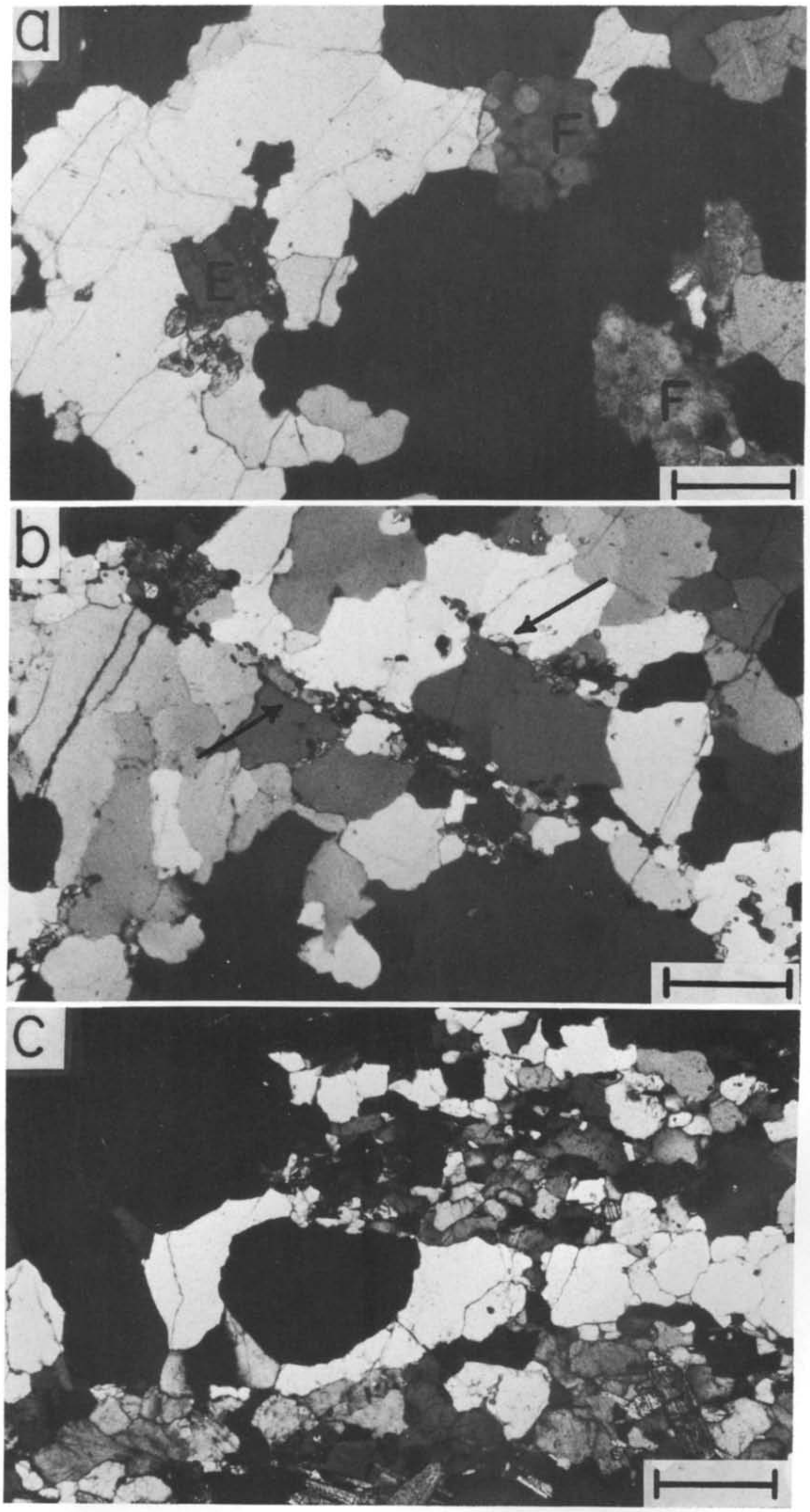

Fig. 7. (a) Part of a quartz-grain aggregate in undeformed granitic gneiss (position A on Fig. 5); epidote (E) and feldspar (F) grains are scattered in a random distribution. (b) Small aggregates of epidote and feldspar grains concentrated along imperfectly defined planes (arrowed) within quartz-grain aggregates adjacent to, but outside, the shear-zone boundary (position B on Fig. 5). (c) The beginning stage in the formation of retort-shaped quartz-grain aggregates (position C on Fig. 5); a short 'tail' of quartz grains (clear) is separated from the main quartz aggregate in a matrix of fine grained feldspar and epidote (darker grey). (a), (b) and (c) have crossed nicols and scale bars 0.5 mm.

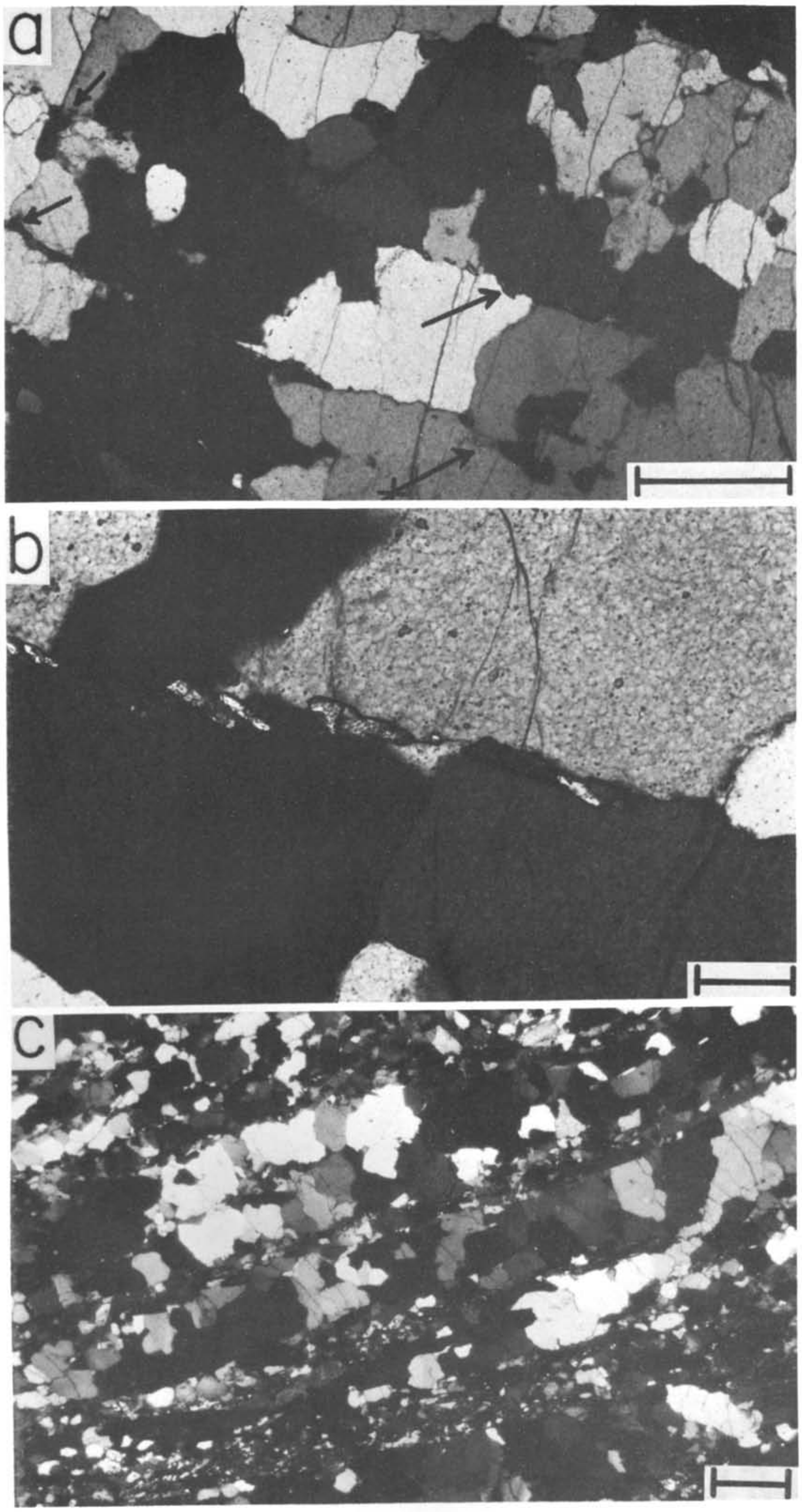

Fig. 9. (a) Two *F* surfaces (arrowed) in quartz-grain aggregates at the shear zone boundary. The lowermost *F* plane terminates within a quartz grain (star-arrow). Note the optical misorientation of adjacent quartz grains across the uppermost *F* plane. (b) Close-up of an *F* plane in (a) above, to show imbricate or en echelon structure of epidote grains along this surface. (c) Quartz in ribbon-like aggregates within the central portion of the shear zone (position D on Fig. 5); quartz 'ribbons' are in a matrix of biotite, epidote and fine-grained feldspar. Scale bars (a) 0.5 mm, (b) 0.1 mm and (c) 0.8 mm, each with crossed nicols.

subgrains that show a progressive misorientation towards the grain boundaries.

Within quartz-grain aggregates at position B on Fig. 5, small grains of epidote and feldspar are often concentrated along short, imperfectly defined planes (arrowed on Fig. 7b). The amount of epidote and feldspar within quartz aggregates adjacent to the shear zone boundary remains the same as within quartz aggregates farther away from the shear zone. These small epidote and feldspar grains occur along quartz–quartz grain boundaries and within quartz grains and have an average grain size of 0.05 mm; that is they are considerably smaller than those seen originally randomly distributed in the quartz-grain aggregates away from the shear zone. No preferred orientation of the long axes of epidote grains could be observed. These very short and discrete trails of epidote and feldspar are often seen to occur in pairs with a very regular spacing of about 0.3 mm, between which the quartz crystals may have a tabular aspect with deformation bands and grain boundaries aligned subperpendicular to the trails. A slightly higher proportion of the quartz grains show deformation bands and subgrains than in region A of the specimen.

Microstructures at the shear zone boundary

At the shear zone boundary (position C on Fig. 5) biotite, epidote and occasional muscovite grains show a fairly well developed preferred shape orientation. Their long axes are aligned at 20–40° to the shear zone boundary in an orientation consistent with the sense of shear. The beginning stages of the formation of 'retort'-shaped quartz aggregates can be seen at the edges of some of the quartz lenses (Fig. 7c). Short 'tails', which are usually one, or rarely two, grains in width, are separated or drawn out from the main quartz aggregate. Individual quartz-grain aggregates take the form of 'tear-drop' shapes as they cross the shear zone boundary (Fig. 8). Within the 'tear-drop' quartz aggregates, biotite, epidote and a small amount of muscovite and feldspar, lie along discrete planes which are parallel to the long edges of the quartz aggregate and have a more or less constant spacing at 0.3 mm (Fig. 6). These planes (here designated *F* planes) seem to be a further development of the imperfectly defined trails of epidote and feldspar seen adjacent to the shear zone boundary. They are defined both by the presence of the new mineral species and by the optical misorientation of adjacent quartz grains (Fig. 9a).

Deformation bands, elongate subgrains, and new grains in the quartz aggregate are at a high angle to the *F* planes. The mica and epidote crystals are not always distributed continuously along the *F* planes and occasionally an *F* plane with its trails of small other phases may end within a single quartz grain, or cut across a single quartz grain. Where an *F* plane cuts across a quartz grain there is no apparent offset of that grain. Where an *F* plane ends within a quartz grain, a network of healed microcracks with 100 μm biotite and epidote grains in the vicinity is sometimes observed (marked with a star-arrow on Fig. 9a). The ends of the *F* planes are often surrounded by strain shadows and subgrains in the host quartz crystal. Most of the mica and epidote grains have their long axes parallel to the *F* plane but, in a few instances, small (20 × 100 μm) epidote grains show a preferred orientation of their long axes at about 25° to the *F* plane (Fig. 9b). The resultant imbricate structure of the epidote grains is oblique to the *F* plane in the opposite sense to that expected from the sense of shear across the zone, although each crystal has its long axis subparallel to the shear zone boundary. The orientation of the shear zone boundary with respect to that of the *F* planes and the imbricated epidote crystals is illustrated in the sketch in Fig. 10.

Single lines and planes of 2 × 5 μm solid inclusions (thought to be epidote from their bluish interference colour) are observed very occasionally within the quartz aggregates at the shear zone boundary and are parallel to the *F* planes with the same 0.3-mm spacing. The long

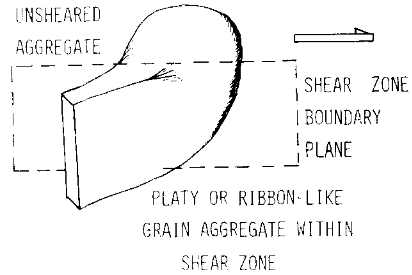

Fig. 8. Schematic diagram to illustrate the formation of a 'tear-drop' shaped aggregate of quartz grains at the boundary of a ductile shear zone in Maggia granitic gneiss (position C Fig. 5). The overall shape change of the quartz aggregate is from equidimensional outside to platy inside the shear zone.

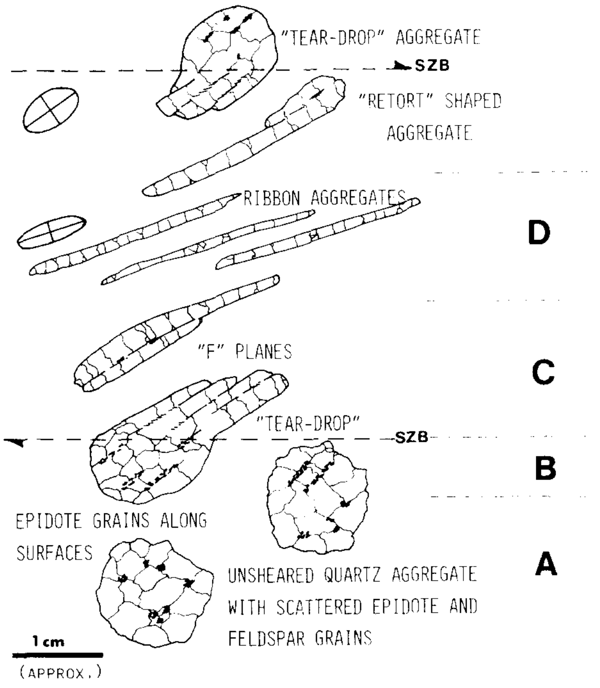

Fig. 10. Schematic diagram, drawn only approximately to scale, to illustrate quartz-grain aggregate shape changes across the small ductile shear zone of Fig. 5. SZB = visible shear zone boundary. Zones A = unsheared rock, B = adjacent to shear zone boundary, C = shear zone boundary region, D = centre of shear zone.

axes of the minute inclusions show a preferred alignment along the length of the inclusion lines, suggesting that these lines represent incipient *F* planes within the quartz aggregates. No evidence has been found for the existence of any similar structures in the unsheared rock.

A progressive reduction in the grain size of plagioclase, from 0.2 to 0.08 mm, is observed across the shear zone boundary. These feldspars are always strain-free with straight grain boundaries that meet in 120° triple junctions. The presence of similar *F* plane-features is more difficult to establish in this fine grained material. Diffuse epidote- and biotite-rich zones are oriented subparallel to the margins of the adjacent quartz aggregates. Similarly oriented trails of epidote have been observed to cross relict K-feldspar porphyroclasts. The presence of these epidote trails in the shear-zone boundary region of the rock and their absence in the unsheared rock suggests an origin similar to that of the *F* planes in the quartz aggregates.

Microstructures in the centre of the shear zone

Within the centre of the shear zone, polygonal plagioclase and orthoclase grains in the matrix adjacent to quartz ribbon aggregates have an average grain size of 0.08 mm and have grain boundaries which meet at 120° triple junctions. Myrmekitic intergrowths of quartz and feldspar are extremely common in the matrix, more so than in the unsheared rock. Although myrmekites and muscovite are found together in the same rock, no direct association between the two minerals has been observed in thin section and a large proportion of orthoclase remains. Large relict orthoclase porphyroclasts are rare, as are large old biotite grains. The long axes of mica and epidote grains show a preferred orientation subparallel to the long axes of the quartz ribbon aggregates and thus produce a foliation. The width of the quartz ribbons is variable (Fig. 9c) but tends to be about 0.3 mm, the same as the spacing between *F* planes in quartz aggregates at the shear zone boundary. It appears as though the quartz ribbons in the centre of the shear zone are the result of intercrystalline slip along several *F* planes in the original quartz aggregates. Many of the quartz grain boundaries are pinned by micas oriented parallel to the ribbon edges, as well as by epidote and feldspar grains. Deformation bands and elongate subgrains in the quartz tend to be subperpendicular to the edges of the ribbons. Small quartz grains (average size 0.15 mm) around the margins of larger grains display only very slight variations in crystallographic orientation with respect to their host, suggesting that the small grains formed syntectonically by progressive rotation and misorientation of subgrains (Poirier & Nicolas 1975). Deformation lamellae have not been found in any of the quartz grains within the shear zone.

QUARTZ C-AXIS PREFERRED ORIENTATIONS

Quartz *c*-axes measured from the unsheared rock at position A on Fig. 5 show a tendency to lie in an ill-defined great circle (Fig. 11a). Other specimens of unsheared rock taken from various positions parallel to the length of the same shear zone have quartz *c*-axis distributions that are either entirely random or else show a tendency to form poorly developed great circles of differing orientation with respect to the shear zone boundary. Unsheared rock from several m outside the shear zone, containing a weak linear fabric, has quartz *c*-axes that tend towards a small-circle distribution about the lineation (Simpson 1980). No consistent quartz *c*-axis fabric has been found for the unsheared rock in this region of the Maggia Nappe core, indicating that the quartz grains have a more-or-less random crystallographic orientation outside the shear zone.

Quartz *c*-axes have been measured from samples taken immediately outside the shear zone boundary where the first evidence for the formation of imperfectly defined *F* planes occurs (position B on Fig. 5). No significant development of a preferred crystallographic orientation of the quartz grains was observed in these samples, despite the existence of occasional deformation bands and subgrains in the quartz aggregates. However, at the shear zone boundary itself (position C on Fig. 5),

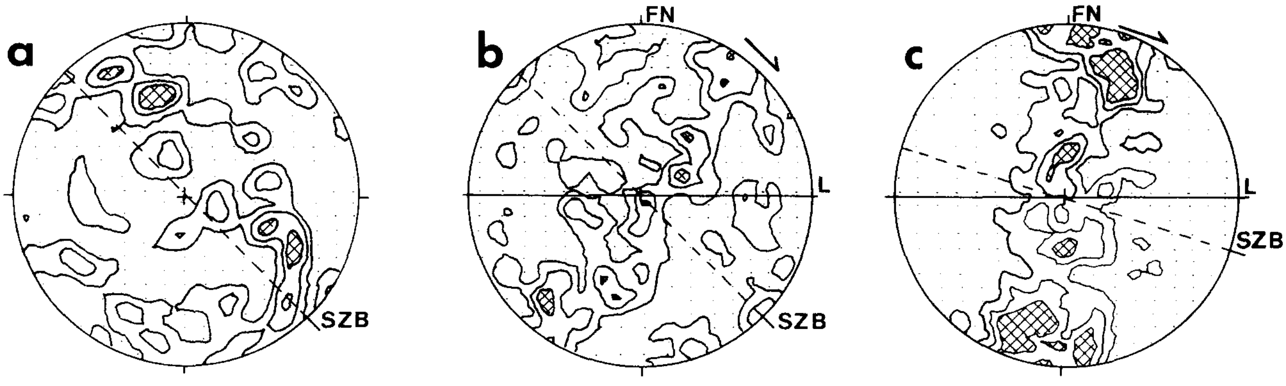

Fig. 11. Lower-hemisphere equal-area stereographic projections of quartz *c*-axes, measured across the shear zone illustrated in Fig. 5. (a) In unsheared wall rock (area A in Fig. 5), 120 *c*-axes contoured at 1, 2, 3 points per 0.8% area. (b) At the shear zone boundary (area C in Fig. 5), 306 *c*-axes contoured at 1, 2, 3 points per 0.3% area. (c) Within centre of shear zone (area D in Fig. 5), 445 *c*-axes contoured at 1, 2, 3 points per 0.2% area. Solid line is foliation trace (vertical E–W), dashed line marked SZB is shear zone boundary trace, FN = foliation normal, L = lineation (horizontal E–W). Sense of shear is dextral.

the quartz *c*-axes show a tendency to lie in a weakly developed single girdle (Fig. 11b) aligned approximately perpendicular to the shear zone boundary and oblique to the foliation-normal in the centre of the shear zone. The sense of obliquity of this girdle distribution of quartz *c*-axes is the same as the sense of shear, i.e. dextral.

In the centre of the shear zone (position D on Fig. 5) the quartz *c*-axes form a well-defined single-girdle preferred-orientation pattern with a tendency for *c*-axis maxima close to the foliation-normal (Fig. 11c). The *c*-axis girdle is again subperpendicular to the shear zone boundary and oblique to the foliation-normal, in a dextral sense.

DISCUSSION

The majority of the foliated and compositionally banded gneisses in the central core of the Maggia Nappe appear to have formed within an anastomosing network of ductile shear zones of Alpine age. Simultaneous movement on sets of anastomosing shear zones with the same displacement sense could more easily accommodate a bulk shape change in the rock than simultaneous movements along conjugate sets with opposite senses of displacement. Recent small-scale experiments using dry sand have shown that it may be possible for contemporaneous movement to occur along crossing conjugate faults with the development of complex interference structures in the intersection zone (Horsfield 1980). Well-developed systems of conjugate shear zones with opposite senses of shear in naturally deformed rocks have been documented (e.g. Ramsay & Graham 1970, Mitra 1979, Ramsay & Allison 1979) but in each case movement on one set occurs before movement on the other set. Conjugate systems of ductile shear zones are not commonly developed in the area of the Maggia Nappe studied, and convincing evidence has not been found for simultaneous movement on the few conjugate sets that have been observed in this region. Anastomosing shear zones with the same displacement sense appear to be responsible for the formation of lozenge- or pod-shaped deformation patterns in these deformed basement rocks.

Formation of a new foliation within the shear zones occurs primarily by a change in shape of quartz and biotite aggregates. The first effect of the shear-zone deformation on the microstructures occurs in the rock immediately outside the visible shear zone boundary, where the imperfectly defined *F* surfaces first appear. At the shear zone boundary, the concentration of epidote and mica increases along longer, well defined and regularly spaced *F* planes which are marked by a change in optical orientation of the quartz crystals. The change in grain-aggregate shapes from equidimensional to 'teardrop' shapes occurs together with the appearance of the *F* planes. Local diffusion of material along these surfaces in response to chemical potential gradients set up as a result of the imposed stress (or temperature) gradient, may have aided the crystallization of the epidote and mica crystals (Carpenter 1968). The presence of microcracks at the termination of some of the *F* planes could indicate that these planes once acted as sliding surfaces. Intergranular slip along the *F* surfaces would have been facilitated by the presence of the new mineral species, especially the micas. Each quartz aggregate was probably transformed into several ribbons separated by *F* planes. Individual ribbons could then move laterally and become physically separated with increasing strain towards the centre of the shear zone.

The polygonal microstructure of the plagioclase and orthoclase grains in the matrix adjacent to the quartz ribbons suggests recovery by progressive misorientation and rotation of subgrains (Poirier & Nicolas 1975). However, at least some of the feldspars now have high-angle grain boundaries indicative of recrystallization. Recrystallized feldspars have a considerably smaller grain size than do the recrystallized quartz grains in these shear zones. A similar relationship has been noted from other amphibolite- or higher-grade shear zones (Christie & Ord 1980, Etheridge & Wilkie 1981). As the quartz-grain aggregates changed their shape and were transformed into ribbons with progressive increase in strain, the deformation in the finer-grained feldspar-rich matrix could have been accommodated easily by grain-boundary sliding. The separation of individual ribbons of quartz grains would also be facilitated by the operation of grain-boundary sliding in the feldspar matrix. The increased proportion of myrmekitic feldspar/quartz intergrowths in the centre of the shear zones suggests that at least on a local scale, feldspar-replacement reactions may have operated in these rocks (Becke 1908, Carpenter 1968, Phillips 1980.) However, the lack of any systematic chemical changes in the shear zones as a whole suggests that any replacement reactions could only have operated on a grain-to-grain scale.

A single-girdle pattern of quartz *c*-axes first develops at the shear-zone boundary and is more strongly developed with increasing strain, indicating internal deformation of the quartz by intracrystalline glide. The observed maximum of quartz *c*-axes close to the foliation-normal (Z) is consistent with deformation of the quartz by predominantly basal slip in the *a* direction (Tullis *et al.* 1973, Tullis, 1977). The observed weak maximum close to the intermediate strain axis Y, suggests that the basal planes of these quartz grains were perpendicular to the foliation and parallel to the finite stretching direction. Basal slip would therefore be unlikely to operate in these grains and slip probably occurred on prismatic $\{10\bar{1}0\}$ planes, again in the relatively easily activated *a* direction (Tullis *et al.* 1973, Wilson 1975, Bouchez 1977, Burg & Laurent 1978, Bouchez & Pecher 1981). The absence of any detectable quartz preferred orientation outside the shear zone boundary where the first *F* planes are observed, suggests that these surfaces were developed at a much lower strain than that required to produce a preferred orientation in the quartz crystals. Intercrystalline slip along the *F* planes probably occurred at the same time as the quartz crystals deformed by intracrystalline glide.

CONCLUSIONS

The formation of a new foliation within ductile shear zones in originally unfoliated granitic gneiss in the Maggia basement has been accomplished through the interplay of several processes, including recrystallization of mica and epidote with a dimensional preferred orientation, and a change in shape of initially equidimensional quartz-grain aggregates to platy or ribbon-like aggregates by a combination of intracrystalline plastic deformation and intercrystalline slip on inclusion-rich surfaces. As the quartz aggregates changed their shape, the feldspar matrix deformed predominantly by grain-boundary sliding. The majority of the foliated gneisses in the Maggia Nappe core probably formed by the same combination of deformation processes. The bulk shape change in the rock was accommodated by movement on sets of anastomosing shear zones with the same displacement sense surrounding remnant pods of relatively undeformed rock.

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