Pergamon

Journal of Structural Geology, Vol. 19, No. 9, pp. 1149 to 1157, 1997

0191-8141/97 $17.00 + 0.00

PII: S0191-8141(97)00035-7

Quartz fabric and strain partitioning in sheath folds: an example from the Voltri Group (Western Alps, Italy)

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(*Received* 23 *April* 1996; *accepted in revised form* 7 *April* 1997)

Abstract—A mesoscopic sheath fold, defined by an almost pure quartzitic level in quartz–mica-schists of the Voltri Group (southeastern border of the Western Alps), was sampled and studied in detail. Microstructural analysis was carried out on thin sections from different structural domains in the quartzitic layer, with the emphasis to analyse quartz-shape fabrics and the crystallographic preferred orientation of the *c*-axes of this mineral. Quartz was dynamically recrystallized but its degree of preferred orientation is not as high as it would be expected in a high shear-strain regime required for the development of sheath folds. This may suggest strain partitioning between the quartzitic level and the micaceous matrix.

Crystallographic preferred orientation of *c*-axes and grain-shape fabric asymmetry indicate the same sense of shear on both fold limbs in the *XZ*-plane; this is in agreement with a model of sheath-fold development by the passive rotation of material lines.

Clustering of the *c*-axis poles shows a configuration indicative of a different strain state in different domains of the sheath fold and suggests an evolution of the fold characterized by combined simple shear and coaxial progressive deformation. © 1997 Elsevier Science Ltd.

INTRODUCTION

The occurrence of highly non-cylindrical folds has been described from the Western Alps (Minnigh, 1979; Harris, 1985; Lacassin and Mattauer, 1985; Capponi *et al.*, 1994) and other shear belts (Rhodes and Gayer, 1977; Ghosh and Sengupta, 1984; Hibbard and Karig, 1987; Skjernaa, 1989). Sheath-, eye-, eyed- and tubular folds are current names used to describe the shape of these non-cylindrical folds. For most of the authors, these terms imply a geometrical rather than a genetic meaning. Folds with these geometrical features can be found in different structural frameworks and are essentially formed by one of the following mechanisms.

(1) The interference of superposed fold systems. If axes and axial planes of interfering fold systems have suitable attitudes, a dome and basin interference pattern will result (type 1 after Ramsay, 1967). A regular repetition of domes and basins is considered to be a diagnostic feature of type 1 interference patterns (Ramsay and Huber, 1987).

(2) Deformation in field 3 of the strain-ellipse fields (Ramsay, 1967). If all directions in a surface undergo contraction, dome- and basin-like structures may form (Ramsay and Huber, 1983). Usually, these structures have less regular shapes than the dome and basin patterns that form by fold interference. However, more or less regular repetition of eye-shaped structures can be expected in cross-section.

(3) Deformation of pre-existing folds in a high shear-strain regime. As supported by Escher and Watterson (1974), Cobbold and Quinquis (1980), Ramsay (1980) and Skjernaa (1989), high shear-strain regimes can change the shape of pre-existing morphological features. In this way, folds with a gently curving axis can develop into strongly non-cylindrical, tight dome and basin structures. The timing between development of the original folds and their successive deformation can be short and the entire evolution can be regarded as a process of progressive deformation. High shear strains are characteristic of ductile shear zones, where non-cylindrical folds are common (Hudleston, 1986). Usually, such folds do not show a regular geometric arrangement and can develop in response to inhomogeneities in the rock.

The non-cylindrical fold that is the subject of this paper occurs in the metasediments of the Voltri Group (Fig. 1). Capponi *et al.* (1994) studied the characteristics of this and other sheath folds (Fig. 2) and suggested that hypothesis (3) (a sheath fold resulting from the deformation of pre-existing folds in a high shear-strain regime) is the most likely mechanism for their formation. The occurrence of sheath folds is in agreement with the observation (Capponi, 1987) that the metasediments acted as preferred sites of shear-strain concentration during the structural evolution of the Voltri Group.

GEOLOGICAL SETTING

The Voltri Group (Chiesa *et al.*, 1975) is a meta-ophiolitic massif, outcropping in central Liguria (Italy) at the southeastern end of the arc of the Western Alps. The main lithological associations are serpentinites with metagabbros and eclogitic lenses, metaperidotites (lherzolites with minor pyroxenite and dunite bodies), and metasediments with metabasite intercalations. The metasediments belong to the 'Schistes Lustrés' complex and

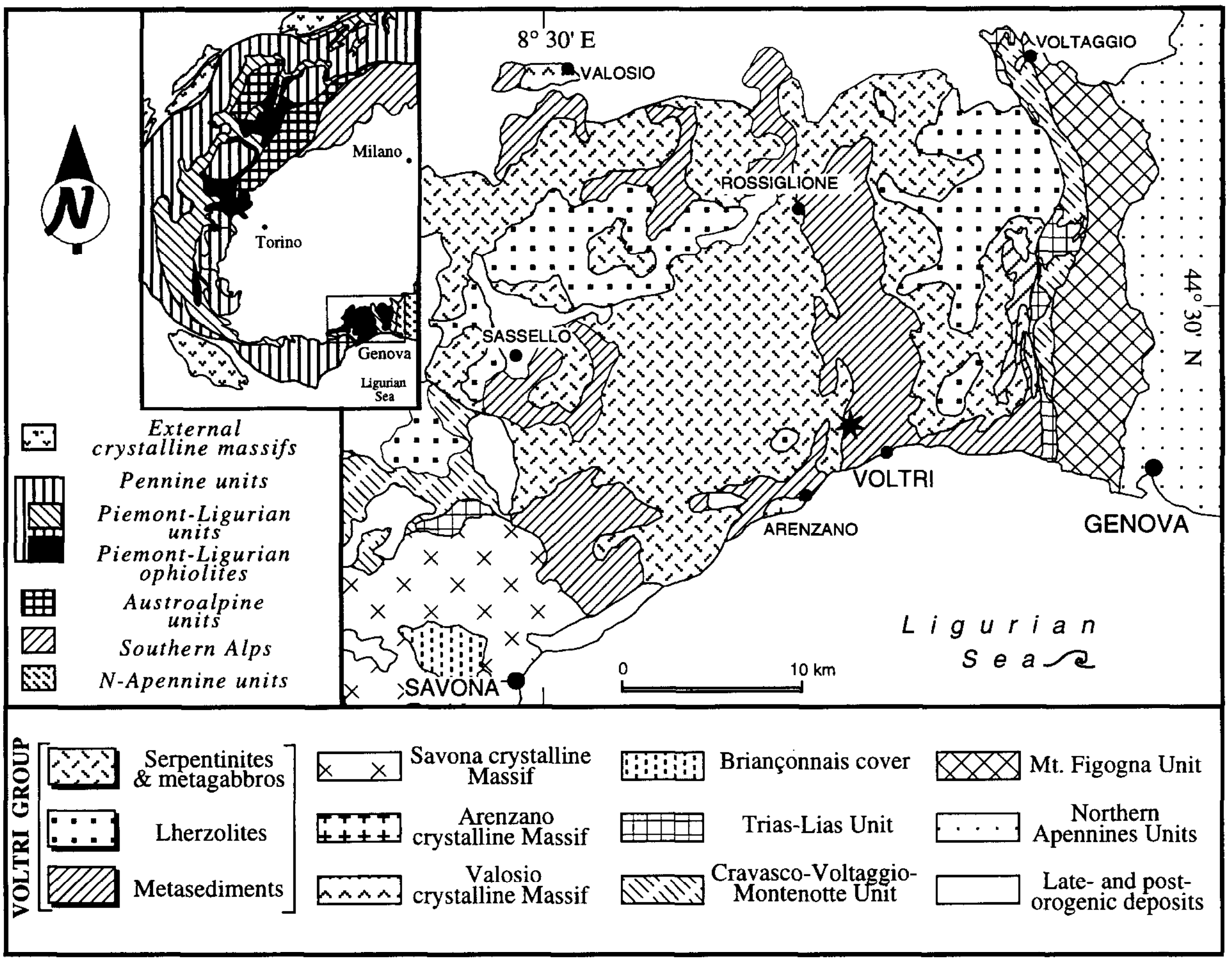

Fig. 1. Tectonic sketch map of the Voltri Group and adjacent units. The inset show a simplified tectonic map of the Western Alps.

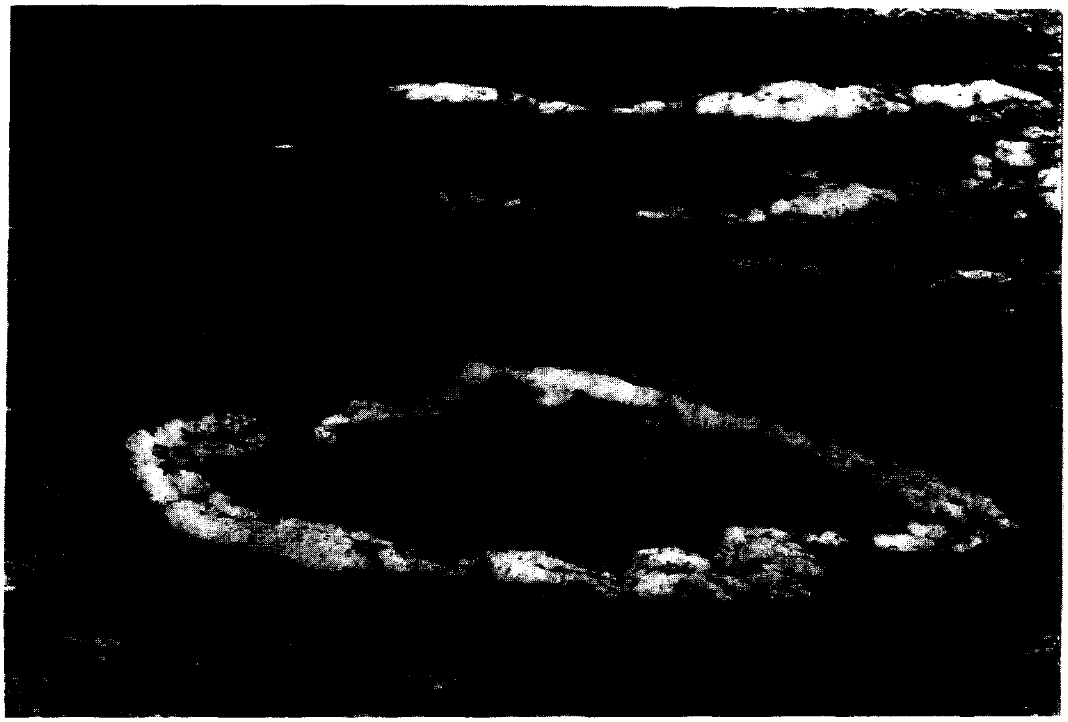

Fig. 2. View of the outcrop investigated for the study of the sheath fold in the metasediments northwest of Voltri. The sampling site is indicated by a star in Fig. 1.

include both the original sedimentary cover of the Liguria–Piemont ophiolitic basement and slices of thinned continental crust. They are characterized by a variable percentage of white mica, calcite and quartz, showing typical gradations from calc-schists to mica-schists and quartz-schists. Serpentinites, metabasites and metasediments belong to the oceanic domain, formed during the Jurassic between Palaeo-Europe and the Apulian microplate (Liguria–Piemont Domain, according to Vanossi *et al.*, 1984). The lherzolites are interpreted to represent a section through the upper mantle of the Apulian microplate (Piccardo *et al.*, 1990). All these rocks were involved in the Alpine subduction-related tectonic events and underwent, to different degrees, metamorphic re-equilibration under eclogite–blueschist-facies (HP–LT) conditions, followed by decompression down to greenschist-facies conditions during the exhumation of the subducted slices (Cortesogno *et al.*, 1977; Messiga *et al.*, 1983; Piccardo *et al.*, 1988; Messiga and Scambelluri, 1991). At present, greenschist-facies assemblages prevail at a regional scale within the studied metasediments (Capponi, 1991).

FOLDING EVOLUTION IN THE METASEDIMENTS

The metasediments of the Voltri Group show a complex deformation history mainly developed during a rotational strain regime (Hoogerduijn Strating, 1990; Crispini, 1995). Structural analysis shows evidence of five different superimposed folding events, developing since the high-pressure stages of the tectono-metamorphic evolution. Paucity of outcrop, heterogeneous distribution of deformation and non-diagnostic metamorphic assemblages within metasediments often preclude a correct understanding of deformation–metamorphism relationships at the scale of the massif. However, in general, the structures related to the high-pressure metamorphic stages (i.e. the structures related to the first two folding events) are present only as relics in certain domains (Capponi, 1987; Crispini, 1995), whereas the three last folding events are contemporaneous with greenschist-facies (GF) metamorphism and are pervasive at the scale of the massif.

The earlier GF folds (F_1 and F_2 of Capponi, 1987, 1991) are tight to isoclinal in shape, with schistosity parallel to the axial plane; locally they are characterized by eyed shapes, as described by Capponi *et al.* (1994). In a few outcrops the GF folds show their mutual overprinting relationships by type 3 and, rarely, type 2 interference patterns (Ramsay, 1967). Some meso- and microstructures related to F_1 and F_2, such as asymmetric δ- and σ-type mantled porphyroclasts, are characteristic of non-coaxial progressive deformation (Simpson and Schmid, 1983; Passchier and Simpson, 1986; Hanmer and Passchier, 1991) and suggest that they developed in a shear-strain regime characterized by values of $\gamma \approx 10$ (calculated from shear zones and inclusion patterns in rotated porphyroblasts; Crispini, 1995). The F_3 folding event represents the last synmetamorphic deformation and is characterized by long-wavelength parallel folds, gentle to open in shape; the main deformation mechanism is flexural-slip/flow. No evident schistosity is related to these folds except for a local rough fracture cleavage.

LITHOLOGICAL AND GEOMETRICAL FEATURES

The studied mesoscopic fold is related to the F_2 folding event, but shows no overprinting by younger folds. It was sampled in quartz–mica-schists which are composed mainly of white mica (phengite and muscovite), Mg-chlorite, quartz and minor rutile and graphite; in the field, mesostructures are outlined by pure quartzitic layers, 0.5–3 cm thick. The fabric of the quartz–mica-schists resembles a type II *S*–*C* arrangement of Lister and Snoke (1984). White mica–chlorite and quartz are arranged in alternating layered microdomains; in quartz-rich microdomains grains are elongated and lie oblique to white mica and chlorite grains, which are parallel to the main GF foliation (Fig. 3).

The XY-plane of the finite-strain ellipsoid derived from the main schistosity is parallel to the axial plane of the fold. The X-direction of the finite-strain ellipsoid is outlined by the stretching lineation and is parallel to the long dimension of the fold. The fold was cut in serial slices normal to the X-direction of the finite-strain ellipsoid in order to study its three-dimensional geometry and related microstructures (Fig. 4). Angular values and ratios between parts of the fold as measured along the X-, Y- and Z-directions are shown in Fig. 5(a). A fold with these geometrical features can be correctly referred to as a sheath fold, according both to Ramsay and Huber (1987) and to Skjernaa (1989). The position of the fold in the PQR diagram after Williams and Chapman (1979) is shown in Fig. 5(b). If we use the same data as in relationship (1) of Lacassin and Mattauer (1985), we obtain a γ value of 8–9. This result is similar to the shear strain derived from other structures observed in the metasediments of the Voltri Group (Crispini, 1995).

MICROSTRUCTURAL ANALYSIS

Microstructural analysis was carried out on thin sections cut from different parts of the sheath fold. The sections were cut from the quartzitic layer which outlines the shape of the fold. The following analyses were carried out:

(1) quartz-shape fabric analysis using an optical microscope;

(2) quartz-shape fabric analysis using Surfor and Paror methods outlined by Panozzo (1983, 1984) on photographic enlargements of thin sections;

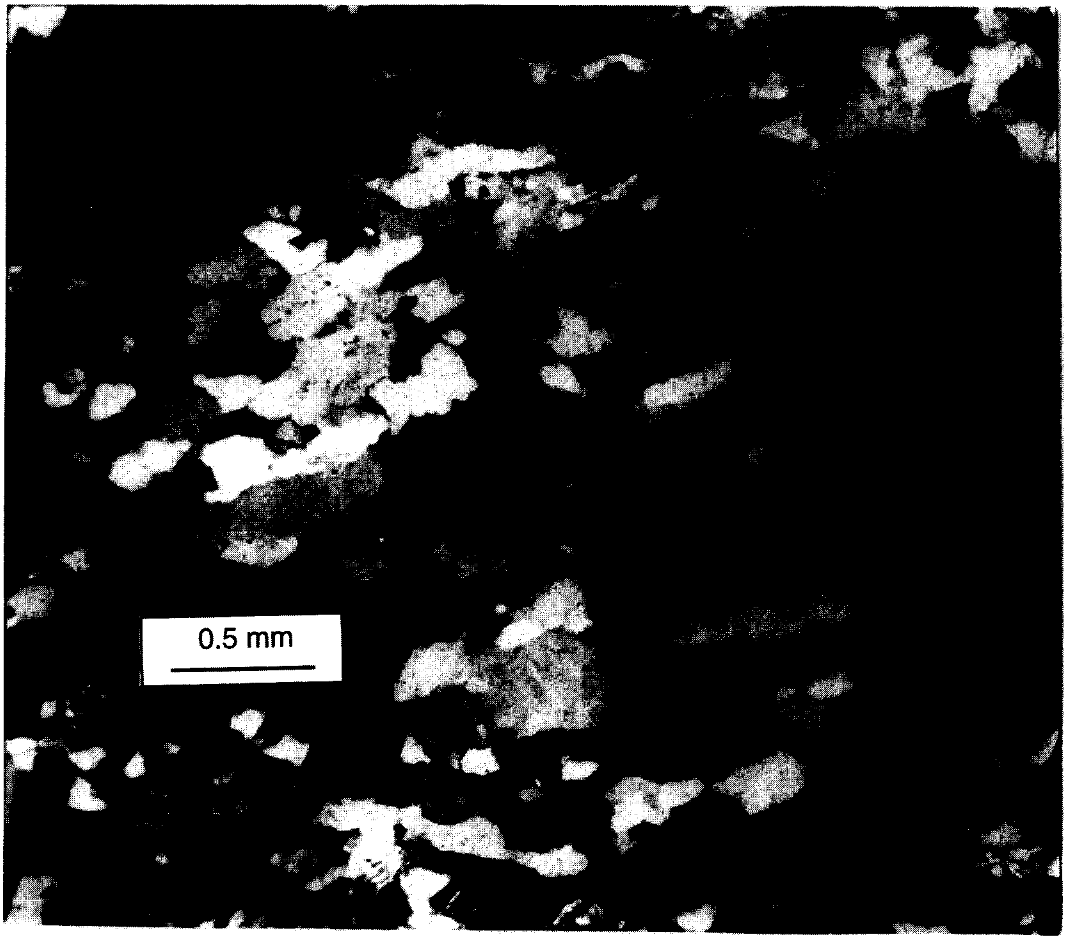

Fig. 3. Quartz microstructure. Grains are elongate and show an asymmetric shape fabric with respect to white micas and chlorite microdomains (oriented as the scale bar and not visible in the photograph). Sutured grain boundaries are indicative of grain-boundary migration.

(3) crystallographic preferred orientation (CPO) analysis on *c*-axes of quartz using the U-stage. About 250–300 grains per thin section were measured on traverses parallel to the X strain direction. A complete fabric analysis was not possible owing to the coarse grain size of the samples.

Quartz-shape fabric analysis

The quartz microstructure shows evidence for dynamic recrystallization. Generally, quartz grains have serrated and straight grain boundaries with a preferred orientation. The growth of subgrains at the expense of coarser grains indicates that rotation recrystallization occurred. In some sites the grain boundaries have an irregular, weakly lobate shape showing that also grain-boundary migration occurs. As a consequence, quartz exhibits two main grain sizes. Coarse old grains are predominant, and have an elongate shape measuring 0.5–0.8 mm for the long axis and from 0.1 to 0.2 mm for the short axis, with a mean ratio of long over short axis of 3.2 in the XZ-plane. The grains show undulatory extinction and a strong crystallographic preferred orientation which indicates the same sense of shear (Simpson and Schmid, 1983; Simpson, 1986) on both limbs of the fold. Smaller grains at the boundaries of the large grains are equant with straight boundaries and an average grain size of about 0.08 mm.

Shape analysis was carried out on thin sections parallel to the XZ-plane of the strain ellipsoid, and shows that there are no significant differences in the preferred orientation of grains between the opposite limbs of the sheath fold.

Quartz-shape fabric analysis using the Surfor and Paror methods

Surfor and Paror diagrams (Fig. 6) show that the ODF (Orientation Distribution Function of Panozzo, 1984) for quartz grains lies 35–40° clockwise with respect to the XY-plane of the strain ellipsoid. This indicates a strong alignment of the grain boundaries in one direction and confirms identical senses of shear on both limbs of the fold (sinistral in Fig. 6).

The degree of preferred orientation is not as high as would be expected in the high shear-strain regime ($\gamma \approx 10$) proposed here. This may possibly be related to the high competence contrast between the thin quartzitic layer

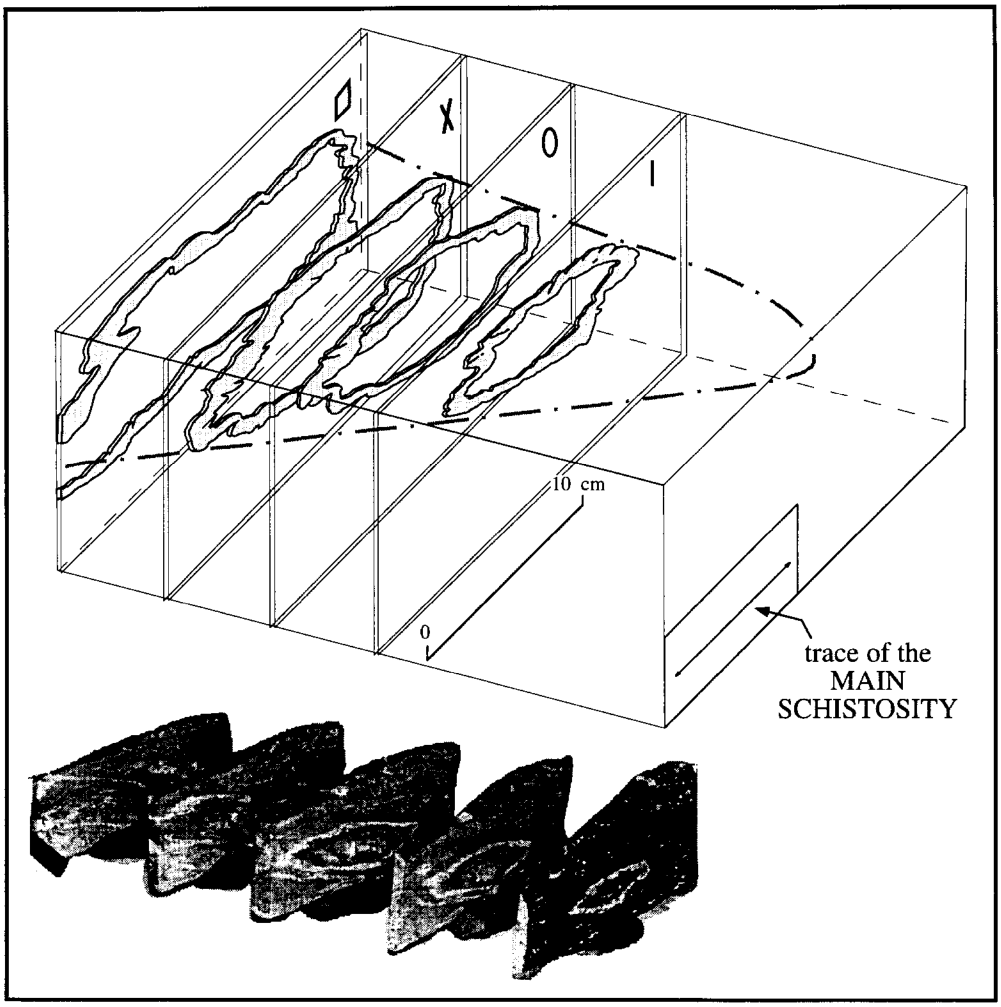

Fig. 4. Sequential slices cut from the block containing the sheath fold and its three-dimensional reconstruction.

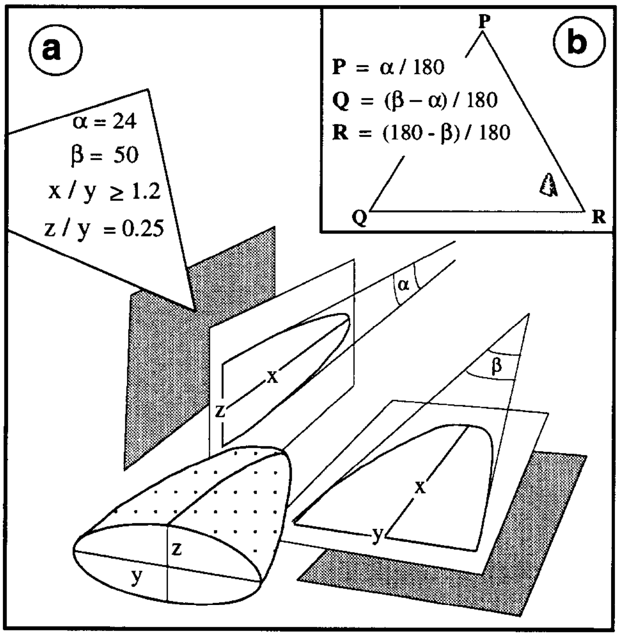

Fig. 5. (a) Geometrical features of the studied fold and (b) its classification according to the PQR diagram (Williams and Chapman, 1979).

and the predominant micaceous matrix which preferentially accommodates the deformation, and/or by a partial annealing of the microstructures.

CPO analysis

Crystallographic preferred orientation (CPO) analysis of *c*-axes in quartz were measured using a U-stage. The results are summarized in the pole figures of Fig. 7. The *c*-axis patterns show the same asymmetry on both limbs of the fold; nevertheless, some differences exist in their arrangement. This is clearly related to the different microstructural position in the fold. The results can be summarized as follows (Table 1).

(1) Thin sections from site 1 (Fig. 7) show a sinistral sense of shear with an asymmetric type I crossed-girdle (in the sense of Schmid and Casey, 1986) pattern in stereographic projection.

(2) Sections from sites 2 and 3 show a sinistral sense of shear with an asymmetric small-circle girdle pattern.

(3) Sections from site 4 show a sinistral sense of shear with an asymmetric single-girdle–type II crossed-girdle pattern.

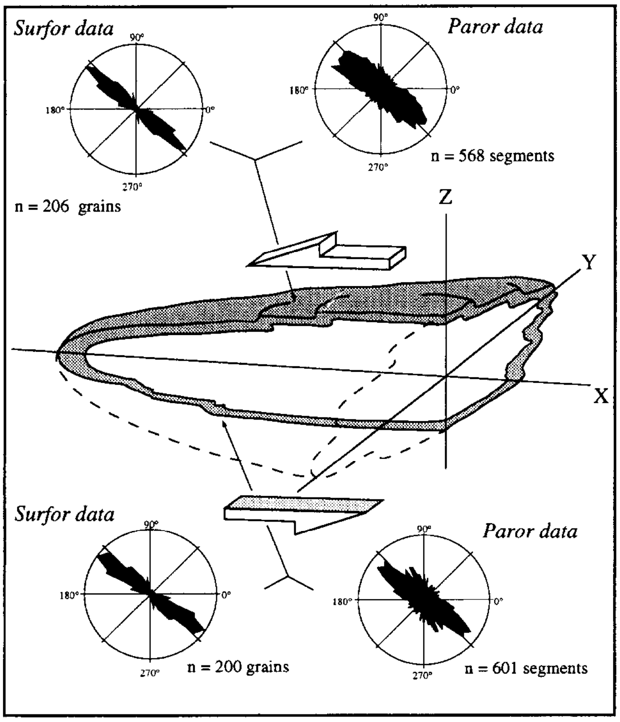

Fig. 6. Quartz *XZ*-shape-fabric diagrams and the inferred sense of shear. Data processed according to Panozzo (1983, 1984).

DISCUSSION

The quartz-shape fabric analysed under the optical microscope using the Surfor and Paror methods is characteristic of non-coaxial flow during progressive deformation. Sense of shear is identical on both limbs of the fold, and the sheath fold and the related grain-shape fabric can therefore be used as a kinematic indicator. The same sense of shear that we have recorded on both limbs of the fold may be in agreement with a model of passive rotation, as in the model supported by Aller and Bastida (1993). In order to explain the geometry of sheath folds, they suggested a passive amplification in non-coaxial flow of a pre-existing fold that initiated by a mechanism of buckling.

The interpretation of the CPO is not unequivocal and needs some discussion. The patterns obtained in this study are quite similar to ones produced by experimental results by Dell'Angelo and Tullis (1989). Dell'Angelo and Tullis (1989) and Law (1990) suggest that the external asymmetry (i.e. the asymmetry with respect to a reference frame; Passchier and Trouw, 1996) can be related to the simple-shear component, whereas the internal geometry (i.e. the shape of the fabric skeleton) is related to the state of strain.

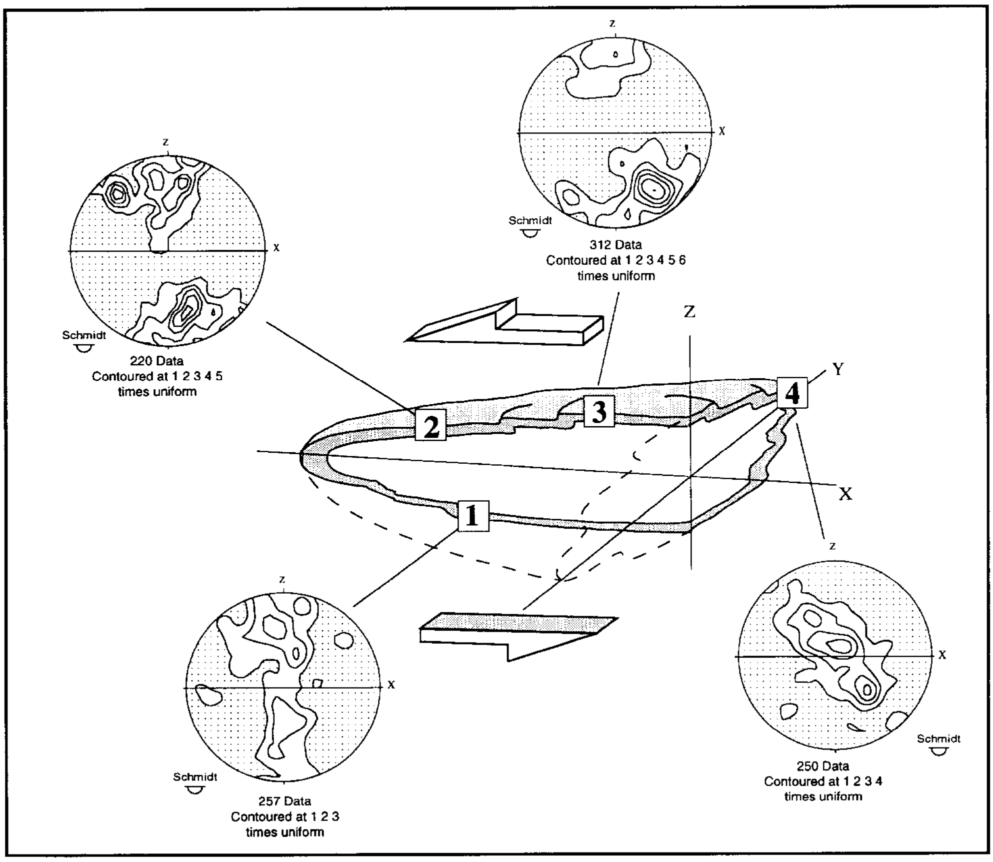

Fig. 7. Quartz *XZ*-*c*-axis pole figures measured in the pure quartzitic layer. *c*-axes of about 250 grains were measured in each location.

Table 1. Results of the microstructural analysis

Site	Sense of shear	*c*-axes patterns	Strain component
1	Sinistral	Asymmetric type I crossed girdles	Flattening
2	Sinistral	Asymmetric small-circle girdle	Flattening
3	Sinistral	Asymmetric small-circle girdle	Flattening
4	Sinistral	Asymmetric single-girdle–type II crossed girdles	Constriction

For site and sense of shear refer to Fig. 7.

As a consequence we can interpret the *c*-axis patterns of the studied fold as being the result of general flow conditions, i.e. simple shear combined with a coaxial flow component. The internal asymmetry, which is related to the state of strain, can be interpreted according to Price (1985) and Schmid and Casey (1986), as indicated in Table 1 and Fig. 8(a).

In site 1, the asymmetric type I crossed-girdle pattern can be related to flattening strain; in site 2, the asymmetric small-circle girdle pattern suggests flattening strain; in site 3, the asymmetric small-circle girdle pattern can be related to flattening strain and suggests that basal glide (Lister and Dornsiepen, 1980; Schmid and Casey, 1986) is the prevailing deformation mechanism; and, in site 4, the asymmetric single-girdle–type II crossed-girdle pattern suggests constrictional strain parallel to the long dimension of the fold, i.e. the *X*-direction. Figure 8(b) shows strain partitioning inside the fold. The limb regions are characterized by flattening while the hinge zone is characterized by constriction.

As far as the external asymmetry is concerned, a transition to increasingly asymmetric *c*-axes patterns is

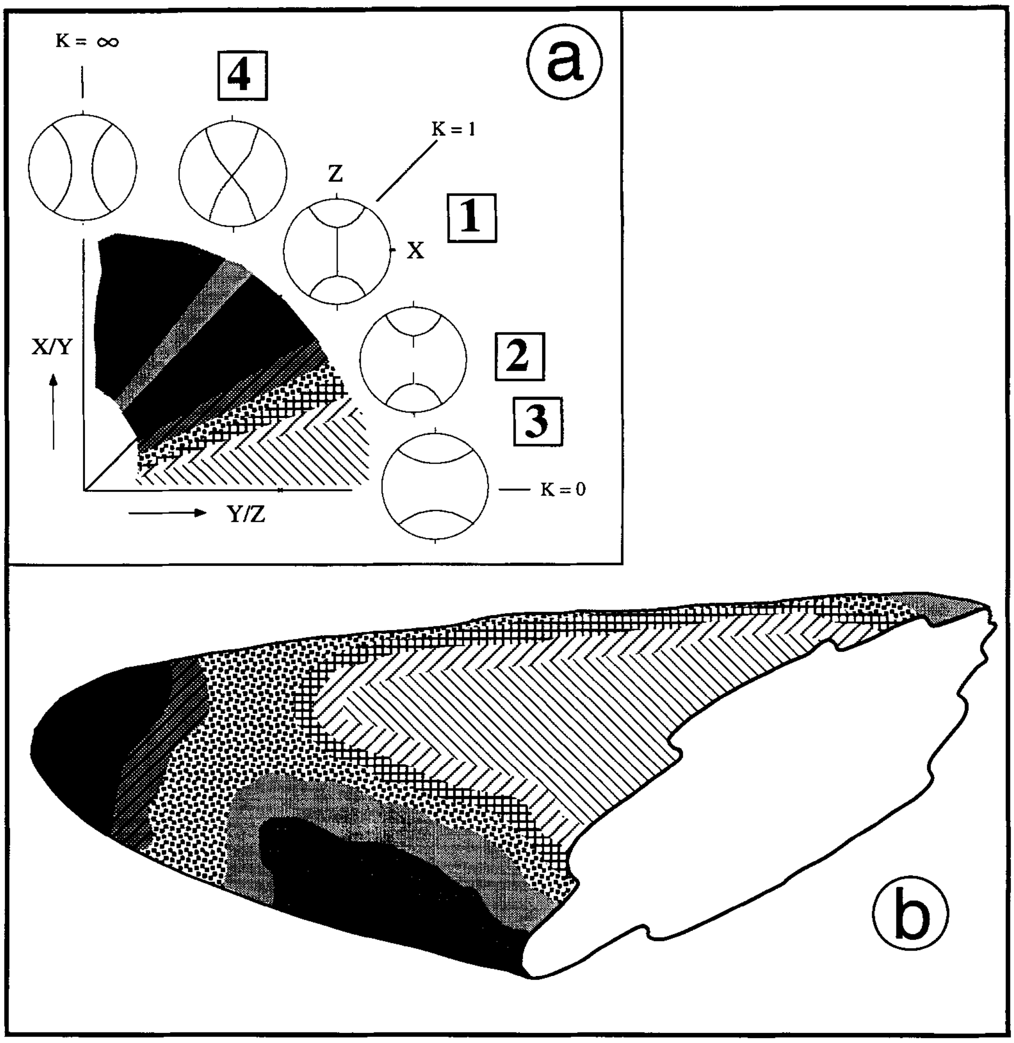

Fig. 8. (a) Flinn diagram according to Schmid and Casey (1986); numbers refer to sites in Fig. 7. (b) Strain distribution map inside the sheath fold according to the *c*-axis patterns.

suggested towards a single-girdle-type pattern in the sequence site 3–site 2–site 1. Thus, different strain states are present in different parts of the fold. The transition (Schmid and Casey, 1986) may be related to an increasing rotational component in the strain path towards site 1, suggesting a partitioning of the rotational component inside the fold.

The results of the performed analyses give a picture of the strain distribution inside a sheath fold. Data from shape fabric and CPO analysis could suggest a complex nature of the deformation, but it is not clear whether these data only give a picture of the local strain state or if they give information on the bulk state of strain during the folding event.

If our data give information on the bulk strain then they show the composite nature of the overall deformation, which is characterized by combined simple-shear and coaxial progressive deformation, i.e. general non-coaxial flow (Hanmer and Passchier, 1991). Such an interpretation is similar to some models of fold development proposed in the literature (Ramsay, 1967; Stünitz, 1991; Aller and Bastida, 1993). Also, the partitioning of the rotational component inside the fold suggests a model of general non-coaxial flow, even if the gradient towards a single-girdle pattern could be influenced by different degrees of recrystallization in different sites of the fold.

Nevertheless, departure from plane strain, like that shown by our CPO analysis, may also develop in an overall deformation characterized by simple-shear flow. Marques and Cobbold (1995) described experimental development of folds around a rigid object, where folding occurs in a homogeneous bulk layer parallel to the flow plane by simple-shear progressive deformation. Although the overall flow regime in the experiment is simple shear, Marques and Cobbold (1995) record local strain patterns with departures from plane strain that occur in peculiar positions around the rigid object. The flow patterns predicted by Marques and Cobbold (1995) match the distribution we found (Fig. 8b) and, if we consider that at a certain stage during the progressive deformation the studied fold could have acted as a rigid object in a deforming matrix, in this case our *c*-axis patterns may reflect only local strain states and cannot be generalized to be the result of the overall flow regime. However, a transition from plastic deformation to a more rigid behaviour of the quartz layer seems unlikely; we suggest the hypothesis of a general non-coaxial flow as the overall regime of deformation.

CONCLUSIONS

This study outlines the occurrence of a systematic distribution of strain states over a sheath fold. CPO data suggest a composite mechanism of deformation. Many studies outline the composite nature of deformation in shear zones (Ramsay and Huber, 1987) and suggest that a mechanism involving both simple shear and coaxial flow is the most likely; as the metasediments of the Voltri Group acted as shear zones (Capponi, 1987) during the structural evolution of the massif, the hypothesis of a general non-coaxial flow is the most likely for the study case. Moreover, recent structural analysis (Crispini, 1995) reveals a complex regime during the F_1 and F_2 deformational events with the combined action of coaxial and non-coaxial flow. The occurrence of the same sense of shear in both limbs of the fold in the XZ-plane agrees with a model of sheath-fold development by the passive rotation of material lines.

Acknowledgements—Microstructural data were processed during a period of study of one of the authors (L. Crispini) at the ETH-Zürich. Helpful suggestions and discussions with N. Mancktelow, D. Grujic, M. Casey and S. Mazzoli are acknowledged. Revisions by S. Schmid and L. Skjernaa helped to improve the manuscript.This paper was financially supported by funds from the Italian M.U.R.S.T. (Ministero per l'Università e per la Ricerca Scientifica e Tecnologica).

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