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Quartz fabrics pattern along the Forcarei synform (NW Iberian Massif) and their tentative tectonic model

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Abstract: Quartz fabric patterns investigated within a suite of metaquartzites collected from the Forcarei synform, in the most internal zone of the NW Iberian Massif, are used to interpret the detailed processes involved in fabric and fold evolution. Quartz fabrics related to the Variscan tectonic foliation S_2 were formed by non-coaxial deformation and under 3-D general monoclinic flow. Regional stretching lineation is sub-horizontal and parallel to the general trend belt. Sinistral shear sense is indicated in both limbs of the synform using several indicators. Latter, coaxial horizontal shortening perpendicular to the L_2 occurred during the third phase of the Variscan deformation and produced the tilting and uprighting of this large-scale fold. A laterally constricted shear zone system formed between the orthogonal flow directions of the upper and lower crust during the thinning of the orogenic wedge is tentatively proposed to explain the main Variscan D_2 deformation event of the basal units and lower allochthon of the Galicia-Trás-os-Montes Zone.

Keywords: quartz *c*-axis fabrics, shear sense indicators, Iberian Massif, Forcarei synform, Variscan tectonics.

Orogenic hinterlands frequently have structures superposed with associated foliations; in many of the areas where various overprinting foliations can be recognised, a 'main foliation' has usually been formed under peak metamorphic circumstances, while later and less penetrative foliations may have been formed under lower metamorphic conditions. Foliations show 'tectonic fabrics' that can be used to obtain information on deformation conditions, to define the relative sequence of deformational events, and to establish geometrical and kinematical relationships with major structures such as folds or shear zones.

Within the Galicia-Trás-os-Montes Zone (GTMZ) of the NW Iberian Massif, allochthonous complexes (Arenas *et al.*, 1995) were tectonically emplaced over the lower allochthon or Schistose Domain (Farias *et al.*, 1987), implying a horizontal displacement of at least 250 km (Fig. 1). The basal units form a fairly continuous thrust sheet consisting of schists and paragneisses alternating with felsic and mafic igneous rocks, of which granitic and peralkaline orthogneisses have yielded Rb-Sr and U-Pb ages of 490-470 Ma (Santos-Zalduegui *et al.*, 1995). The basal units record a high-P regional metamorphic event not found in the lower allochthon. Peak pressures reached 1.5-1.7 GPa in a W-directed subduction zone (in present coordinates), as is deduced from the pressure gradient (Martínez-Catalán *et al.*, 1996), implying a vertical displacement of the basal unit of at least 40 km. Subduction may have started ca. 380 Ma and ended ca. 365 Ma (Rodríguez *et al.*, 2003).

The Forcarei synform (Marquínez, 1984) crops out to the south of the Ordenes Complex and involves the basal unit and the lower allochthon (Fig. 1b).

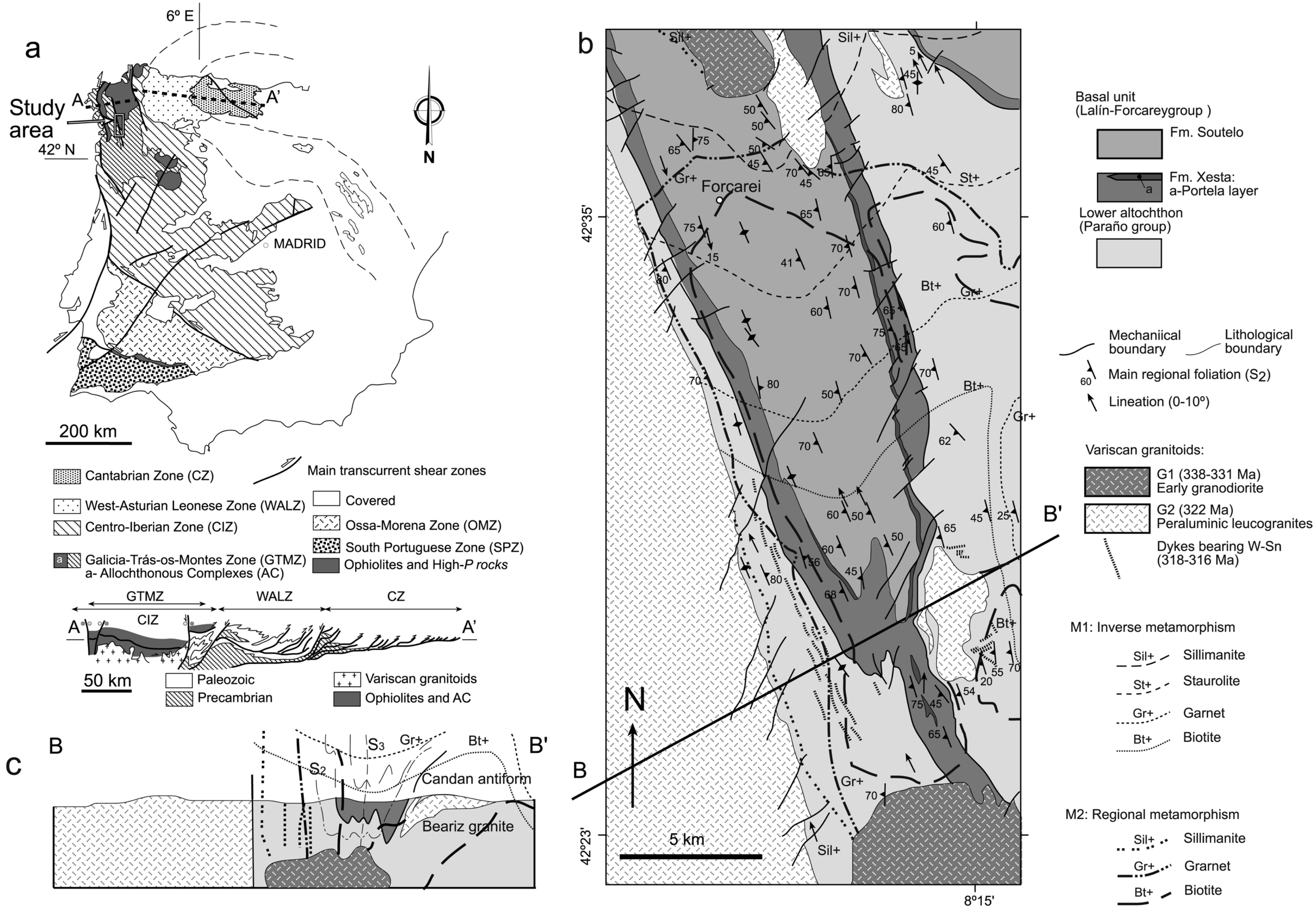

Figure 1. (a) Location of the study area in the Iberian Massif. The A-A' cross section has been modified after Pérez-Estaún *et al.* (1991), (b) geological map of the study area based on Marquínez (1984), (c) cross section through the southern part of the Forcarei syncline. Variscan granitoids after Gonzalez-Cuadra *et al.* (2006) and Gloaguen (2006), regional metamorphism after Marquínez and Klein (1982) and inverse metamorphism after Martínez-Catalán *et al.* (1996).

The main foliation (S_2) is a flat-lying schistosity spaced in domains Q-M that has a stretching lineation frequently parallel to the trend of the Variscan belt (Fig. 1). The Forcarei synform was interpreted as a D_3 fold because it has a well developed crenulation cleavage parallel to the sub-vertical axial plane folding the S_2.

In this study, a suite of metaquartzites and quartz-schists have been collected from the Forcarei synform for quartz *c*-axis fabrics analysis in combination with shape fabric analysis, for the characterization of the flow type and deformation conditions of the main foliation (S_2). In addition, field mapping of other shear sense indicators and superimposed structures at outcrop scale has allowed the interpretation of the processes involved in fabric and folding evolution.

The study area

The Forcarei synform is a sub-horizontal upright isoclinal fold outcropping within an approximately 275 km^2 area. Its axis trends NNW parallel to the trend belt (Fig. 1). A substantial layer of quartz-mylonite, the Portela layer (Hilgen, 1971), occurs interbedded into the basal unit. The exact origins of this pervasively deformed and thinness layer (10 cm-5 m) is uncertain, but it is known to be derived from a metaquartzite and has been sampled because it is the most suitable rock type of the stratigraphic sequence for quartz *c*-axis fabric analysis; complementarily quartz-schists samples of lower allochthon were also collected (Fig. 2).

At least two foliations can usually be observed: the main foliation S_2 and a crenulation cleavage attributed to the third phase of the Variscan deformation (Marquínez, 1984; Díaz-García, 1991, 1993). The main foliation S_2 is a schistosity in domains Q (microlithons of quartz) and M (cleavage defined by micas) that seems to be more evolved in the basal unit, where a previous cleavage is preserved only into porphyroblast of albite and garnet, than in lower allochthon. The regional S_2 shows a mineral, elongation lineation that is subhorizontal and parallel to the rootless centimetric folds which appear in the upper part of the lower allochthon as sheat folds. This main foliation was later affected by an open upright fold, the Candan antiform (Fig. 1c) that locally developed a spaced crenulation cleavage (Marquínez, 1984). The S_3 often presents minor structures frequently associated with such as minor fold, conjugated shear bands and symmetric boudinage. Despite both S_2 and S_3 foliations apparently have the same orientation (Fig. 2); in some locations it is possible to observe S_3 superimposed on S_2 and forming type 2 and 3 Ramsay fold interferences (Ramsay, 1962). Consequently, they can only be differentiated because S_2 is most penetrative than S_3; the symmetry of the fabric and associated structures suggests that D_2 is characterized by non-coaxial deformation, whereas D_3 is basically coaxial (Fig. 2).

Crystallization-deformation relationships suggest a prograde metamorphic evolution from S_2 to the Variscan granitoids intrusion (Marquínez and Klein, 1982; Díaz-García, 1993). In the study area, the Beariz granite (Fig. 1c) was emplaced in the final stages of the S_2 development, and was slightly folded into the upright Candan antiform showing top-to-the south kinematic criteria (González-Cuadra *et al.*, 2006). In the northern part of Forcarei synform a pre-D_3 previous metamorphic inverse zonation has been mapped, related to the emplacement of the ophiolitic unit onto the basal unit (Martínez-Catalán *et al.*, 1996). Inverse isogrades partially transect the Forcarei synform and appear folded by the Candan antiform (Figs. 1b and 1c). Metamorphic and structural relationships suggest that Forcarei synform had been initiated before the emplacement of the ophiolitic unit, and was tilted and tightened during the latter stages of the Variscan deformation.

Quartz *c*-axis fabric and kinematic interpretation

Eleven hand-collected samples have been used in this preliminary study of quartz *c*-axis preferred orientation. Two samples were collected from the Portela layer (F-22 and F-138) and the other samples were collected from the lower allochthon within both limbs of the Forcarei synform (Fig. 2). Microstructurally, metaquartzites and quartz-schist present a composite foliation defined by coarse-quartz domains and fine-grained matrix domains composed of quartz (50-70%), biotite + muscovite ± garnet ± staurolite (20-40%) and feldspar (<10%). Coarse-grained domains are in fact quartzitic veins within the matrix, which presumably were formed also during D_2. Samples were basically taken in areas of dominant S_2 regional foliation where later deformation is not involved.

Quartz *c*-axis fabrics were studied using a Zeiss U-stage in *XZ*-section (perpendicular to the S_2 foliation and parallel to L_2) and in *YZ*-section. In all samples, the *c*-axes were measured separately within the

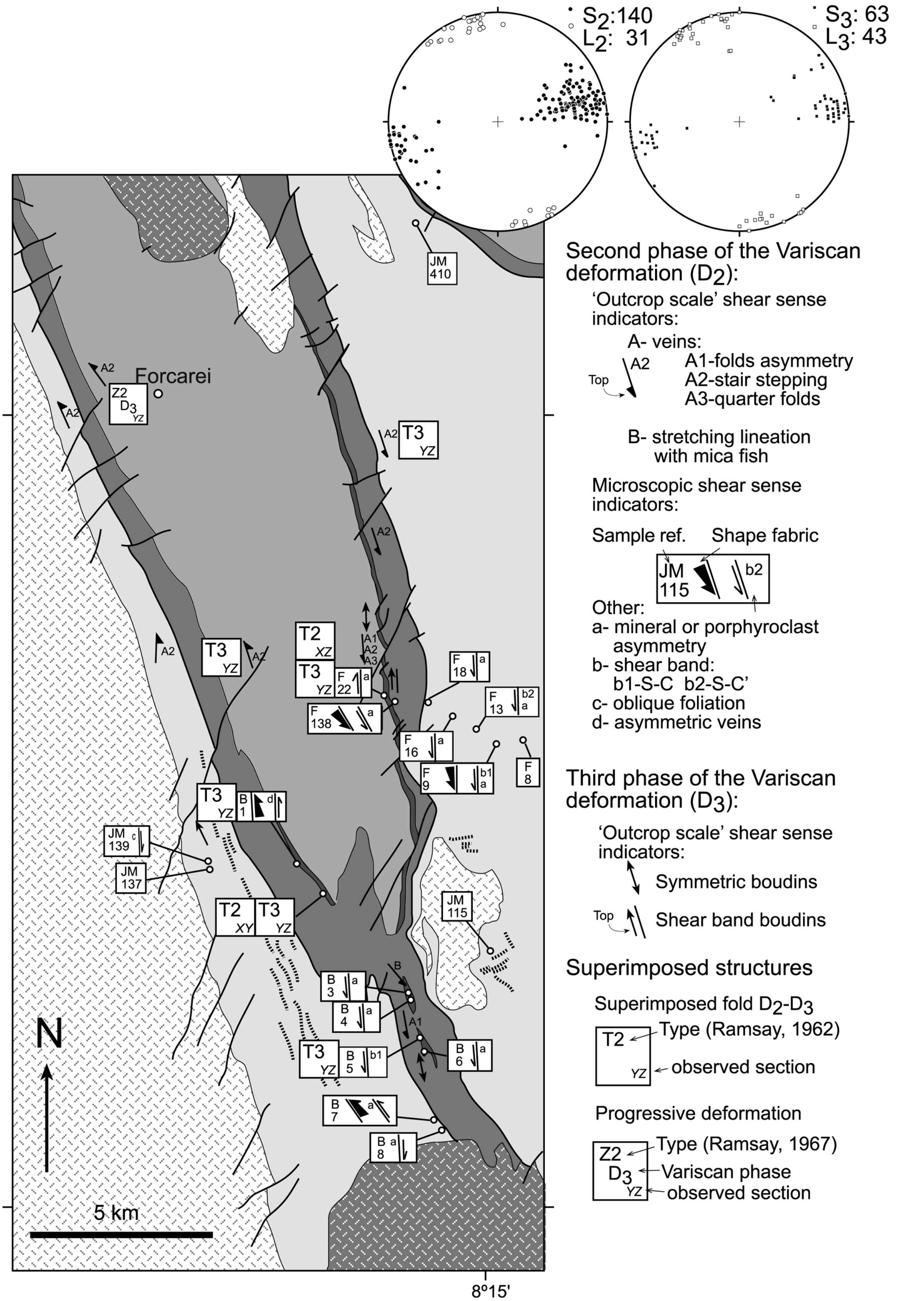

Figure 2. Structural and kinematic map of the study area showing the sample location, the shear sense indicators (see Passchier and Trouw, 2005, for details), and the superimposed D_2 - D_3 structures. All diagrams are lower hemisphere equal-area projections.

domains of coarse and fine-quartz, but not significant differences within the fabric patterns have been appreciated. The quartz *c*-axis patterns show rather anomalous girdles (Fig. 3). In most cases the quartz *c*-axis corresponds to positions favourable for slip in the basal (maximum around *Z*) and prismatic planes (maximum on *Y*), indicating that they developed at temperatures ranging from 300 to 600 ºC (Christie and Green, 1964; Bouchez and Pêcher, 1981, Takeshita and Wenk, 1988) in agreement with the Variscan metamorphic conditions (Fig. 1). Sample F-138 developed a quartz *c*-axis pattern defined by two point maxima around *Z*. In addition, some of the samples show a maximum point of lesser intensity close to *X* (JM-410, JM-139, F-138, F-8, F-13 and F-18).

Usually patterns of quartz *c*-axes obtain an asymmetry when they accumulate by non-coaxial progressive deformation, and this asymmetry can be used to deduce the sense of shear. The internal asymmetry of *c*-axis girdles in most cases are in agreement with the external asymmetry of the patterns with respect to the foliation and lineation frame, S_2 and L_2, respectively, with the exception of samples F-16 and F-18, whose internal asymmetry points to the opposite sense (Fig. 3). Occasionally fabrics present kinematic domains of less than thin-section scale, similar to the effect described by García-Celma (1982). Since within the Forcarei synform S_2 is sub-vertical and L_2 sub-horizontal, shear sense is indicated as dextral or sinistral; the reproduced geometries, together with the external asymmetry, would indicate sinistral sense of shear in five samples of the east limb, and in the three samples of the west limb (Fig. 3). In addition, the unequal distribution and intensity of homologous maxima in basal and prismatic position with respect to the S_2 and L_2 defines a third type of asymmetry, called here 'triclinic' because it is due to the apparent rotation of the pattern about the *X* and the *Z* axes.

Interpretation of shear sense using exclusively quartz *c*-axis preferred orientation is not recommendable (Passchier and Trouw, 2005). The shear sense of the main S_2 regional foliation has been determined, therefore, using other kinematic indicators, such as the asymmetry of the shape fabric (SPO), measured for all the samples following the procedure explained in Fernández *et al.* (2005). Fold asymmetry, shear veins, quarter fold veins, shear bands and oblique foliations have also been used. All the kinematic indicators have been represented in figure 2 and summarised in table 1, and strongly suggest a bulk sinistral shear sense during the development of the non-coaxial D_2 deformation. In the field, only a small number of sets of shear band boudins have been found deforming the S_2 foliation and indicating locally dextral sense of shear (Fig. 2). They have been interpreted as later D_3 structures related to a bulk coaxial extension parallel to the fold axis.

Constraints of the tectonic framework for D_2 within GTMZ

Structural and metamorphic observations along the whole of the HP basal units indicate that they were subjected to regionally intense non-coaxial shearing during their exhumation from 30-40 km depth. This deformational event (D_2) extended laterally for almost 250 km developing a penetrative S_2 schistosity and recumbent folds (Carrio, Silleda, Galiñeiro and probably Forcarei) within a coherent sinistral (belt parallel) kinematics (Díaz-García, 1991, 1993; Llana-Fúnez, 2002; Díez-Fernández *et al.*, 2002 and this paper). The schistosity S_2 is also well developed within the lower allochthon of the GTMZ, and has been characterized by quartz *c*-axis patterns of apparent 'triclinic' symmetry. Quartz fabrics are similar to others reported in the same units of the NW of Iberian Massif (Llana-Fúnez, 2002); this suggests that this tectonic regional foliation is produced by a lateral extrusion of rock masses during a regime of 'tectonic escape'. However, we tentatively propose that this shear zone represents an accommodation structure between two different 3-D tectonic flow directions into the orogenic wedge of the NW Iberian Massif. Thus, the presumable lateral spreading of the lower crust induced by the thinning and tapering of the orogenic wedge will have occurred coeval with a perpendicular flow direction of the upper crust characterized by thin- and thick-skinned thrust tectonics toward the foreland (Fig. 1a). Between both 3-D flow directions, a laterally constricted shear zone system will have developed the main foliation of the GTMZ, and will have been the most efficient structure to accommodate deformation during the continuous thinning of the wedge.

Kinematic and fabric analysis of other similar shear zones of the Variscan belt in Europe is needed for a better understanding of complex shear zones characterized by *c*-axis quartz fabric with low order symmetry.

Preliminary conclusions

Field mapping of shear sense indicator within the Forcarei syncline and microstructural analysis, reveal that the flat-laying foliation S_2 was formed by a non-

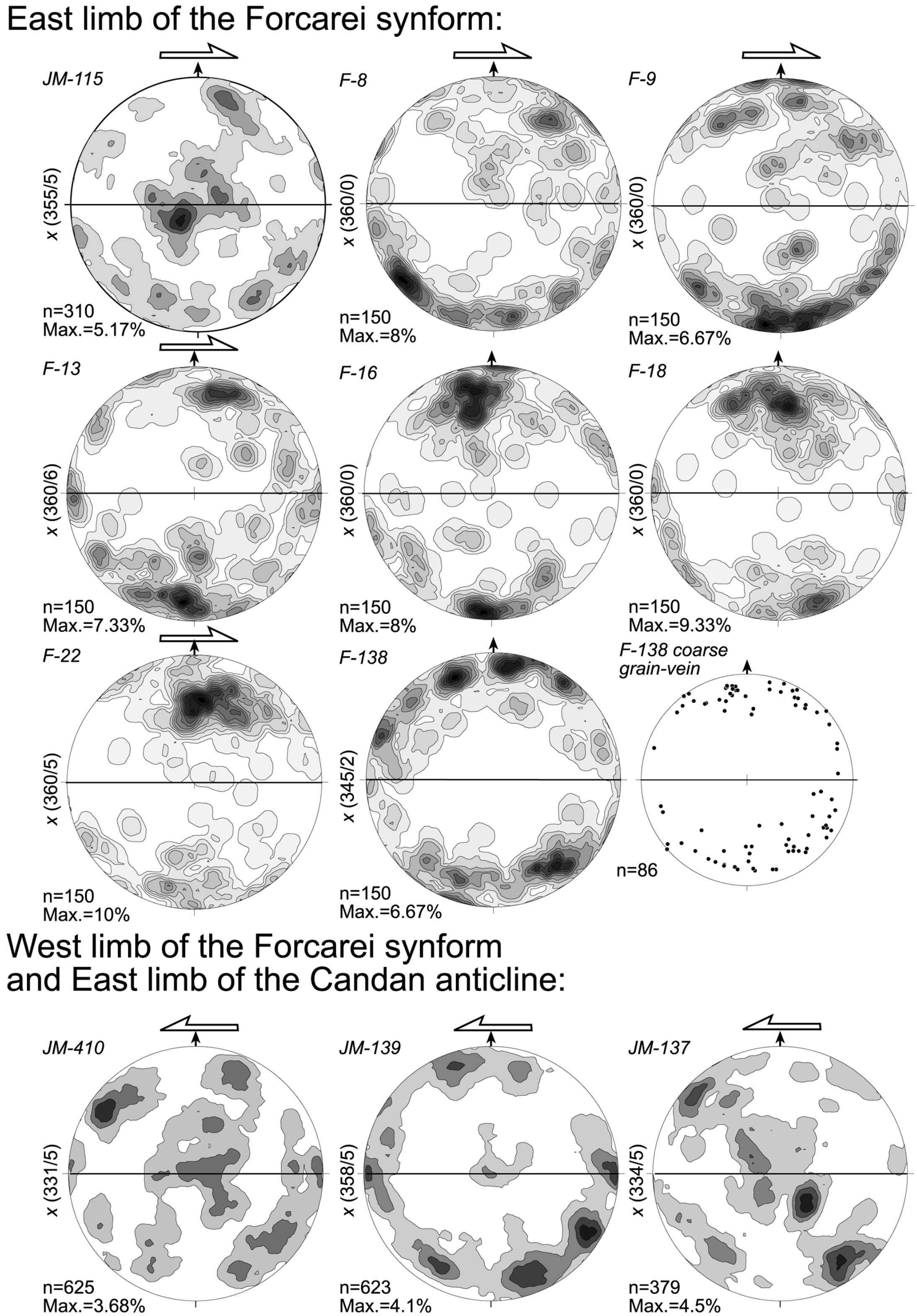

Figure 3. Quartz *c*-axis textures from the regional Variscan fabric in parautochtonous quartz-schists and in metaquartzites from the basal unit. Location samples are in figure 2. Pole figures are contoured in 1% intervals, starting from 1%, in equal area lower hemisphere projections; solid line: rock foliation (normal to *Z*); *X* is horizontal (stretching lineation). North is approximately to the left and the arrows indicate the shear sense of fabric patterns using the external frame (S_2 and L_2) as a reference system.

Sample	***Quartz c-axes***	***Shape fabric***	***Porphyroclast asymmetry***	***Shear bands***	***Stair steeping***
(West limb of the Forcarei synform and east limb of the Candán anticline)					
JM 410	sinistral	-	-	-	-
JM 137	sinistral	-	-	-	-
JM 139	sinistral	-	-	-	-
Other	-	-	-	sinistral (in 1 locality)	sinistral (in 4 localities)
(East limb of the Forcarei synform)					
F 8	sinistral	-	-	-	-
F 9	sinistral	sinistral	sinistral	sinistral	
F 13	sinistral	-	sinistral	-	sinistral
F 16	-	-	sinistral		-
F 18	-	-	sinistral	-	-
F 22	sinistral	-	dextral	-	-
F 138	-	sinistral	sinistral	sinistral	
JM 115	sinistral	-	-	-	-
Other	-	-	-	dextral (in 1 locality)	sinistral (in 4 localities)

Table 1. Summarised shear sense indicators from quartz fabric analysis and local field observations (Fig. 2). Note sinistral, according to the stratigraphic way-up of units within the Forcarei syncline, is top-to-the south along the east limb, but is top-to the north along its west limb.

coaxial deformation. The assessment of the shear sense using quartz *c*-axis patterns, SPOs, microstructures and other 'field' shear sense indicators strongly suggest a sinistral rotation in both limbs of the synform. Consequently, the fold and S_2 fabrics have been formed contemporaneously in a shear zone parallel to the structural trend of the orogen. Later, coaxial horizontal shortening perpendicular to the fold trace occurred during the third phase of the Variscan deformation and produced crenulation cleavage, and boudinage extension parallel to L_2, minor folds superposition and the upright of the Forcarei synform.

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