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Quartz *c*-axis fabric development and large-scale post-nappe folding (Wandfluhhorn Fold, Penninic nappes)

EVA M. KLAPER

Geologisches Institut, Universität Bern, Baltzerstr. 1, 3012 Bern, Switzerland

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Abstract—Quartz *c*-axis fabrics have been investigated within a suite of quartz veins and monomineralic layers around a major post-nappe fold hinge (the Wandfluhhorn Fold) in the Bosco area (Swiss–Italian border) within the lower Penninic nappes.

Two kinematic domains which are separated by the axial plane trace of the Wandfluhhorn Fold are recognized; on the lower limb the measured quartz *c*-axis fabric asymmetry indicates a sense of shear in which the overlying layers move to the southwest (i.e. top-to-SW) whereas on the upper limb the shear sense is reversed with the top moving to northeast. The shear direction (N60°E–N80°E), however, is constant in both areas and oblique to an older stretching lineation as well as to the D_3 fold hinge. Such a distribution of asymmetric quartz *c*-axis fabrics and the constant orientation of their interpreted shear direction, which is apparent only from the fabric data and not from field evidence, indicates fabric development pre- or early syn-Wandfluhhorn folding, with subsequent folding and modification of the existing textures and possibly rotation of the initial fold axis.

An overall westward-directed shear has been suggested for the whole of the Lepontine Alps. However, this study demonstrates that this simple general pattern has been modified locally by later folding. It also demonstrates that the dominant lineation may be a finite stretching lineation due to more than one phase of deformation and is not necessarily related to any particular transport direction.

INTRODUCTION

IT IS frequently recorded in rocks from the deeper levels of intensely sheared orogenic terrains that fold hinges lie subparallel to a well defined stretching lineation (Sanderson 1973, Escher & Watterson 1974, Bell 1978, Simpson 1982). In these cases, it is generally assumed that the stretching lineation indicates the transport or shear direction. The fold axes may have formed in other orientations and been rotated into parallelism with this direction (Sanderson 1973, Escher & Watterson 1974), or they may have developed subparallel to a pre-existing linear structure as a result of some mechanical constraint (e.g. Cobbold & Watkinson 1981).

Quartz *c*-axis fabrics from monomineralic quartz layers and veins commonly display systematic patterns which are related to the local kinematic framework (e.g. Law *et al.* 1984, Mancktelow 1985). This paper investigates how such fabrics are related to the orientation, geometry and kinematics of a major isoclinal fold in the lower Penninic nappes which formed subparallel to a pre-existing fold axis and stretching lineation. The regional significance of this post-nappe fold will be discussed elsewhere (Mancktelow & Klaper in preparation).

GEOLOGICAL SETTING

The Lepontine Alps of southern Switzerland and northern Italy comprise N-closing anticlinal fold nappes, characterized by cores of pre-Triassic basement metamorphic complexes with envelopes of calcareous Mesozoic rocks. The lower Penninic nappe pile shows polyphase penetrative deformation and amphibolite-facies metamorphism of Tertiary age (Niggli 1970, Ayrton & Ramsay 1974, Milnes 1974). In the lower Penninic nappes, intense post-nappe folding has taken place (Milnes 1974). These folds are large recumbent structures with limbs roughly the same scale as the nappe units (Fig. 1).

The main Wandfluhhorn Fold, first recognized by Schmidt & Preiswerk (1908), has been described in some

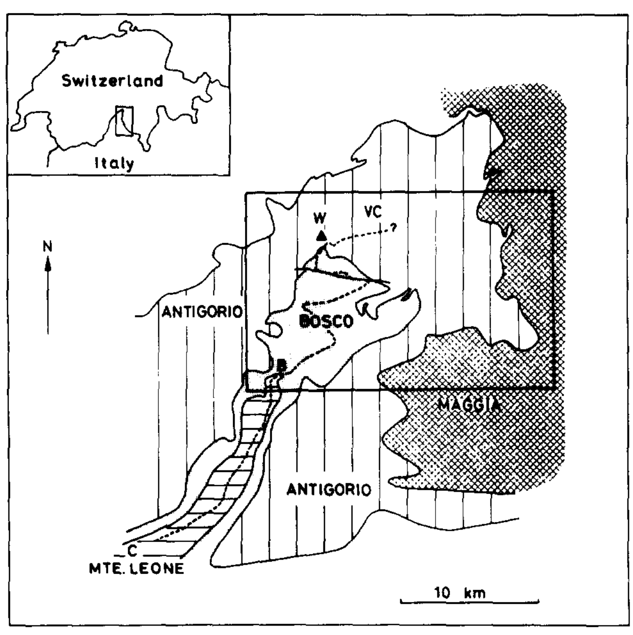

Fig. 1. Location map and tectonic sketch map. Place names used: B: Alpe Bosa, C: Crevola (Valle dell'Isorno), VC: Val Calnegia, W: Wandfluhhorn. Dashed line: Wandfluhhorn Fold axial plane trace. Inset shows the area covered in Fig. 7. The cross-sections (Fig. 2) run N–S through the summit of the Wandfluhhorn (W).

detail by Gruetter (1929), Hunziker (1966), Wieland (1966), Hall (1972) and Milnes (1974). The Wandfluhhorn Fold is considered by these authors to be the most important post-nappe structure in the Lepontine Alps. At the 'type locality', on the Wandfluhhorn northwest of Bosco-Gurin, as well as on nearby Alpe Bosa (Fig. 1), a spectacular fold hinge with granitic gneisses of the Antigorio Nappe on the outside and Monte Leone gneiss, Bosco Group and streaks of cover metasediments in the core, plunges gently ESE. The fold is perfectly isoclinal and affects an already well-developed foliation.

STRUCTURAL ELEMENTS

The structural features observed indicate three major Alpine deformations, which are designated D_1, D_2, D_3 (Figs. 2 and 3). The earliest deformation resulted in the emplacement of large folded basement thrust sheets separated by Mesozoic rocks, later deformed during two successive fold phases D_2 and D_3 (Fig. 2). The D_1 and D_2 events produced a first recognizable (D_2) fabric, which was then overprinted and modified by a younger crenulation-type D_3 event.

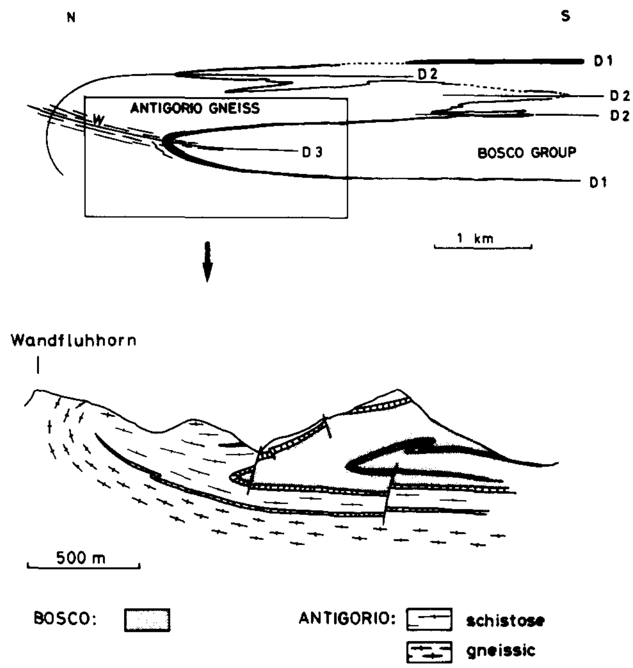

Fig. 2. Schematic and geological N–S cross-sections of major structures in the Wandfluhhorn area, drawn according to Hall (1972) and own data.

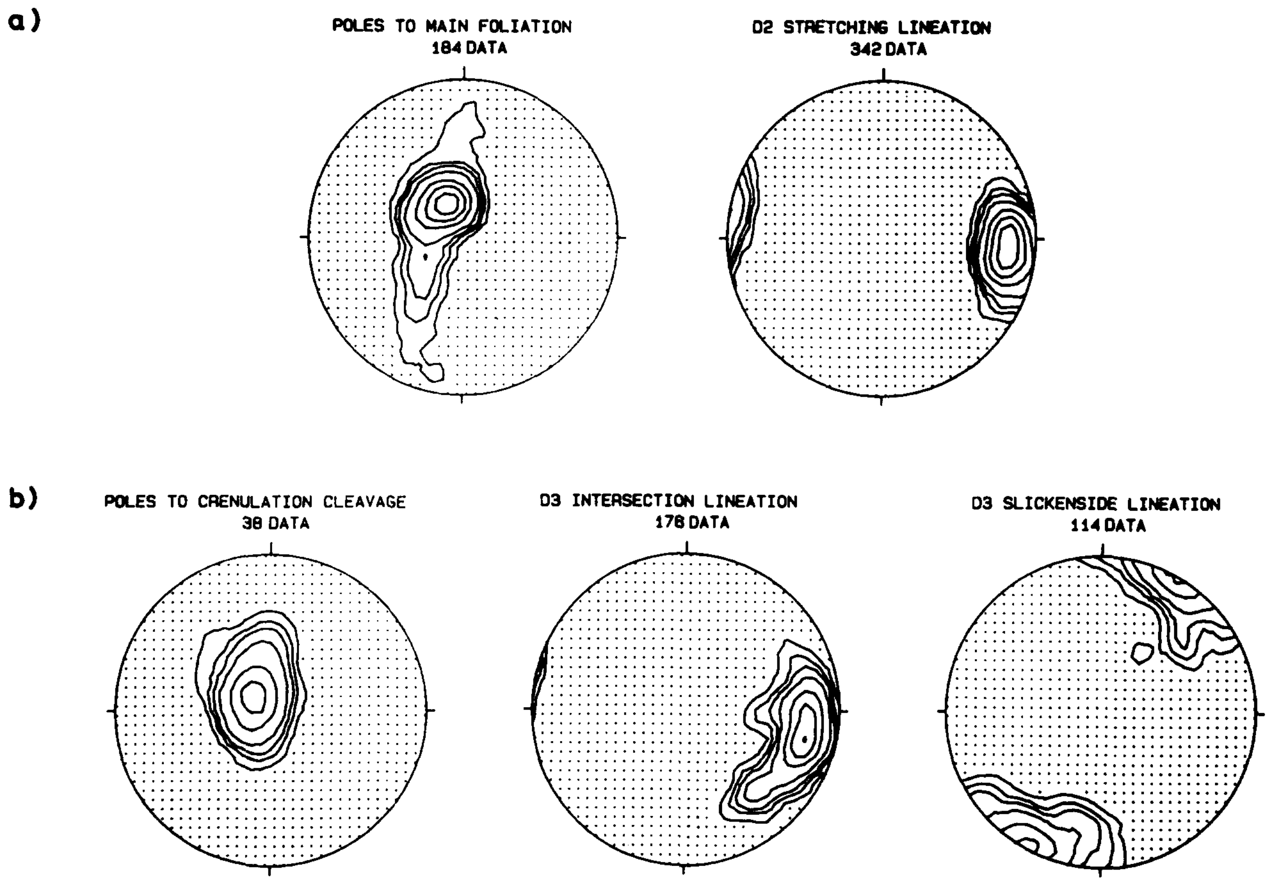

Fig. 3. Orientation data for structural elements. Plotting and contouring (contoured at 1.0, 2.0, 3.0, 5.0, 10.0, 15.0, 20.0 times uniform) is in the lower hemisphere, using a FORTRAN computer program described by Starkey (1979). (a) Deformation phase D_2, (b) deformation phase D_3.

D_2 *deformation*

The granitic rocks of the Antigorio Nappe in Val Calnegia are largely undeformed and only cut by discrete anastomosing shear zones separating lozenge-shaped undeformed bodies. However, the strain increases markedly towards the Mesozoic rocks separating the Antigorio gneiss from the Bosco Group and, therefore, also towards the axial plane of the Wandfluhhorn Fold (Fig. 1). The originally granoblastic textures become strongly schistose as the average grain size decreases and individual grains develop distinct dimensional and crystallographic preferred orientation. A strong schistosity (S_M) penetrates the rock and a pronounced stretching lineation appears on the schistosity planes (Fig. 3). The poles to the foliation (S_M) plot on a great circle which defines the D_3 axis of the Wandfluhhorn Fold (N100°E/20).

The stretching lineation (N100°E/20) is formed dominantly by aligned mica flakes, elongated quartz grains and feldspar eyes, and occurs in all rock types. Flat quartz sheets have subparallel grooves and aligned mica flakes on their surface. The D_2 stretching lineation is identically oriented on both limbs of the Wandfluhhorn Fold and is coaxial to the later D_3 Wandfluhhorn Fold axis and an intersection or crenulation lineation (see below). This D_2 lineation is a true stretching lineation since it is parallel to the long axes of deformed xenoliths in the schistose margin of the Antigorio Nappe.

D_3 *deformation*

The Wandfluhhorn Fold affects an already well developed D_2 foliation (S_M) and is perfectly isoclinal about an axis N100°E/20. The geometry of small-scale parasitic folds systematically is that of similar folds (class II, Ramsay 1967) (Fig. 4). The Wandfluhhorn Fold developed an axial planar crenulation cleavage (S_C) (Figs. 2 and 3) in the hinge area, especially within the Antigorio gneiss, in uppermost Val Calnegia and in some minor fold hinges in other parts of the area. The crenulation cleavage is commonly zonal, but may be discrete in places (Gray 1977) with tiny fold limbs making up the new cleavage planes. The relict traces of the foliation are not always continuous across the cleavage zones. In places, tiny flakes of biotite have grown aligned in the new crenulation cleavage.

A lineation parallel to the major Wandfluhhorn Fold axis occurs in all rock types but is especially common in the Bosco Group rocks. This lineation (N100°E/20) is formed by the alignment of minute crenulations of thin mica layers (small fold hinges) or by an intersection of the main foliation (S_M) and the crenulation foliation (S_C).

Another lineation which post-dates the D_2 stretching lineation, but is oblique to the Wandfluhhorn Fold axis, can be observed occasionally in the Bosco Group and in the Antigorio gneisses of the Wandfluhhorn hinge area. This lineation appears as tiny striae, with no associated mineral growth. Its orientation is towards N20°E–N40°E plunging 10–30°, which is almost perpendicular to the Wandfluhhorn fold axis.

Interpretation of the D_3 *lineations—a possible fold forming mechanism*

It is proposed that the striation formed as schistosity planes slipped over each other as the Wandfluhhorn Fold formed partly by a flexural-slip mechanism. Such oblique slip occurs when the layers being folded are obliquely inclined to the principal axes of the bulk strain (Ramsay 1967, pp. 396, 466). Small-scale folds which may display a deformed D_2 lineation, as shown in Fig. 5,

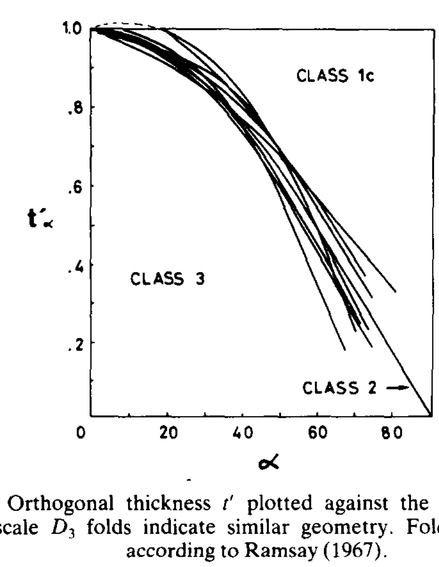

Fig. 4. Orthogonal thickness t' plotted against the angles of dip: small-scale D_3 folds indicate similar geometry. Fold classification according to Ramsay (1967).

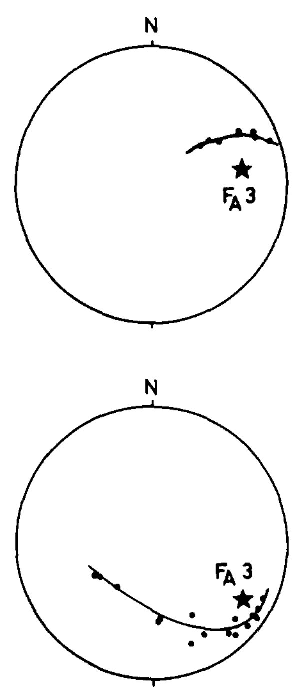

Fig. 5. Two examples of D_2 lineations (dots) deformed by small-scale D_3 folds: The locus of the deformed lineations corresponds to the loci of lineations deformed in oblique (and flattened) flexural slip folds (Ramsay 1967, p. 465).

also indicate a flexural-slip component to the fold forming mechanism. Therefore, a combination of local flexural-slip within a flexural-flow fold and a strong component of homogeneous strain, plus inhomogeneous shear (forming a similar fold, class II, Ramsay 1962) seems to be the most probable deformation mechanism for the Wandfluhhorn Fold.

It is assumed that the Wandfluhhorn Fold axis formed parallel to the D_2 stretching lineation because of this pre-existing mechanical constraint (cf. Cobbold & Watkinson 1981), since it is much easier to deform an anisotropic body of rock with a strong linear and planar fabric coaxial with, rather than oblique to, the earlier linear fabric (see below).

OPTICAL MICROSTRUCTURES

The least deformed Antigorio gneiss in Val Calnegia has a typical granoblastic, polygonal texture with an average grain size of 1–2 mm. As the strain increases towards the axial plane, the grain size decreases and this texture is replaced by a schistose microstructure. The two most typical microstructures of deformed quartzites observed in the studied area are illustrated in the photomicrographs of Fig. 6.

On the lower limb of the Wandfluhhorn Fold increasing dimensional and lattice preferred orientation (Fig. 6a, sample 240) can be observed in quartz veins and layers. The quartz grains have serrated boundaries and show strain features (e.g. undulatory extinction). The serrated grain boundaries are indicative of recrystallization by grain boundary migration. Subgrains and new grains (oblique shape fabric, S_B, e.g. Law *et al.* 1984) are elongate and aligned at an angle of approximately 25° to the dominant D_2 foliation (S_A) which can also be seen in the gneisses containing the quartz veins.

A zone of mylonitic gneisses occurs close to and above the axial plane of the Wandfluhhorn Fold. The quartz veins from this zone generally show ribbon microstructures (sample 338, Fig. 6b) indicating high strain. Within the ribbon-shaped old grains a dispersed development of elongate subgrains and new grains of small grain size with fairly regular grain boundaries can be observed. The ribbon grains define a dominant grain shape fabric (S_A) which is parallel to the foliation measurable in the field. Elongate subgrains, deformation bands and new grains define a weakly developed oblique foliation (S_B).

QUARTZ *c*-AXIS PREFERRED ORIENTATION PATTERNS AROUND THE WANDFLUHHORN FOLD

The strongly deformed quartz veins used for this study are 1–5 cm thick and are concordant to the regional (D_2) foliation. The veins are embedded in quartzo-feldspathic to semipelitic gneisses of the Antigorio Nappe and the Bosco Group and underwent deformation under amphibolite-facies conditions (Frey *et al.* 1980 and own data). The geographic distribution of quartz *c*-axis fabrics obtained from the Bosco area is shown in Fig. 7. Orientated thin-sections of quartz veins or monomineralic quartz layers within the gneisses were cut perpendicular to the foliation and parallel to the stretching lineation. The orientation of quartz *c*-axes was measured optically using a universal stage and plotted onto upper-hemisphere equal-area projections. Representative samples are shown on Fig. 7.

Samples which were cut parallel to the observable stretching lineation usually show asymmetric girdles of quartz *c*-axis distributions which do not go through the center of the projection diagrams. This suggests that the shear direction in these samples is not identical with the orientation of the stretching lineation. Rotation of the girdle through the angle β (Simpson 1980) into the center of the projection allows the deduction of the true shear direction (Fig. 8). This rotation is based on the assumption that the girdle represents slip with a Burger's vector parallel to $\langle a \rangle$ and, therefore, the true shear direction and the stretching lineation are not the same. Single girdle *c*-axis patterns are interpreted (Etchecopar 1977, Schmid & Casey 1986, among others) as the result of the preferred alignment of the *a*-axes into parallelism with the shearing direction of the rock. The similarity between the single girdle *c*-axis patterns described in Schmid & Casey (1986) with the ones observed in the Bosco area seems to justify this assumption.

In Fig. 7, only these true shear directions (termed lineation vectors) which trend towards N60°E–N80°E are given. There is a very weak mica lineation parallel to the D_3 shear direction on some of the quartz veins, although the country rock does not show any hint of a lineation with this orientation. It follows, therefore, that the D_3 shear direction is not identical with the D_2 stretching lineation, but is at an angle of 30–50° to it.

Quartz fabrics measured below and above the axial plane trace always show a marked asymmetry, indicating that there was a major shear component to the deformation. The sense of shear deduced from these patterns clearly shows a systematic distribution about the axial plane trace of the Wandfluhhorn Fold (Fig. 7). In general, the *c*-axes define a single girdle, occasionally with weakly developed vestiges of the crossed-girdle segments (Lister 1977).

Quartz fabrics measured from two samples along the axial plane of the Wandfluhhorn Fold show a different pattern from the one displayed by the mylonitic rocks below and above the axial plane zone (Fig. 7). It is only due to the topographic effect that the two samples 216W and 217W plot away from the axial plane trace given in Fig. 7. In the Alpe Bosa area, specimen 217W shows the *c*-axis maxima spread along small circles centered around the foliation normal, which suggests flattening strain (Schmid & Casey 1986, fig. 15). The pattern in sample 216W shows a tendency to become a (symmetric) crossed-girdle.

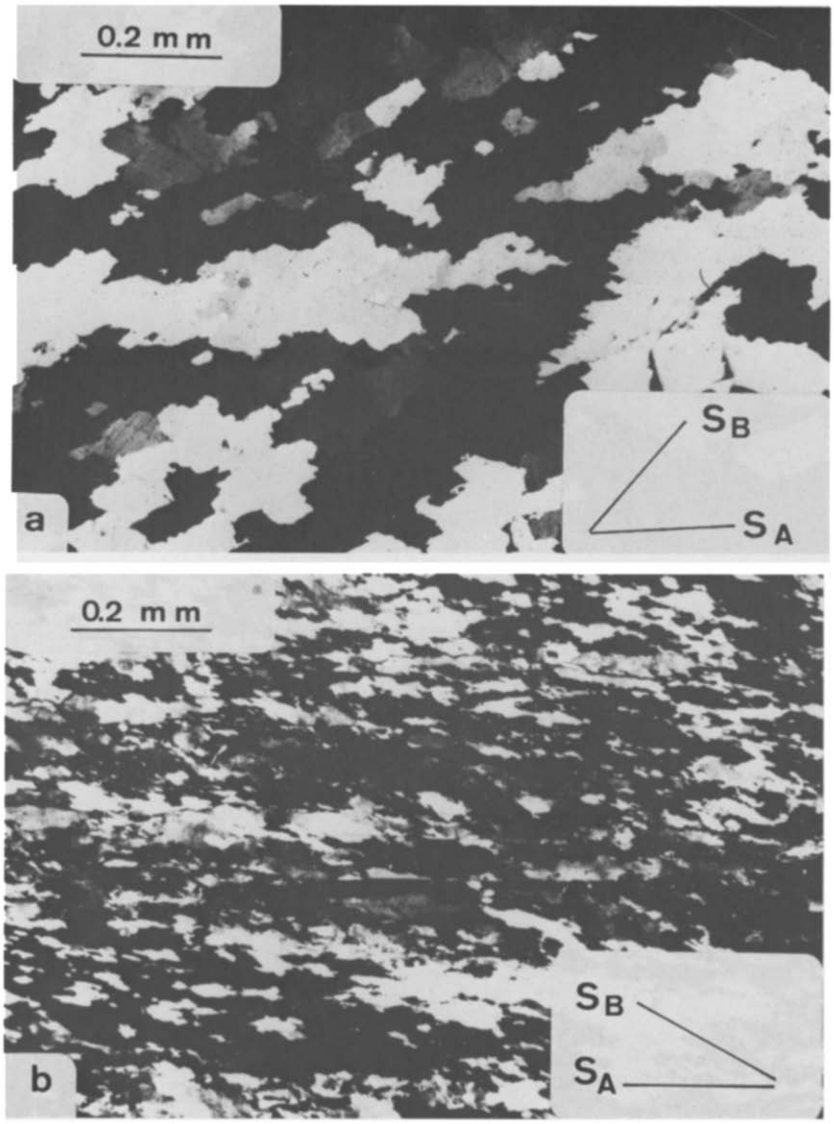

Fig. 6. (a) Optical microstructure of sample 240W, which has a quartz texture typical for the Bosco area: S_A is the dominant foliation as seen in the gneisses containing the quartz veins and in the veins themselves by elongated grains. S_B is the more weakly developed, oblique shape fabric defined by elongate recrystallized grains (e.g. Law *et al.* 1984). (b) Optical microstructure of sample 338W, which has a quartz texture typical for the most strongly sheared zones close to the Wandfluhhorn axial plane. S_A is defined by elongate ribbon grains, while S_B is defined by the oblique shape fabric of recrystallized grains.

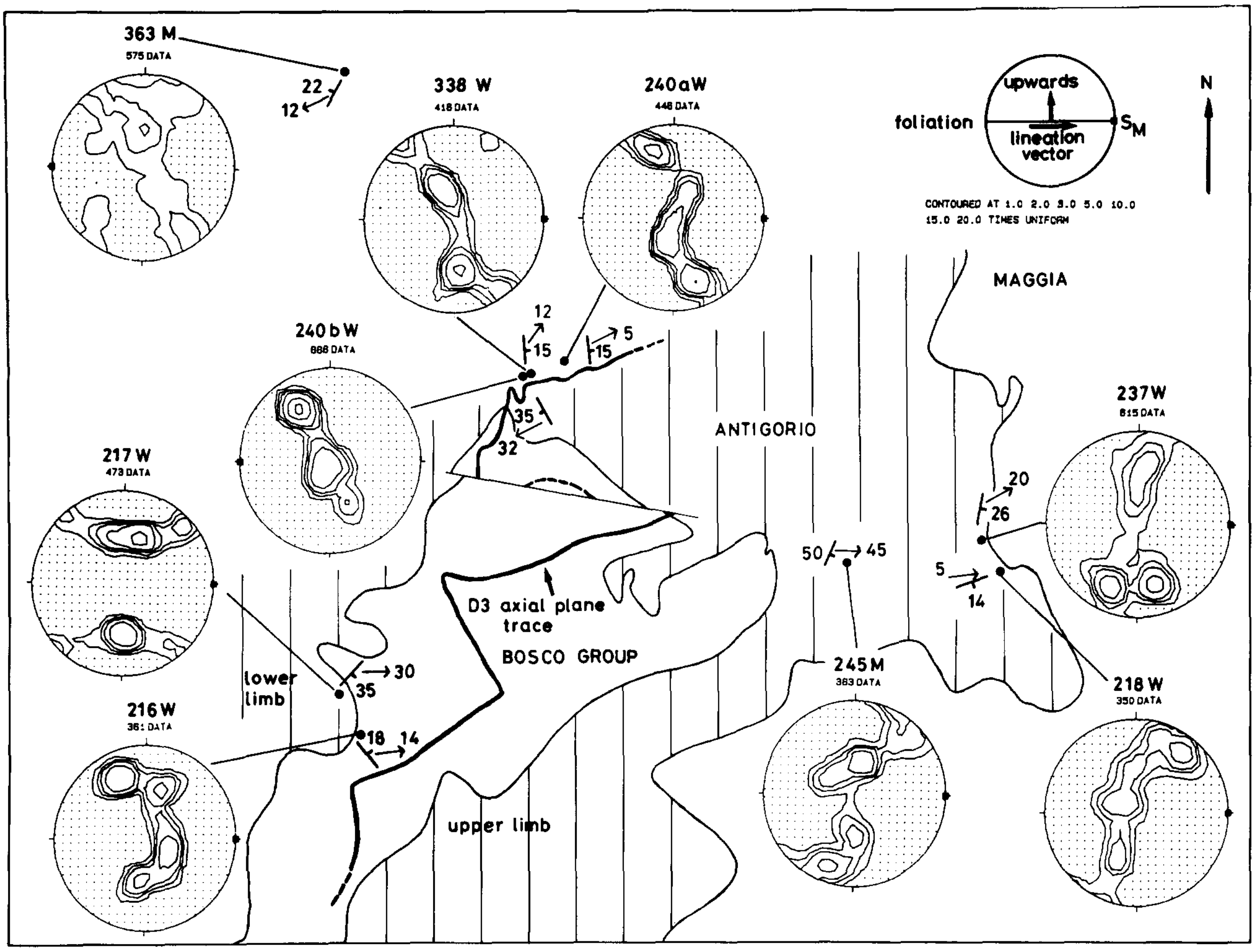

Fig. 7. Contoured quartz *c*-axis orientation diagrams from the Bosco area (Bosco Group: white, Antigorio: dashed). Equal-area upper-hemisphere stereoplots, S_M vertical left–right, lineation vector horizontal, directed towards the black square on the diagrams. Foliation orientation and lineation vector given for each sample.

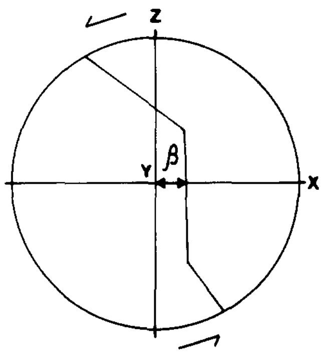

Fig. 8. The angle 'β' is the angle of rotation applied to single girdle fabric diagrams which do not cross through the center of the projection to deduce the true shear direction.

KINEMATIC INTERPRETATION OF QUARTZ c-AXIS FABRICS

In principle, there are three different relationships possible between the Wandfluhhorn Fold and the quartz c-axis fabric: (a) the quartz c-axis pattern may be imposed after folding and is, therefore, identical on the upper and lower limb of the fold; (b) the quartz c-axis orientation pattern formed prior to folding and has been folded passively about a (non-rotating) D_3 fold axis. In such a case the orientation of the extension direction is either parallel to the fold axis and, therefore, remains constant or would have to change orientation across the axial plane of the related fold; and (c) the pattern formed synchronous to the Wandfluhhorn folding with a constant extension direction, but a change in shear sense across the axial plane.

The shear direction is given by the quartz c-axis patterns according to Fig. 7. The assignment of a vector direction to the D_3 shear direction (termed lineation vector) allows a three-dimensional orientation of a specimen to be described uniquely by reference to this vector and the foliation S_M. Such a unique orientation for specimens is critical for the interpretation of the kinematics around the Wandfluhhorn Fold.

The observed fabric asymmetry in the oriented specimens of Fig. 7 indicates a sinistral sense of shear on the lower limb of the Wandfluhhorn Fold, i.e. west of the Wandfluhhorn axial plane trace in Fig. 7 (Eisbacher 1970, Simpson 1980, Mancktelow 1985). The direction assigned to the lineation vector indicates that the displacement direction is top-to-SW. On the upper limb of the Wandfluhhorn Fold, however, the shear sense is reversed, indicating that the top moved towards the northeast.

This study shows that the direction of the D_3 strain increment associated with the Wandfluhhorn folding has been oblique to a pre-existing foliation. However, there are two possibilities for the initiation of the fold axis: (a) it formed coaxial to D_2 due to mechanical constraints (Cobbold & Watkinson 1981) or (b) it initially formed perpendicular to the shear direction and rotated into its present orientation (Sanderson 1973, Escher & Watterson 1974), now enclosing an angle of 30–50° between the fold axis and the D_3 shear direction. Such a formation of the Wandfluhhorn Fold would imply that it could well be a sheath fold.

From the data presented in this study it is not possible to distinguish unambiguously between these two cases and the problem will be treated in detail in a regional study (Mancktelow & Klaper in preparation). However, because the D_3 striation lineation is practically perpendicular to the Wandfluhhorn Fold axis and the parasitic D_3 folds show only a rather limited spread of their orientations, possibility (a) is preferred.

The D_3 shear direction of N60°E–N80°E which has been deduced from asymmetric quartz c-axis patterns for the Wandfluhhorn area, however, is typical for the whole of the western Lepontine Alps (Mancktelow 1985). Several other independent shear criteria (Simpson & Schmid 1983) such as shear bands, augen textures and obliquely oriented quartz grains in thin sections support this kinematic interpretation.

CONCLUSIONS

The observed fabric asymmetry in the oriented specimens on the almost flat-lying lower limb of the Wandfluhhorn Fold (Fig. 9) indicates a sense of shear, in which the overlying layers move to the southwest (i.e. top-to-SW), whereas on the upper limb the shear sense is top to the northeast. The constantly oriented shear direction as deduced from quartz c-axis patterns, is oblique to an older stretching lineation as well as to the D_3 fold hinge and is apparent only from quartz c-axis data and not from field evidence alone. The observed D_3 lineations and the distribution of quartz c-axis fabrics around the Wandfluhhorn Fold, therefore, indicate fabric development pre- (or early syn-) Wandfluhhorn folding. Folding by a flexural-flow mechanism and modification of this pre-existing fabric is the most plausible interpretation for the observed geometry and kinematics. This study demonstrates that the dominant lineation may be a finite stretching lineation due to more than one phase of deformation. The orientation of such a stretching lineation can, therefore, not always be taken as the regional transport direction, but has to be interpreted with care.

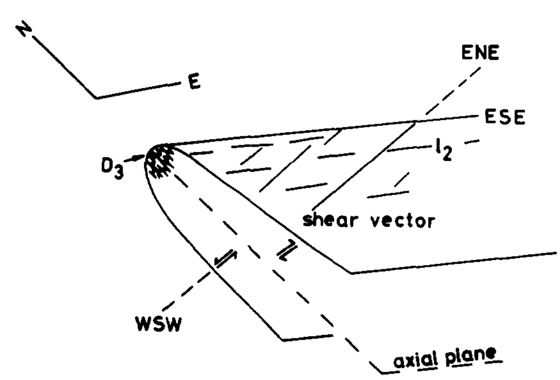

Fig. 9. Wandfluhhorn Fold sketch showing the orientation of the fold axis (ESE) parallel to the stretching lineation (l_2) and the shear vector which is oblique to the fold axis.

An overall southwestward-directed shear has been suggested by several authors for the upper Penninic nappes relative to the lower Penninic nappes in the Lepontine area (Heller 1980, Steck 1984, Mancktelow 1985). The present study seems to confirm this view of a major NE–SW-directed movement phase in the Central Alps which may, however, be masked by later folding events.

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