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Quartz *c*-axis texture mapping of a Variscan regional foliation (Malpica–Tui Unit, NW Spain)

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Abstract

Mineral assemblages developed under high pressure and low to intermediate temperature conditions (H*P*–LI*T*) are found in eclogites, orthogneisses and metasediments of the Malpica–Tui Unit (MTU), either defining or surrounded by a regional foliation that was mostly re-equilibrated under amphibolite to greenschist facies conditions. This regional tectonic foliation, tracking the exhumation path of the MTU in the context of the Variscan collision in SW Europe, has been studied using the microstructural record in quartz from the different rock types. Most of the quartz *c*-axis patterns show two distinct asymmetries, contained in perpendicular planes, which are related to two different non-coaxial components of the finite fabric (i.e. the regional foliation and the lineation). The asymmetry of deformation inferred from quartz *c*-axis textures suggests that fabric accumulation during exhumation occurred under 3-D general flow, departing strongly from the simple shear type. This has significant tectonic implications for the interpretation of regional stretching lineations, which in the present geodynamic setting of irregular collisional tectonics, are not parallel to the direction of general tectonic transport and, ultimately, to the plate convergence direction.

Keywords: Quartz *c*-axis textures; Exhumation; Distributed deformation; Collisional tectonics; Nappe tectonics; Variscan belt

1. Introduction

The theoretical background for studying ductile deformation in rocks, developed in the middle of the 20th century, was basically concerned with shear zones where the simple shear flow was shown to be predominant: in these cases, the stretching lineation developed is parallel to the tectonic transport direction and can be used as a kinematic indicator (Ramsay and Graham, 1970). However, the simple shear regime is a very particular flow regime, developed in plane strain. Provided that there are no volume changes, the boundaries of the shear zone need to be planar and remain parallel during deformation; in addition, wall rocks should also remain internally undeformed (Ramsay and Graham, 1970). The simple shear model is a good approximation for deformation in shear zones restricted to upper crustal levels where deformation bands are 'discrete'. In contrast, at lower crustal depths, rheological contrasts are smoothed (Handy, 1990) and ductile deformation affects both the wall rocks and the shear zone itself, making it appear that the boundaries of the shear zones are diffuse (Sibson, 1977).

Recently, more general non-coaxial flow types have been considered to play a significant role during ductile deformation of rocks. The approach to this was done in relation to transpressive/transtensive shear zones (e.g. Fossen and Tikoff, 1993; Robin and Cruden, 1994; Teyssier et al., 1995; Druguet et al., 1997; Jones et al., 1997; Tikoff and Greene, 1997; Lin et al., 1998), lateral extrusion in shear zones (Gilotti and Hull, 1993) and laterally constricted shear zones (Passchier et al., 1997), but also in more general theoretical cases (Passchier, 1997, 1998; Jiang and Williams, 1998). In these flow regimes, the stretching lineation observed in rocks do not have the same interpretation as in simple shear flow and its use as an indicator of tectonic transport direction is not correct (e.g. b-lineations of Sander, 1950).

The geometrical analysis of crystallographic preferred orientation (CPO) or texture (following the terminology in Wenk and Christie, 1991), of deformed polycrystalline aggregates can contribute to close the gap between the generalized application of the simple shear model to study deformation of deep crustal rocks and the inference of flow geometries occurring during natural deformation (suggested partially by Schmid, 1982 and by Price, 1985). In many

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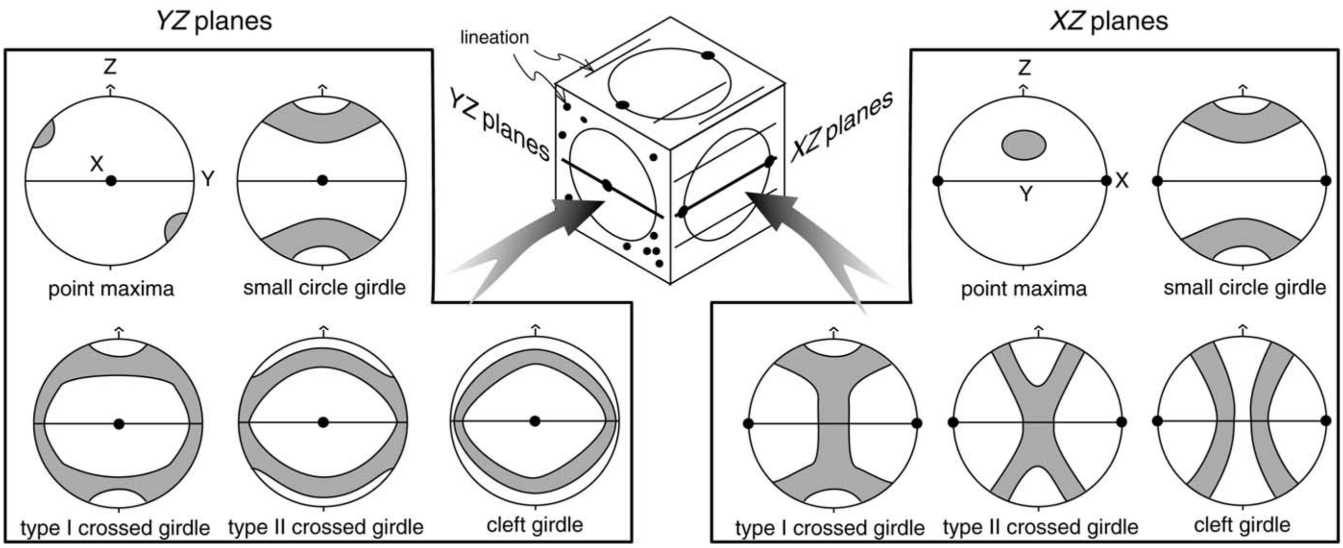

Fig. 1. Basic geometric elements in quartz *c*-axis textures seen in sections perpendicular to the lineation (*YZ* planes) and parallel to the lineation (*XZ* planes), both perpendicular to the foliation plane: point maxima, small circle girdle, type I crossed girdles, type II crossed girdles and cleft girdles (or small circle girdles around the *X*-axis). Kinematics of deformation in quartz is not always in agreement with the structural reference frame, so it is useful to know how 'typical' patterns (those in *XZ* planes) look like in *YZ* planes.

cases, a significant participation of pure shear is needed in order to interpret correctly some texture elements (Lister and Dornsiepen, 1982; Law, 1990) and it has been argued that the existence of coaxial overprints, thus 'polyphasic' deformations, is required to interpret some textures (Hobbs, 1985).

According to several authors (Lister and Hobbs, 1980; Price, 1985; Schmid and Casey, 1986), in coaxial deformation a whole range of intermediate texture elements exist between small girdles around the *Z*-axis, that represent flattening, crossed girdles (types I and II), that are better developed in plane strain, and cleft girdles (small circle girdles around the *X*-axis), formed in constriction (Fig. 1). When a non-coaxial component is involved in ductile deformation of rocks, former orthorhombic symmetry evolves to monoclinic symmetry, observed in sections perpendicular to the foliation and parallel to the lineation (e.g. Lister and Williams, 1979; Lister and Hobbs, 1980; Choukroune et al., 1987).

Schmid (1982) and Price (1985) suggested the importance of studying textures in gneissic bodies where deformation was not restricted to discrete shear zones but was, instead, extended to wide areas (termed 'fabric mapping' by Price, 1985). In this contribution, results are presented of the analysis of quartz *c*-axis textures of a regional tectonic foliation, which is a widespread structure in an allochthonous thrust sheet unit (the Malpica–Tui Unit, MTU) in the Variscan belt of SW Europe. The foliation developed during the exhumation of high pressure and low to intermediate temperature (H*P*–LI*T*) rocks in the MTU in relation to collisional tectonics (Llana-Fúnez, 1999). The strain record in the regional foliation started under high pressure conditions in mafic rocks (up to 2.5 GPa) and finished in orthogneisses under amphibolite facies conditions, although some further overprint under greenschist facies conditions is observed in schists and paragneisses.

The study of plastic deformation in quartz, through analysis of CPO, aimed to characterize the flow regime during the exhumation process. The texture elements (girdles and point maxima) exhibit in the same pattern two components of asymmetry: a predominant one, seen and contained in *YZ* sections (perpendicular to foliation and lineation) and defined by *c*-axis maximum in positions favourable for rhombic and prismatic slip, and a secondary one, seen and contained in *XZ* sections (perpendicular to foliation and parallel to lineation), which is defined by unequal development of arms in *c*-axis girdles. If asymmetry in the distribution of texture elements in quartz *c*-axis patterns is related geometrically with non-coaxial components during deformation of the aggregate, then the flow type that better explains the textures departs from the simple and pure shear modes and approaches a 3-D type of unusual monoclinic or even triclinic symmetry. The major consequence of this interpretation of the data is the relation between the orientation of the stretching lineation in the rocks and the direction of tectonic transport during exhumation of the MTU, which is no longer parallel. This topic is treated in more detail in the discussion where it is also placed in the geodynamic context of the Variscan belt in SW Europe, where indentation tectonics have been argued to explain the development of the Ibero–Armorican Arc (Matte and Burg, 1981; Matte, 1986, 1991; Dias and Ribeiro, 1994, 1995).

2. Geological setting

The Malpica–Tui Unit is a tectonic sheet belonging to the

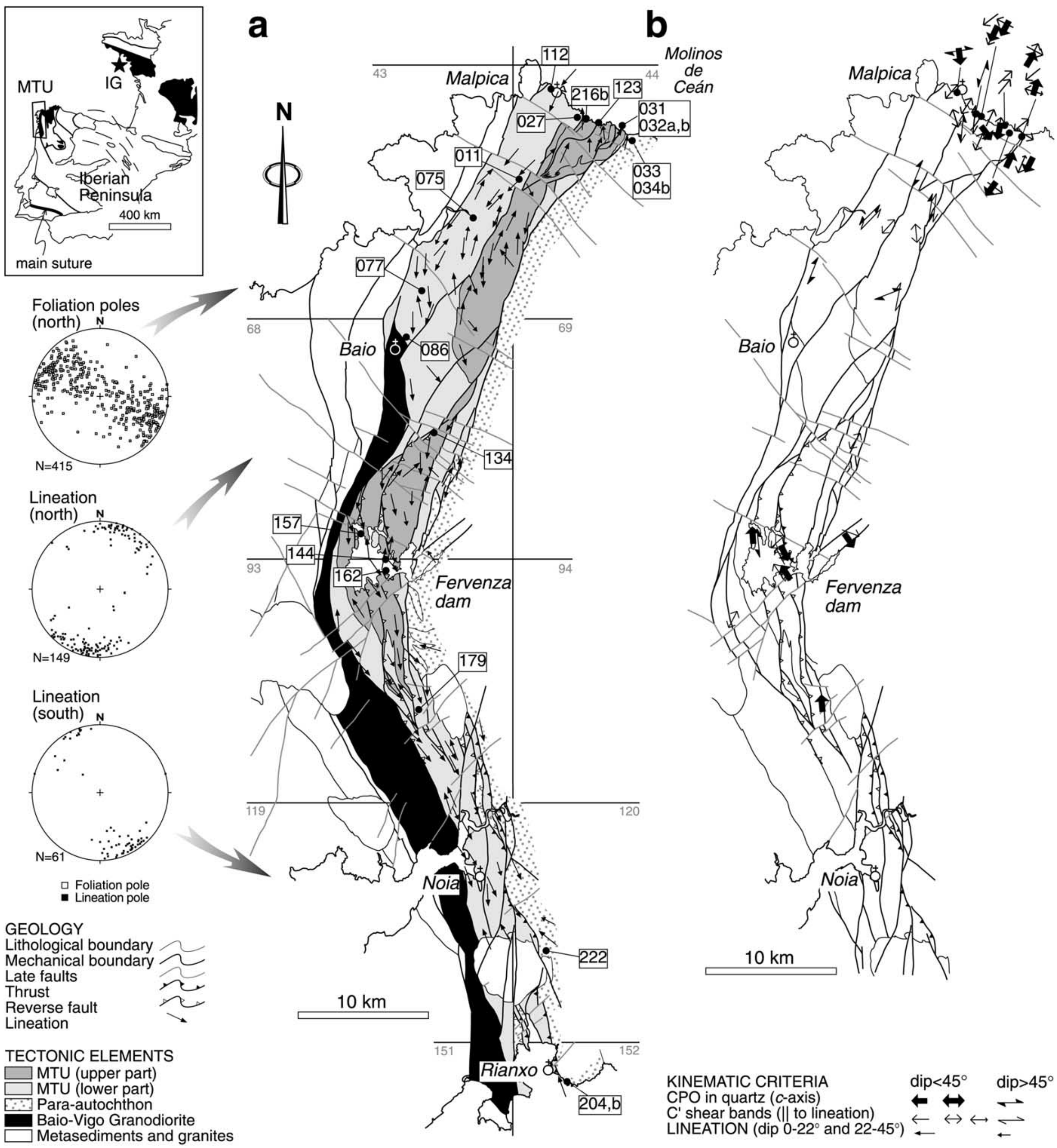

Fig. 2. (a) Orientation of the main lineation, indicated by arrows, in rocks of the Malpica–Tui Unit (MTU) and location of samples used for quartz *c*-axis texture analysis. (b) Senses of shear inferred from quartz *c*-axis textures asymmetries (only the ones seen in sections parallel to the *X*-axis, i.e. parallel to lineations) and C′ shear bands. The geology has been simplified from the map after Llana-Fúnez (1999). The numbered grid corresponds to the Spanish geographical grid for 1:50.000 scale maps. Inset, based on Julivert et al. (1972) and Martínez Catalán (1990), shows location of MTU and Ile de Groix (IG) in the Ibero–Armorican Arc: in black are the allochthonous complexes and the main suture zone.

allochthonous complexes (crystalline nappes) of NW Iberia, which was emplaced on the Iberian plate during the Variscan collision of SW Europe (Fig. 2). This unit is composed of a metasedimentary sequence interlayered with several bodies of Ordovician metavolcanics and intruded by calc-alkaline and (per-)alkaline orthogneisses, also Ordovician in age (Gil Ibarguchi and Ortega, 1985; Ribeiro and Floor, 1987; Pin et al., 1992). The present thickness of the sheet is more than 2.5 km and it extends at least 150 km parallel to the orogen (Fig. 2; Llana-Fúnez, 1999).

Most of the rock types included in the MTU preserve evidence of H*P*–LI*T*metamorphic conditions, calculated at ca. 600–650°C and 1.3–2.5 GPa (van der Wegen, 1978; Gil Ibarguchi and Ortega, 1985; Gil Ibarguchi, 1995; Rodríguez Aller et al., 1997a) 370–360 Ma ago (van Calsteren et al., 1979; Santos Zalduegui et al., 1995; Rodríguez Aller et al., 1997b). This metamorphism was produced simultaneously with the development of a pervasive tectonic foliation parallel to the lithological boundaries, that probably started to form during burial.

On the scale of the tectonic sheet, the foliation is defined by different mineral associations indicating variable metamorphic conditions, from high pressure (van der Wegen, 1978; Gil Ibarguchi and Ortega, 1985; Rodríguez Aller et al., 1997b) to amphibolite facies conditions (Llana-Fúnez, 1999). A strongly decompressive *PT* path for MTU rocks can be outlined from the published metamorphic data, interpreted as reflecting the exhumation of these rocks from high pressure conditions to the middle crust (Matte, 1998; Llana-Fúnez and Marcos, in review), where final emplacement by shear zones in greenschist facies and later overprinting strike-slip tectonics occurred.

The boundaries of the internally deformed MTU thrust sheet are not accurately known. The lower limit is a greenschist facies shear zone that overprints the regional foliation in the MTU and separates this unit from the Para-autochthon, located beneath (Llana-Fúnez and Marcos, in review). It is strongly reworked by late Variscan strike-slip structures (Llana-Fúnez and Marcos, 2001). The upper limit is not seen in the MTU, but in an equivalent unit farther to the east (in the Órdenes Complex) it is reported as a greenschist facies shear zone separating this tectonic sheet from overlying ophiolithic units (Martínez Catalán et al., 1996).

2.1. The regional foliation

The development of the main foliation, though widespread, is developed with a different intensity in the MTU and some rocks appear almost undeformed. However, both foliation and lineation in the different rock types, from quartz–feldspathic orthogneisses to amphibolites and schists, are consistently oriented and show similar cartographic patterns (lineations are represented in Fig. 2; Llana-Fúnez and Marcos, in review). This may indicate that during the development of the main foliation the kinematic reference framework remains more or less constant. In the field, gently westward-dipping foliations show a sub-horizontal stretching lineation in orthogneisses and a similarly oriented mineral lineation in amphibolites and schists, both parallel to the general structural trend of the belt (Fig. 2).

In quartz–feldspathic orthogneisses the tectonic fabric is mylonitic and varies from planolinear SL and LS to linear L. A gneissic banding is defined by lensoid-shaped polycrystalline aggregates composed largely of quartz, K-feldspar and plagioclase. Other minerals in apparent equilibrium with the foliation in orthogneisses are oriented white mica, aggregates of clinozoisite and plagioclase, and garnet grains that appear in contact with white mica and may show corona textures (in the fine-grained calc-alkaline orthogneisses). The same metamorphic mineral assemblage appears in deformed coarse grained calc-alkaline orthogneisses (bearing primary biotite). In both types of calc-alkaline orthogneisses, the H*P*–LI*T* assemblages are preserved in the relatively undeformed parts: van der Wegen (1978) and Gil Ibarguchi and Ortega (1985) studied the mafic inclusions in the finer grained calc-alkaline orthogneisses and Gil Ibarguchi (1995) reported the breakdown of plagioclase in the undeformed cores of coarser grained calc-alkaline orthogneisses.

The tectonic fabric in the metasediments, schists and paragneisses, is basically of planar type (S) and is defined by a compositional banding of tectonic origin and the preferred orientation of white mica. Other mineral phases assumed to be in apparent equilibrium with this foliation are garnet, chloritoid and rutile as the first mineral assemblage and chlorite, ilmenite and plagioclase, as the second. In the scarce bodies of layered amphibolites included in the metapelitic sequence, the orientation of blue-green amphibole defines the planolinear–linear fabric (LS to L). Rutile, garnet blasts with inclusion trails, chlorite and lensoid aggregates of zoisite–clinozoisite are also found defining the main tectonic foliation.

2.1.1. Kinematic indicators

The metasediments do not provide reliable kinematic indicators during the development of the regional fabric because schists and paragneisses are frequently retrograded and affected by later structures (e.g. folds). In the orthogneisses, kinematic criteria such as mica fish, asymmetric pressure shadows and shape fabric in quartz are rarely found, but C′ shear bands and CPO in quartz are more uniformly distributed in the study area and are therefore of use for the regional analysis. In these rocks, aggregates of quartz and feldspar defining the foliation and lineation show, in most cases, a symmetric shape in both *XZ* and *YZ* sections. However, some asymmetry in the aggregates similar to sigmoidal profiles, has been found in both sections (see sections *YZ* in Fig. 3).

Senses of shear inferred from C′ shear bands parallel to stretching lineation in orthogneisses in regions where the main fabric is mainly sub-horizontal or gently dipping to the west, show top-to-the-north displacement (Fig. 2b). This is the case for the samples from the Fervenza dam to the Malpica coast. Only around Molinos de Ceán (locality in Fig. 2a), a general top-to-the-south displacement was observed, which is explained by the fact that the data have been taken from the reverse limb of the only recognized recumbent fold of hectometric scale in the MTU

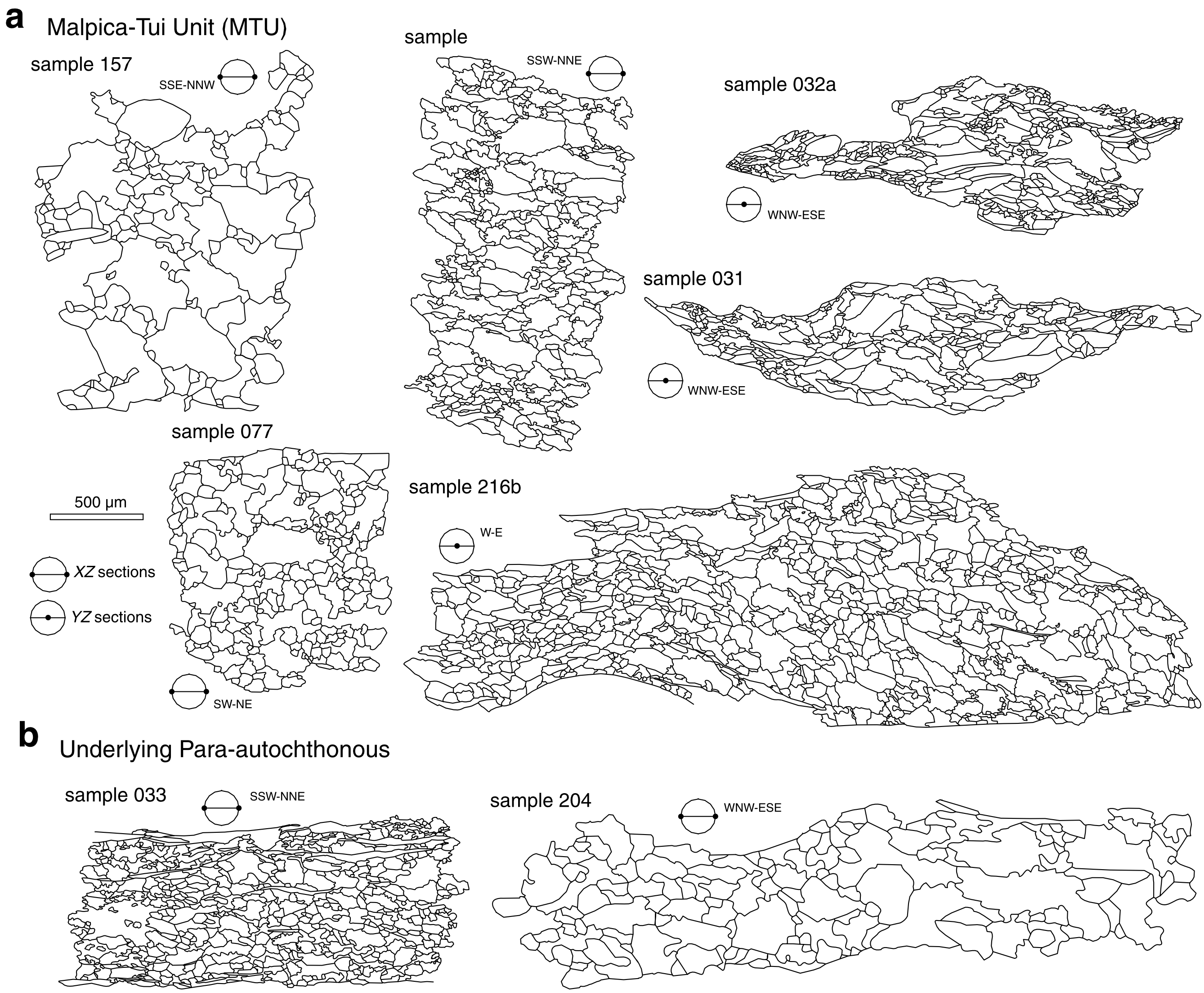

Fig. 3. Partial and complete drawings of some representative polycrystalline aggregates of quartz used for microstructural analysis from the: (a) Malpica–Tui Unit, and (b) its Para-autochthon. In each sample is indicated the orientation of the section in geographical coordinates and its structural framework.

(Llana-Fúnez and Marcos, in review). In the present case, the shear zones do not show signs of retrogression and they probably form at the same metamorphic conditions as the foliation itself, once the planar structure is developed (according to Platt and Vissers (1980), C′ shear bands require a previous planar fabric to be formed), but prior to recumbent folding. In domains where the foliation is subvertical, the very scarce available data do not indicate a clear sense of shear, probably due to the favorable orientation for later strike-slip overprinting.

3. Procedure

Quartz–feldspathic orthogneisses were selected as the reference lithology for the microstructural analysis in quartz because they are widespread in the MTU and because they show clearly the linear stretching fabric parallel to the general structural trend. The fabric is defined by the orientation of elongated polycrystalline aggregates of quartz (Fig. 3), K-feldspar and plagioclase (Fig. 4a) showing similar shapes in terms of size and aspect ratio. According to this, it is assumed that at the scale of the thin section deformation is reasonably homogeneous.

Eleven samples have been used for texture analysis in quartz–feldspathic rocks, which present a planolinear (SL) to linear fabric (L). Samples were basically taken in flat-lying domains of the regional foliation or in areas not involved in later strike-slip reworking (location of samples in Fig. 2a). Most thin sections used for *c*-axis measurements (with the U-stage), grain size analysis and microstructural observations were cut perpendicular to the foliation and parallel to the stretching lineation (*XZ* sections), defined by elongated aggregates of quartz, plagioclase and K-feldspar. However, some were also cut and studied perpendicular to lineation (*YZ* sections; samples 031, 032a, 216b, 034b, 204b, 222) where

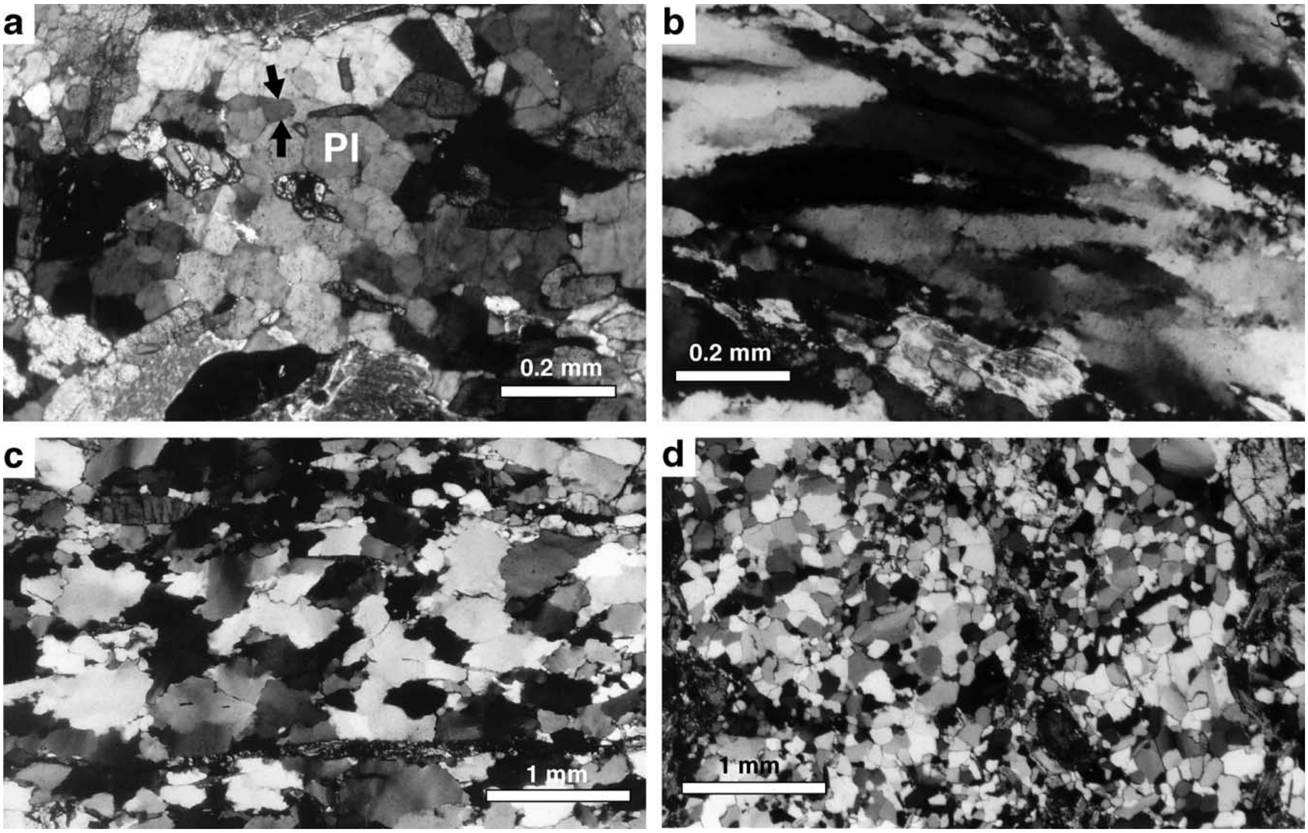

Fig. 4. Photomicrographs showing some of the microstructural features of the main tectonic foliation: (a) recrystallization of plagioclase during the development of the mylonitic fabric in the orthogneisses, sample 031 (new grains are indicated by arrows); and different types of quartz grains in orthogneisses, (b) ribbon (sample 032b), (c) irregular (sample 162), and (d) polygonal (sample 112).

some asymmetry is observed in *c*-axis textures and in sigmoid aggregates (Fig. 3). To complete the texture analysis and to compare the patterns, five samples from quartzites (samples 033, 034b, 204, 204b and 222), two samples from schists (samples 123, and 179) and one from an eclogite (sample 134) were also studied.

The *c*-axis textures shown in Fig. 6 are all presented with the crossed girdles centered in the projection (except 157), in order to ease comparison of patterns. The external structural framework, i.e. the foliation plane and the lineation pole (measured in the field), appears in most of the cases as a vertical plane and horizontal pole oriented both east–west in the projection, in agreement with kinematics of quartz deformation. However, in certain cases (samples 086, 112 and 216b) an extra rotation of *c*-axis was necessary in order to center the girdles.

Finally, the grain size analysis in quartz was carried out in some of the studied sections from the hand drawings of the grains using the image processing of National Institutes of Health (NIH), Image 1.62 (public domain program at http://rsb.info.nih.gov/nih-image/). NIH Image 1.62 measures areas of grains from binary images. The diameter of the circle with the same area as the grain measured and a small correction representing the thickness of grain boundaries was taken as the grain size in Fig. 5.

4. Deformation in quartz

4.1. Microstructure

Three types of quartz microstructures were used for texture analysis: polycrystalline aggregates with lensoid shape in orthogneisses, quartzose domains alternating with micaceous domains in schists and scattered grains in an eclogite (the content of quartz in this case is under 30%). In general, the distribution of types of grains is homogeneous on the scale of the polycrystalline aggregates with no clear domainal distribution that might influence the interpretation of the *c*-axis textures (Fig. 3). In other words, the homogeneity of the microstructure at the scale of the aggregates is interpreted as reflecting homogeneous deformation. However, to avoid any unidentified domainal distribution, *c*-axis measurements were always done across the aggregates, in transverse profiles.

Four main grain types can be distinguished: ribbon or lozenge grains (Fig. 4b), irregular grains (Fig. 4c), polygonal grains (Fig. 4d) and sub-spherical grains (Fig. 4b). Ribbon grains are rather common in orthogneisses; they are variably elongated (ratios from 2:1 to >4:1) and show grain boundaries from straight to diffuse and generally irregular (sutured). Evidence of internal

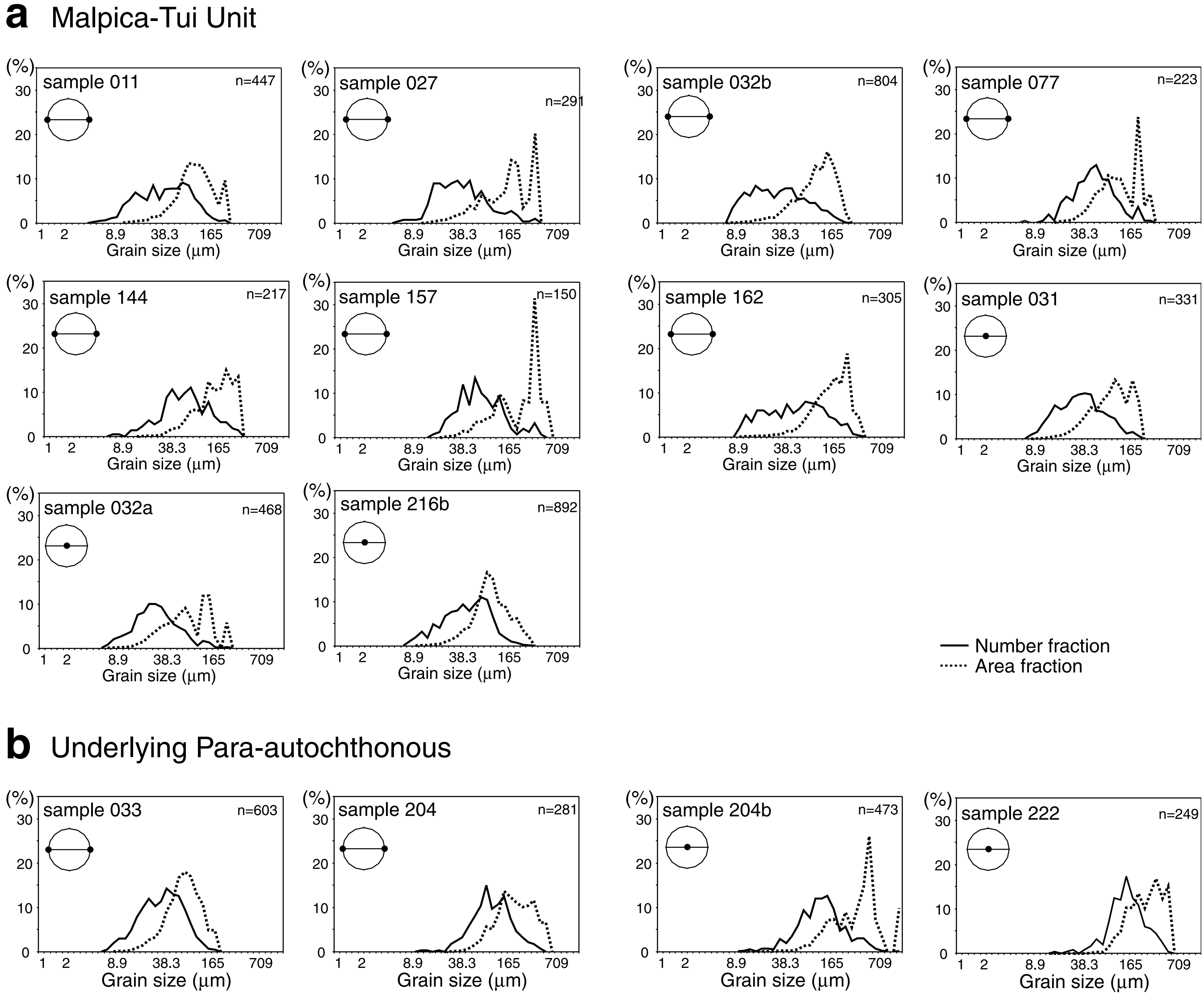

Fig. 5. Quartz grain size histograms (number and area fractions, explained in text) from some of the samples where quartz *c*-axes were measured: (a) in the Malpica–Tui Unit, and (b) in the underlying rocks from the Para-autochthonous. Note the orientation of the lineation in the thin section used for measurements, as indicated in a small projection in the upper left corner of each sample.

deformation, like undulose extinction and subgrain formation, are rather frequent (Fig. 4b). They are present in samples 011, 031, 032a, 216b and 123 (see drawings in Fig. 3). The irregular grains exhibit a wide range of morphologies; shapes are slightly elongated, sometimes tabular, with clean but strongly irregular grain boundaries, which are often lobate (Fig. 4c). Internal deformation of grains is weaker than in the ribbon grains. They appear in samples 027, 086, 144, 157, 162 and 179 (Fig. 3). The third group is characterized by their polygonal shape, with clean and straight grain boundaries, and by the absence of internal deformation within the grains (Fig. 4d). They are usually equigranular but their absolute size is very variable (150–500 μm). Despite their appearance (resembling strong thermal recrystallization), they preserve previous CPO textures (sample 086 in Fig. 6). They were observed in samples 086, 112 and 134. The last group, that of subrounded grains, includes grains with spherical to slightly elongated shapes. These grains occur either within 'transitional' (mantle–core structures) or in neat boundaries of bigger ribbon and irregular grains (100–300 μm) and their boundaries are usually, but not always, of low angle. Subrounded grains can be found in variable amounts in samples where ribbon and irregular grains are cited.

Some of the grain microstructures mentioned above correlate with those observed in quartz aggregates deformed experimentally. Ribbon and polygonal grains resemble the S-type (elongated) and P-type (polygonal) of Masuda and Fujimura (1981) and characterize, respectively, deformation regime 2 and 3 of Hirth and Tullis (1992). According to this, in samples with predominance of ribbon grains (diagnostic of regime 2) recrystallization occurred by progressive

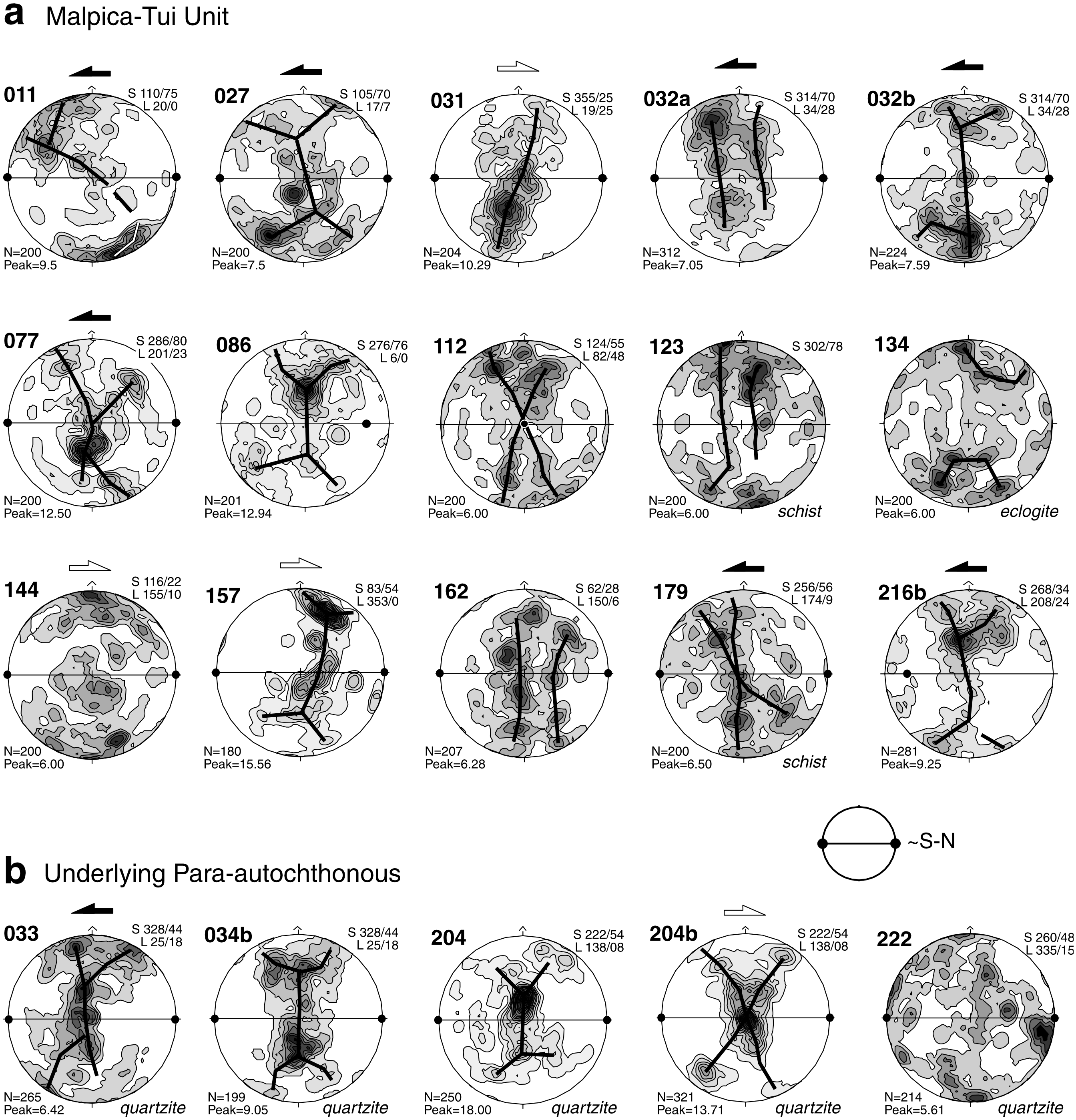

Fig. 6. (a) Quartz *c*-axis textures from the main fabric in MTU rocks and (b) in quarzites from the Para-autochthon, both measured with the U-stage (location of samples is in Fig. 2). Pole figures are contoured in 1% intervals, starting from 1%, in equal area lower hemisphere projections. The main fabric is the vertical plane (drawn as a straight line) and the lineation is indicated by black dots. North is approximately to the right in all of them. Lithology is indicated when it is not an orthogneiss.

subgrain rotation producing core and mantle structures ('transitional' grain boundaries). In samples with a predominance of polygonal grains, recovery is probably significantly accommodated by grain boundary migration, though subgrain rotation might also act during the recrystallization process to explain the lack of weakening associated with the grain boundary migration in this regime 3 (following Hirth and Tullis, 1992). Finally, samples with irregular grains can be considered as transitional between regimes 2 and 3 as they preserve elongated big grains but with strong recrystallization, which is likely to occur by grain boundary migration within the big grains and also in the smaller ones.

The distribution of grain sizes in the aggregates were studied using two variables: the number fraction (NF), that represents the frequency of different grain sizes, and the area fraction (AF), that represents the area occupied by the different grain sizes (Fig. 5). Although both variables are dependent, they were plotted in the same graph as the information they give is easier to read. The most common distribution is the one showing an outstanding difference between peaks in the number and area fraction curves, indicating the predominance in surface of few bigger grains over numerous much smaller ones. This might suggest the existence of a limited amount of recrystallization in the aggregate during the last increment of deformation. In contrast, some samples (216b, 077, 011) show a distribution where peaks of number and area fraction curves are more or less in the same range of grain sizes (66–80 μm), indicating that a certain equilibrium between the distribution of small and big grains is reached. This is probably related to a higher rate of recrystallization during deformation of the aggregate that could be closer to a 'steady state', at least from the point of view of the microstructure.

4.1.1. Microstructural evolution

An ordered sequence from ribbon to irregular to polygonal grains can be inferred from the studied samples that might be interpreted as progressive in time and related to an increasing role of grain boundary migration as the recrystallization mechanism during regional deformation. In this scheme, sub-spherical grains, more frequently associated with ribbon and less often with irregular ones, would represent grains developed by subgrain rotation recrystallization. Microstructure in samples 112 (Fig. 4d) and 086, with predominance of polygonal grains and relatively well-developed texture, could be considered as a 'steady state' microstructure, typical of deformation regime 3 in Hirth and Tullis (1992).

From results in experimental deformation (following Masuda and Fujimura, 1981; Hirth and Tullis, 1992), the microstructural evolution envisaged, from ribbon to irregular and polygonal grains, can be related with: the presence of water during deformation, which is not known with certainty in the present case; with increasing temperature, however, here exhumation is isothermal (Matte, 1998; Llana-Fúnez and Marcos, in review); and with decreasing strain rate, most likely to be the case as rocks approach the middle crust and further ascent into the crust is driven by nappe tectonics.

4.2. Quartz c-axis textures

With some exceptions, quartz *c*-axis textures show rather well-developed crossed girdles (Fig. 6). These are of type I in samples 011, 027, 032b, 086, 157, 216b, 033, 034b and 204; type II in samples 112, 179 and 204b; and very likely cleft girdles in samples 123 and 162. In other cases single girdles develop, as in samples 031 and 032a, or patterns are not clearly defined, as in samples 144, 134 (very vague small circle girdles around the *Z*-axis) and 222.

Factors that may have influenced the geometry of the quartz *c*-axis patterns studied, such us the lithology or the microstructural type of grains (referring also to the distribution of grain sizes), do not seem to play a major role. CPO patterns from schists (samples 123 and 179) and orthogneisses are comparable. Only the texture pattern in the eclogite sample (134) shows a significant difference, due to the fact that the quartz grains are scattered and represent a fraction of less than 30% of the rock (they are not the supporting framework of deformation). In a similar way, the microstructural types of grains predominant in the sample do not significantly influence the texture pattern. This probably suggests that the shape features of grains are only representative of the final stages of microstructural evolution, i.e. not necessarily related to the effect of dislocation creep but to the mechanism of recrystallization that varies in these cases between competing grain boundary migration and subgrain rotation.

In the texture patterns, some specific *c*-axis maxima appear within the girdles. In most of the cases, these maxima correspond to positions favorable for slip in prismatic (027, 031, 077, 162, 033, 204 and 204b) or rhombic planes (032a, 032b, 086, 123, 157, 216b and 034b), indicating that they developed at medium to relatively high temperature (400–600°C; Takeshita and Wenk, 1988), although other maxima are seen in basal positions (011, 123, 144 and 033), dominant at lower temperature conditions (300–400°C; Takeshita and Wenk, 1988). The unequal distribution and intensity of homologous maxima in prismatic, rhombic and basal positions with respect to the foliation plane defines an asymmetric pattern, called here 'unusual monoclinic pattern', because it is contained in the *YZ* plane and its symmetry axis is the lineation pole (Fig. 7). This type of asymmetry has not been previously taken into much consideration in texture analysis, although it is certainly present in naturally and experimentally deformed rocks (e.g. Fueten et al., 1991; Stünitz, 1991; Fueten, 1992; fig. 26 in Wenk, 1994; Pauli et al., 1996).

5. Discussion

5.1. Interpretation of quartz c-axis textures

The quartz *c*-axis textures studied in relation to the Variscan regional foliation in MTU are characterized by several types of crossed girdles. In general, *X*-, *Y*- and *Z*-axes related to plastic deformation in quartz (in coaxial deformation, see Fig. 1) show good correlation with the external structural framework of the polycrystalline aggregate, represented by the foliation plane and the lineation pole (Fig. 6). However, there are three possibilities of obliquity of texture elements with respect to *X*-, *Y*- and *Z*-axes, which are all present in the set of samples studied

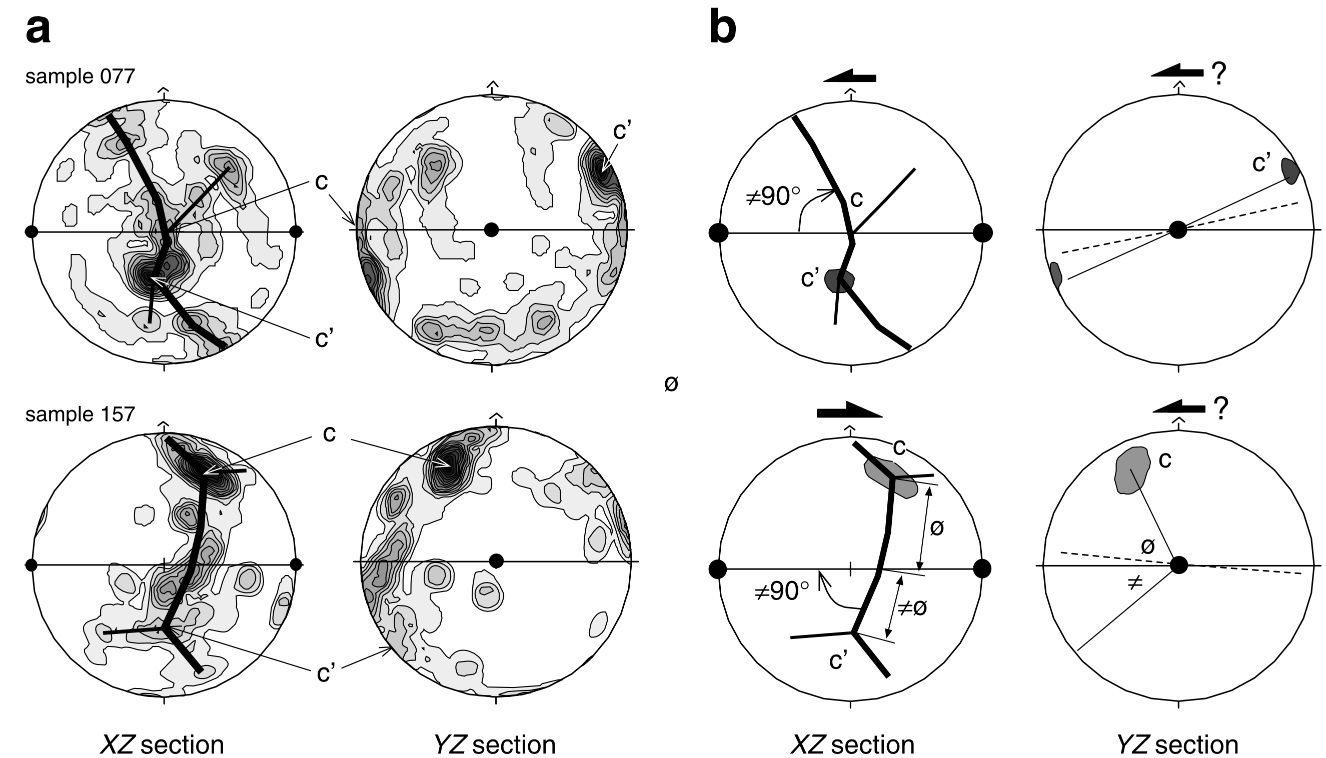

Fig. 7. The two major asymmetries in quartz *c*-axis textures, defined by apparent rotation about the *Y*-axis (conventional monoclinic asymmetry developed under simple shear) and the *X*-axis (unusual monoclinic symmetry), are shown in two well-developed patterns (samples 077 and 157). The original *c*-axis textures are plotted in *XZ* and *YZ* planes in (a) and the interpretation of the external and internal asymmetries is shown in the same planes of projection in (b). As a reference, homologous key positions in the fabric skeleton were indicated as **c** (upper sub-hemisphere) and **c**′ (lower sub-hemisphere) in the patterns and ø as the angle from **c** to the foliation plane in sample 157. The different angles of **c** and **c**′ (ø in sample 157) with the foliation plane and the difference in the intensity of measurements define, respectively, the external and internal asymmetry in both cases, contained in the *XZ* and *YZ* planes. The positions of **c** and **c**′ selected would correspond approximately to orientations favorable to slip in prismatic planes for sample 077 and in rhombic planes for sample 157. The kinematic interpretation of maxima in such positions is expected to be different.

(Fig. 6): apparent rotations about the *Y*-, *X*- and *Z*-axes. The first type is associated commonly with simple shear deformation or sub-simple shear deformation by several authors (e.g. Ramsay and Graham, 1970; Lister and Williams, 1979; Dell'Angelo and Tullis, 1989; Passchier and Trouw, 1996; Fig. 7). It includes an external asymmetry of the pattern, indicated by the obliquity of the texture elements (in this case the girdle), and by an internal asymmetry defined by differences in intensity of measurements (following Passchier and Trouw, 1996). This asymmetry in *XZ* planes has been reproduced in a number of experiments and simulations (e.g. Lister and Williams, 1979; Dell'Angelo and Tullis, 1989; Wenk et al., 1989) and according to the reproduced geometries, it would indicate top-to-the-south sense of shear in seven samples (011, 027, 032a and 032b, 077, 179, 216b and 033) and top-to-the-north sense of shear in four of them (031, 144, 157 and 204).

The second asymmetry is due to the apparent rotation of the pattern about the *X*-axis, producing what was called in the previous section an 'unusual monoclinic' pattern (Fig. 7). Again, it includes external and internal asymmetries (Fig. 7). In the present study it is found in 10 out of 14 samples from the same structure in rocks from the MTU (samples 027, 031, 032, 077, 086, 123, 144, 157, 179 and 216b) and from the underlying Para-autochthonous (samples 033, 034b, 204). It is defined either by *c*-axis maxima in orientation favorable for prismatic, rhombic and even basal slip. As asymmetry in quartz *c*-axis textures is frequently associated in plane strain with a contribution of non-coaxial deformation to the general flow regime (see, among others, Lister and Williams, 1979; Bouchez and Pecher, 1981; Passchier, 1983; Law 1990), it is also related here with a non-coaxial component during deformation perpendicular to the lineation. Until now, this sort of asymmetry in quartz *c*-axis textures has not been reproduced in either experiments or simulations. However, a theoretical approach by Passchier (1998) to 3-D flow regimes not restricted to plane strain considers such an asymmetry in textures (in basal position, see his fig. 13) as a consequence of deformation under Xi shear zone segments, where stretching (i.e. lineation) is perpendicular to the non-coaxial component of deformation.

The kinematic interpretation of this asymmetry is not known yet. When it is defined by orientations favorable for basal slip (as in Passchier, 1998), the sense of shear is relatively easy to infer as the slip plane is perpendicular to the *c*-axis and there is only one possible slip direction, the *a*-axis. However, when asymmetry is defined by maxima favorable for slip in rhombic and prismatic planes, two slip directions are possible, but it is not feasible to identify them from *c*-axis texture patterns. To interpret this correctly, complete texture analysis and simulations are required, presently not available for comparison with natural examples such as this.

Finally, there is a third type of asymmetry indicated by the apparent rotation of texture elements about the *Z*-axis, which is present in samples 086, 112, 216b and 157. Three of them (086, 216b and 157) show a small angle of obliquity (<20°), probably due to local flow heterogeneities that do not influence greatly the regional analysis (in addition, samples 216b and 157 are predominantly planar) and the fourth one is found in a planar fabric with a very weakly developed lineation, and therefore is regarded as being not reliable.

5.2. Other reported quartz textures with similar geometry

Fabric mapping of deformed areas on a regional scale reporting quartz *c*-axis textures indicating generalized 3-D general flow as shown above are not reported so commonly in the literature as in other cases where deformation is concentrated in discrete bands. Wenk (1994), reviewing data from Behr (1964), shows an increasing triclinic distortion in quartz *c*-axis textures in relation to a gabbro intrusion (fig. 26, p. 197 in that paper) but no relation with flow regime was inferred. With respect to deformation in high pressure domains, Cannat (1985) studied the regional foliation in an allochthonous unit from Ile de Groix in France (location in Fig. 2), but she assumed simple shear deformation during foliation development. This unit records a H*P*–LI*T* metamorphic event, which is comparable with the one in the MTU and related probably to the same Variscan collision in SW Europe. This author measured quartz *c*-axis textures in 13 samples, 11 of which show exactly the same predominant asymmetric distribution as the one described here in the *YZ* plane (see figs. 3, 5, 7 and 8 in Cannat, 1985). Initial assumptions for the type of flow during the regional fabric development led to different interpretations; however, it is very significant that in both cases (MTU and Ile de Groix rocks), the measured textures are comparable and related to the same process.

Unusual monoclinic or triclinic quartz *c*-axis textures might also be found in rocks within discrete shear zones where deformation is strongly heterogeneous or where lateral extrusion is not discarded. This is the case for the domainal quartz *c*-axis fabrics described by Fueten et al. (1991). Although the scale of observation and its structural implications are different, the interpretation about local flow type might be the same.

5.3. Constrains of the tectonic framework on the exhumation process and deformation geometry

The development of unusual monoclinic and triclinic asymmetries (simultaneous combination of unusual and conventional monoclinic asymmetries; Fig. 8) in quartz *c*-axis textures in relation to the regional deformation studied, has major implications for the interpretation of the flow regime during the exhumation of MTU high pressure rocks. The most significant is the relation between maximum stretching in rocks, represented by the lineation, and the direction of tectonic transport, in tectonic terms related to the direction of compression and plate convergence. In the present regional scheme, neither are parallel any longer, as they would be under generalized simple shear conditions.

The orientation of the stretching lineation has been shown previously to be parallel to the structural trend in the southern branch of the Ibero–Armorican Arc (Dias and Ribeiro, 1995; Llana-Fúnez and Marcos, in review, and references therein). Concerning the general tectonic transport in the orogen, there are some qualitative observations proving that the direction of convergence that gave place to the Variscan belt in SW Europe initially had a high angle in relation to general plate boundaries. The first evidence is the development of high pressure and low to intermediate

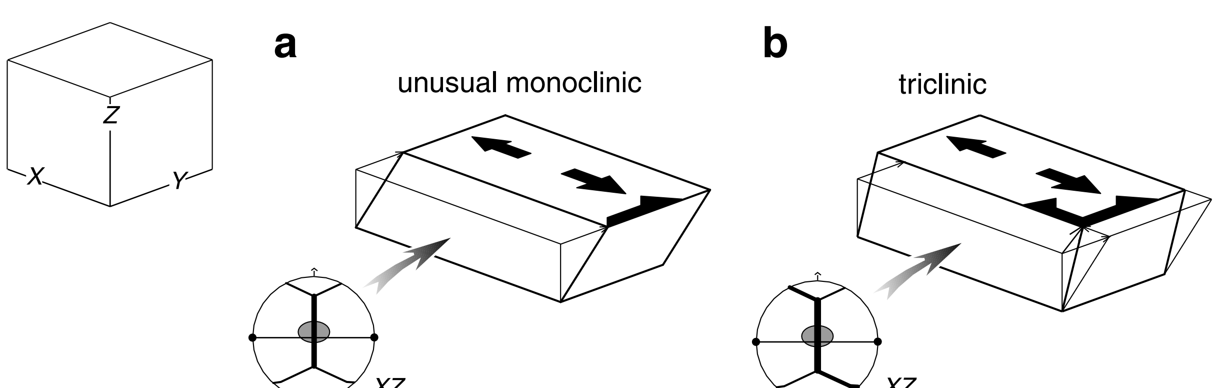

Fig. 8. Sketch showing the geometry of deformation under: (a) unusual monoclinic symmetry, where stretching is perpendicular to the non-coaxial component of deformation, and (b) triclinic symmetry, where there are two components of non-coaxial deformation, which are parallel and perpendicular to stretching. A tentative prediction of quartz *c*-axis textures is shown in both cases. The first flow type (a) would be equivalent to the ones proposed by other authors: 'rolling dough' type (Lister and Price, 1978), sub-horizontal pure shear (Gilotti and Hull, 1993) and Xi segment shear zone (Passchier, 1998).

metamorphism during the Variscan collision, which cannot be produced in strike-slip orogens (Thompson et al., 1997). The second evidence is the development of an orogenic wedge where relics of exotic terranes preserved in the allochthonous nappes (in NW Iberia and also in Brittany) overlap the Iberian plate, located under the suture, indicating its partial buring during the collision (e.g. Pérez-Estaún et al., 1991; Martínez Catalán et al., 1997). The general tectonic framework is complicated a bit further by the development of an arc mega-structure, the Ibero–Armorican Arc, which has been related to an irregular continent–continent collision in which the Iberian plate is indented onto the exotic terranes located to the West, presumably in the Laurentia realm (Matte and Burg, 1981; Matte, 1986, 1991; Dias and Ribeiro, 1994, 1995).

The process of indentation tectonics implies stress and pressure gradients along the collisional front (Mancktelow, 1993), therefore, there is likely lateral extrusion of rock masses, 'tectonic escape' at the surface (Tapponnier and Molnar, 1976; Ratsbacher et al., 1991). This indeed precludes simple shear flow as the deformation regime in the rocks involved in regional ductile deformation and extensive foliation development, and favors the consideration of 3-D general geometries for this distributed deformation. During the indentation of the Iberian plate, the sides of the orogens might have remained unconstrained, allowing lateral flow at high angles to the convergence direction. In this hypothesis, the lateral flow would be recorded in rocks by the regional stretching lineations.

One of the present-day tectonic settings for these indentation processes is the Nanga Parbat syntaxis in the Himalayas (Matte, 1986), where deformation partitioning associated with the indentation of India against Asia is probably the expression at the surface of a more continuous deformation at depth, where rheological constrasts are smoothed, thus favoring ductile lateral extrusion and 3-D flow types. In ancient orogenic belts a similar tectonic interpretation related to the development of b-lineations has also been reached by Gilotti and Hull (1993) from a widely deformed area under amphibolitic conditions, in relation to the deep parts of a continent–continent collision in the Scandinavian Caledonides.

6. Concluding remarks

The development and accumulation of the finite tectonic fabric in the rocks of the Malpica–Tui Unit during their exhumation to the middle crust from H*P*–LI*T* conditions, has been studied through the plastic deformation recorded in quartz. CPO analysis in major mineral components supporting strain in rocks is a useful tool for the understanding of widespread deformation processes in the inner parts of orogens, as it provides 3-D information about kinematics during deformation.

The 3-D flow regime inferred to produce the quartz *c*-axis textures described in this contribution, with stretching perpendicular to the major non-coaxial component of deformation, based on regional geology and tectonics (Llana-Fúnez, 1999; Llana-Fúnez and Marcos, in review) and supported by recent theoretical approaches, has not yet been reproduced either by experimental deformation or computer simulations, though some of their properties, the plastic anisotropy, have already been studied (Takeshita and Wenk, 1988). The occurrence of such 3-D flow geometries in natural deformation make more sense in certain deep tectonic settings and seem to be more realistic than the more extreme flows like pure and simple shear considered to-date in distributed ductile deformation. Future simulations and experiments of 3-D non-coaxial deformations are needed to properly interpret the kinematics of these textures and should open new insights in structural geology in order to understand widespread ductile deformation in collisional orogens.

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