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Stepped fibres in sillimanite-bearing veins: valid shear-sense indicators in high grade rocks?

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Abstract

Sillimanite-bearing veins with striking lineated and stepped fibre surfaces occur in migmatitic amphibolite- and granulite-facies sillimanite-bearing gneisses in the Betic Cordillera, southern Spain. The quartz-dominated and peraluminous leucogranite veins occupy brittle to semi-brittle hydraulic fractures and shear fractures that cross-cut the main foliation of the gneisses. The shear sense suggested by fibre steps concurs with independent criteria where observed (e.g. foliation deflection at vein margins). Petrographic study suggests that oriented quartz–sillimanite fibres were formed during vein dilation, and experienced later ductile and brittle strain, with microboudinage and microfracturing of sillimanite aggregates perpendicular to the long axes of the fibres due to their pronounced anisotropy. The geometry of the steps is thus controlled by the initial fibre orientations, reflecting the original sense of shear during vein formation. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The interpretation of small-scale shear-sense indicators in deformed rocks is fundamental to our understanding of continental deformation and orogenic evolution (e.g. Dewey et al., 1989; Platt et al., 1989; Ring et al., 1989; Lonergan, 1993; Little et al., 1994), and the kinematic significance of these structures needs to be assessed with care (e.g. Means, 1990; Hanmer and Passchier, 1991). This paper describes the first recorded examples of brittle steps in fibrous sillimanite aggregates on vein surfaces from the Betic Cordillera, southern Spain. The surfaces are reminiscent of fibre-lineated fault surfaces (e.g. Fleuty, 1975; Durney and Ramsay, 1989; Urai et al., 1991) with a silky, rather than polished, lustre, and discrete steps cutting fibres in a consistent orientation, suggesting brittle fracture during simple shear. Study of the veins leads to some clarification of their origin, their use in kinematic analysis, and implications for deformation mechanisms in high grade rocks.

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2. Geological setting

The Internal Zones of the Betic Cordillera (southern Spain) are a well-documented example of an orogenic belt which experienced Oligo–Miocene extensional collapse to below sea level (Platt and Vissers, 1989; García-Dueñas et al., 1992). This study focuses on parageneses within the Alpujarride nappe complex, the middle of three major Internal Zone complexes (e.g. Torres-Roldán, 1979). Alpujarride rocks are regionally at greenschist grade, but attain granulite facies adjacent to tectonic sheets of subcontinental mantle lithosphere (e.g. Vissers et al., 1995).

The Carratraca massif, 4 km WNW of Málaga (Fig. 1), is the smallest of three lherzolite massifs (the 'Ronda Peridotites'), exhumed during extensional dismemberment of the orogenic edifice (Platt and Vissers, 1989; Vissers et al., 1995). The 2-km-thick peridotite sheet underlies a drastically thinned, 4 km crustal section (the Jubrique Unit), with greenschist facies phyllites at the top and granulite gneisses in contact with the peridotite (Loomis, 1972a,b; Westerhof, 1977; Balanyá et al., 1993). This apparent thermal gradient (144°/km) results from about 90% shortening normal

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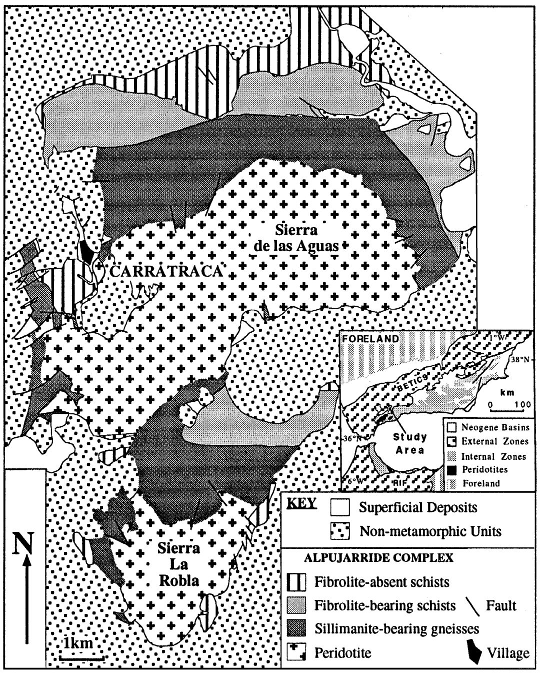

Fig. 1. Summary geological map of the Carratraca area, showing subdivision of the metapelitic Jubrique Unit into distinct metamorphic zones. Inset shows location of study area within the Betic-Rif orogenic arc in the western Mediterranean.

to the foliation, accompanied by heating from asthenospheric mantle replacing detached lower lithosphere (Argles et al., 1999). Early Alpine fabrics in the metapelites were transposed during coaxial vertical shortening, which formed an exhumation-related foliation that was itself partly overprinted by LP metamorphism. With exhumation to higher crustal levels, deformation became increasingly non-coaxial, and this NE-directed shearing phase culminated in low-angle, extensional fault zones which excised parts of the section (Argles et al., 1999).

3. Description

3.1. Host rocks

Stepped veins formed in coarse, metapelitic gneisses (quartz–k-feldspar–plagioclase–garnet–sillimanite/kyanite–biotite–corderite–hercynite–illmente/rutile) with abundant sillimanite both defining and statically overprinting a strong LS fabric; few sillimanite-bearing veins from overlying schists are stepped. Lineation trends vary between NW and NE, but NE-trending lineations dominate late parageneses (cross-cutting leucogranite veins and retrograde shear zones), implying that the NW trend is a relic of an earlier kinematic regime. Local, peraluminous partial melts were generated throughout the exhumation process.

3.2. Sillimanite-bearing veins

All schists with sillimanite contain sillimanite-bearing veins: including early veins with relict kyanite; synmetamorphic, concordant quartz–sillimanite–biotite $\pm$ plagioclase($\pm$tourmaline) veins with sillimanite–biotite lineations sub-parallel to the regional extension lineation; and similar veins in shear fractures (or otherwise discordant fractures), which may be stepped. In the gneisses sillimanite is more abundant than in the schists, but many of the sillimanite-bearing veins are locally-derived, peraluminous quartz–k-feldspar–plagioclase–tourmaline–sillimanite $\pm$ garnet $\pm$ corderite $\pm$ muscovite leucogranites. Stepped, sillimanite-rich surfaces are most characteristic of quartz-rich veins, containing some K-feldspar and plagioclase, and biotite that is embayed and rimmed by sillimanite, as in the host gneiss. Both concordant and discordant veins occur; those at low angles to the foliation generally contain fibre lineations only slightly oblique to the regional extension lineation.

4. Structural aspects of the veins

4.1. Mesostructure

As well as the veins, there are many quartz–sillimanite gneissic segregation layers concordant with the foliation containing sillimanite crystal aggregates aligned parallel to the regional extension lineation. Discrete, ductile shear surfaces of similar material occur in the leucogranites. Discordant veins range from ductile to brittle: some occupy shear zones which deflect the gneissic foliation, but others cross-cut and truncate the fabric sharply. Several vein surfaces are exposed in the Carratraca area (see Figs. 2 and 3). They are irregular, roughly planar features with clear sillimanite lineations, and the fibres are commonly stepped like slickenfibres, implying a sense of shear if the same mechanism is invoked for their formation (see Fig. 2a and b) (e.g. Durney and Ramsay, 1989). The 'fibres' are aggregates of sillimanite and quartz a few centimetres long (Fig. 2c). Fibre lineations may vary across an outcrop; thin laminae of fibres with different lineation trends may overlap on the same surface (Ramsay and Huber, 1983, pp. 257–261); some fibres are curved. The millimetre-scale steps are roughly perpendicular to the long axes of the fibres and restricted to the vein material; few brittle fractures penetrate far into the vein walls. There is no *S–C* fabric related to the steps in the adjacent gneiss, and the steps themselves are not striated. Independent shear sense for stepped veins was observed at three localities in the gneisses, where the veins occupy asymmetric mylonitic shear zones; sig-

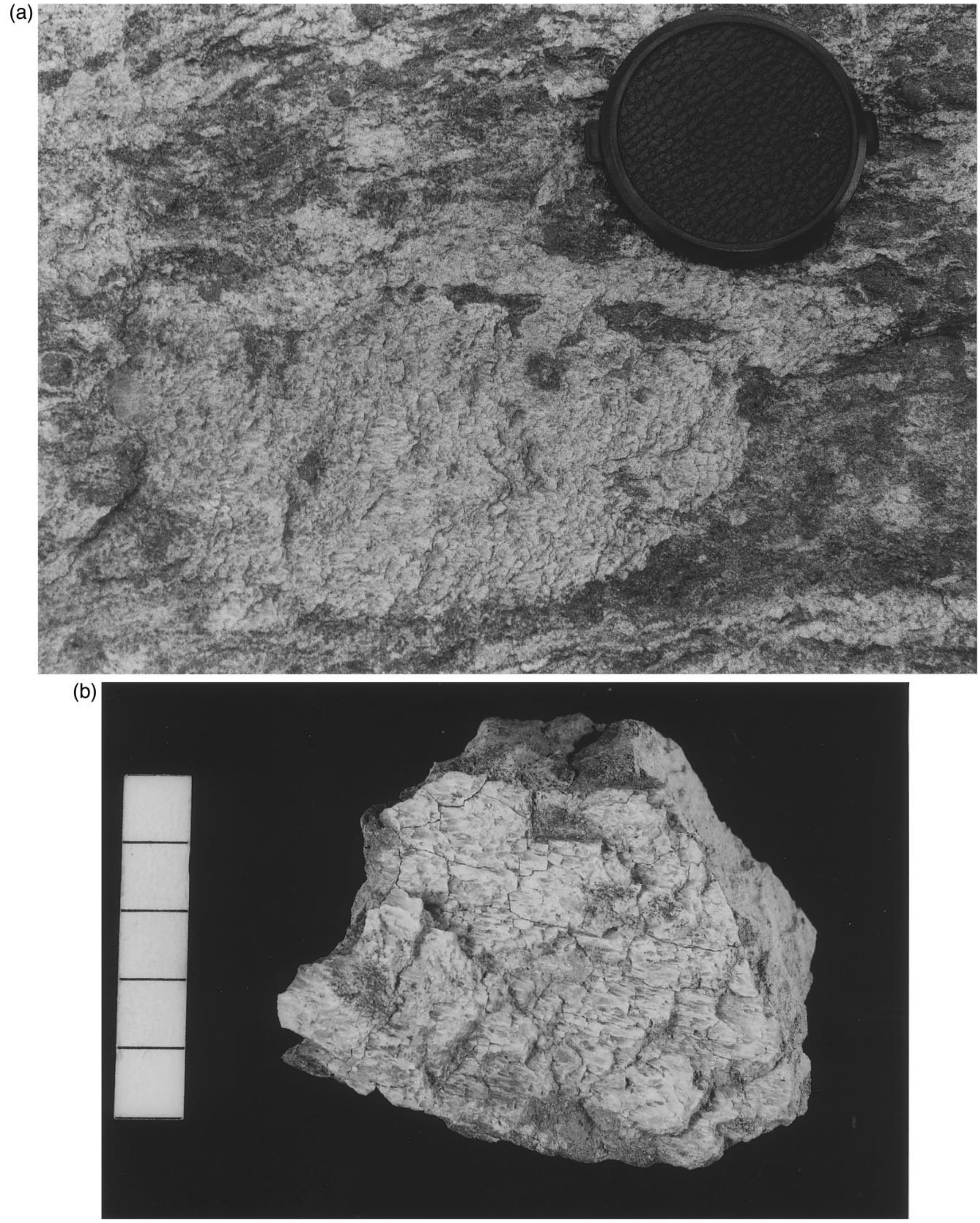

Fig. 2. (a) Portion of irregular, brittle, vein surface showing sillimanite–quartz fibres with steps giving a systematic top-to-the-right (NE) sense of shear. This vein cross-cuts gneissic foliation; there are also concordant sillimanite-bearing leucosomes at this locality. Lens cap has a diameter of 62 mm. (b) Stepped sillimanite–quartz fibres from same locality as (a). Shear sense as above; relief of vein surface has been exaggerated by lighting. Scale bar 5 cm. (c) Photomicrograph showing fracture cross-cutting sillimanite aggregate (centre) and quartz in vein from same locality as (a). Fracture cuts sillimanite aggregate at 90°, in contrast to its orientation in the quartz matrix. Scale bar 100 μm (aligned parallel to vein margin). (d) Photomicrograph of part of preserved, stepped edge of the same vein. Note obliquity of sillimanite aggregates to trend of vein margin (parallel to photo edge), and the stepped geometry of the vein edge due to preferential fracturing either orthogonal or parallel to fibre aggregates. Diffuse, irregular vein/gneiss margin partly reflects post-veining recrystallization and deformation. Scale bar 500 μm.

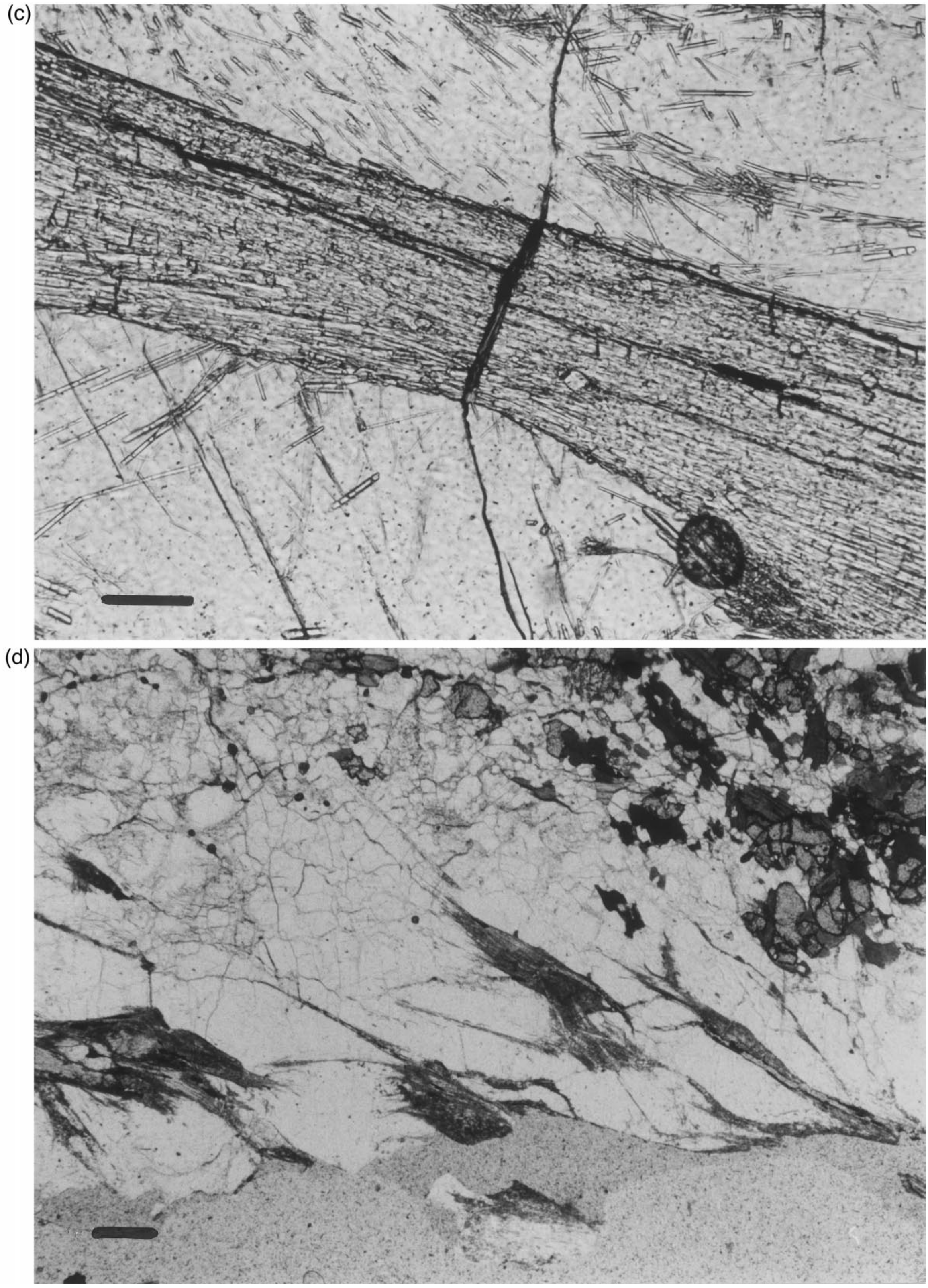

Fig. 2(c, d).

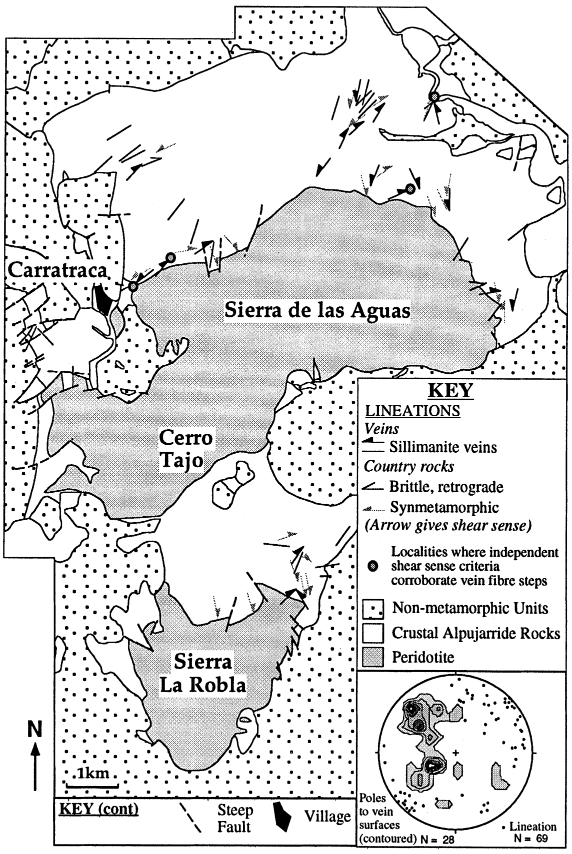

Fig. 3. Map of the Carratraca area showing lineation data for sillimanite-bearing veins. Sense of shear (arrows) is that suggested by fibre steps for veins, and diverse ductile criteria for host rocks. Localities where fibre step shear sense is confirmed by independent criteria are marked. Inset shows a stereogram incorporating a 1% contour plot of poles to vein surfaces and sillimanite lineations. These are dominantly NE–SW, but there is a cluster of SE-trending points.

moidal foliation deflection gives the shear sense across the vein (Fig. 4c). At two localities, the shear zones are part of a whole suite with consistent shear sense, some with synkinematic leucogranitic material, others lacking veins altogether; i.e. foliation deflection was not a local response to the veins. One vein in a schist formed in an asymmetric shear fracture where foliation trajectories give a shear sense again consistent with that suggested by fibre steps. No examples of conflicting shear sense on veins were found. Many veins show NE-directed shear (Fig. 2a), in common with other late-stage parageneses; a few are SE-directed, corresponding to the local sense of shear in the gneiss (Fig. 3). Diverse vein (and lineation) orientations in many cases reflect local strain accommodation rather than a systematic set of structures.

4.2. Microstructure

Elongate quartz is coarser in the veins than in the gneiss (Fig. 2d), with some subgrain development; sillimanite aggregates are concentrated along grain boundaries, but quartz also contains oriented sillimanite inclusions. Many sillimanite aggregates show localised cross-cracks, some infilled with quartz or white mica, perpendicular to the long axes of the fibres; most later brittle fractures cross-cut aggregates at 90° or run parallel to the fibres, regardless of their orientation in adjacent vein quartz (Fig. 2c). Individual sillimanite needles are microboudinaged, with quartz infilling boudin necks, which may coincide with fluid inclusion arrays. Some vein sillimanite aggregates are continuous with randomly oriented sheaves of sillimanite after biotite in the gneiss wall; the vein margin is irregular, with no consistent stepped geometry, reflecting the inhomogeneity of the gneiss at the grain scale (Fig. 2d).

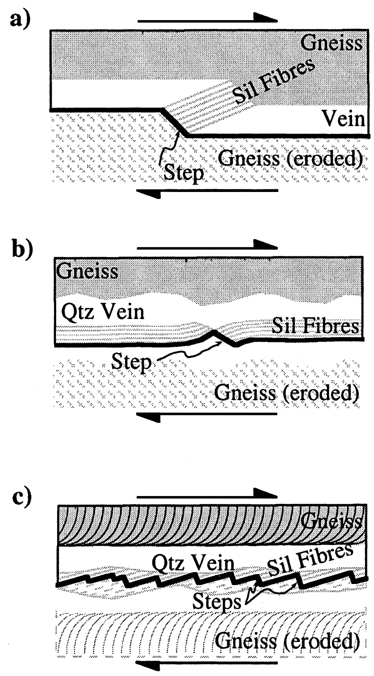

Fig. 4. Sketch models for origin of stepped sillimanite-bearing vein surfaces (steps exaggerated for clarity). Shear sense during vein formation dextral in all cases. Uneroded outcrop outlined in black; thick lines mark observed surface. (a) Steps correspond to vein wall irregularities where fibres nucleated; analogous to slickensides. (b) Composite vein (e.g. two-stage growth). Steps form along sillimanite–quartz interface following asymmetric foliation boudinage of originally-concordant sillimanite aggregate. Note the lack of obliquity in the fibres, so that no shear sense is implied in this case for vein formation. (c) Composite or heterogeneous vein in ductile shear zone. Brittle fracture parallel, or at 90°, to oblique sillimanite fibres results in stepped surface. Many fractures exploit earlier microboudin necks at 90° to fibre aggregates [i.e. a combination of (b) and (c)]. Foliation deflection in adjacent gneiss confirms shear sense suggested by fibre steps as described in text. This model best fits the available evidence.

5. Discussion

It is tempting to use these stepped fibres as simple kinematic indicators of fault motion, analogous to slickenfibres. However, sillimanite growth suggests temperatures above 570°C (Holland and Powell, 1990), while the gneisses record still higher temperatures (700–750°C at 400–800 MPa: Argles et al., 1999). It is essential to consider their formation more fully.

The veins formed by shear or hydraulic fracture during late-stage partial melting and metamorphism, largely post-dating pervasive ductile deformation. Vein material was either peraluminous melt, or silica-rich fluid containing aluminium in some form; the absence of tourmaline and apatite from quartz-rich assemblages argues for a locally-derived metamorphic fluid source rather than influxes of exotic, alkali-rich fluids (Kerrick, 1988, 1990; Cesare, 1994). Some steps may mirror initial fracture-wall irregularities where fibres nucleated, as in slickensides (Fig. 4a); however many aggregates are isolated from the gneiss (Fig. 4c). Vein textures in the schists suggest co-precipitation of quartz and fibrolite in dilational shear fractures after initial vein formation, but exposure of the steps has erased much of the evidence.

The veins experienced solid-state deformation, causing microboudinage of sillimanite crystals and aggregates, analogous to foliation boudinage (Platt and Vissers, 1980). Asymmetric microfractures could have formed during non-coaxial strain on vein-parallel fibres (Fig. 4b), though observed fractures are at much higher angles to the fibres than would be expected for this process. Later brittle fractures were largely controlled by the strong anisotropy of the sillimanite aggregates, exploiting microboudin necks or running parallel to the fibres; they commonly exhibit a stair-stepping geometry reflecting any original obliquity of the fibres to the vein walls, and thus the sense of shear during vein formation (Fig. 4c).

Recent studies on *ductile* ridge-in-groove slickenside striae with associated steps (Wilson and Will, 1990; Lin and Williams, 1992) are not directly applicable to these structures; the vein surfaces lack such striations, and there are no *S–C* fabrics in the vein or wallrock.

6. Conclusions

The use of fibre steps in sillimanite veins as kinematic indicators at amphibolite grade and higher is tentatively endorsed. It should be stressed that the steps themselves are in most cases simply a consequence of fibre geometry and may have been formed by processes acting considerably later than vein formation. However, by reflecting the obliquity of fibres to the vein walls, they record the sense of motion during vein formation. The examples described above appear consistent with independent shear-sense indicators, and contribute to the regional kinematic scheme. With careful examination of the field and petrological relationships, such veins can provide discrete, dateable kinematic information related to processes such as partial melting, ductile shear and shear fracture.

The veins record extensive hydraulic fracturing in high grade metamorphic rocks, where strongly anisotropic materials are susceptible to brittle boudinage even at high grades.

Veins acted as fluid sinks, and maybe conduits, in an anatectic migmatite zone, focusing locally-derived metamorphic fluids and partial melts. Further research is planned to clarify the source of the aluminium silicates in veins throughout the metapelitic section, but preliminary work suggests the majority are derived from local metamorphic reactions by diffusion into synmetamorphic fractures and boudin necks, as documented elsewhere by Cesare (1994).

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References

Argles, T.W., Platt, J.P., Waters, D.J., 1999. Attenuation and excision of a crustal section during extensional exhumation: the Carratraca Massif, Betic Cordillera, southern Spain. Journal of the Geological Society of London 156, 149–162.

Balanyá, J.C., Azañon, J.M., Sanchez-Gomez, M., García-Dueñas, V., 1993. Pervasive ductile extension, isothermal decompression and thinning of the Jubrique unit in the Paleogene (Alpujarride complex, western Betics Spain). Comptes Rendus de l'Academie des Sciences 316, 1595–1601.

Cesare, B., 1994. Synmetamorphic veining: origin of andalusite-bearing veins in the Vedrette di Ries contact aureole, Eastern Alps, Italy. Journal of Metamorphic Geology 12, 643–653.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics. Geological Society Special Publication 45, pp. 265–283.

Durney, D.W., Ramsay, J.G., 1989. Incremental strains measured by syntectonic crystal growths. In: Dejong, K.A., Scholten, R. (Eds.), Gravity and Tectonics. John Wiley, New York, pp. 67–96.

Fleuty, M., 1975. Slickensides and slickenlines. Geological Magazine 112, 319–322.

García-Dueñas, V., Balanyá, J.C., Martínez-Martínez, J.M., 1992. Miocene extensional detachments in the outcropping basement of the Northern Alboran Basin (Betics) and their tectonic implications. Geomarine Letters 12, 88–95.

Hanmer, S., Passchier, C.W., 1991. Shear-sense indicators: a review. Geological Survey of Canada Paper 90-17.

Holland, T.J.B., Powell, R., 1990. An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: the system K_2O–Na_2O–CaO–MgO–MnO–FeO–Fe_2O_3–Al_2O_3–TiO_2–SiO_2–C–H_2–O_2. Journal of Metamorphic Geology 8, 89–124.

Kerrick, D.M., 1988. Al_2SiO_5-bearing segregations in the Lepontine Alps, Switzerland: Aluminium mobility in metapelites. Geology 16, 636–640.

Kerrick, D.M., 1990. The Al_2SiO_5 polymorphs. Mineralogical Society of America Reviews in Mineralogy 22.

Lin, S., Williams, P.F., 1992. The origin of ridge-in-groove slickenside striae and associated steps in an *S–C* mylonite. Journal of Structural Geology 14, 315–321.

Little, T.A., Miller, E.L., Lee, J., Law, R.D., 1994. Extensional origin of ductile fabrics in the Schist Belt, Central Brooks Range, Alaska—I. Geologic and structural studies. Journal of Structural Geology 16, 899–918.

Lonergan, L., 1993. Timing and kinematics of deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, southeast Spain. Tectonics 12, 460–476.

Loomis, T.P., 1972a. Contact metamorphism of pelitic rock by the Ronda ultramafic intrusion, southern Spain. Geological Society of America Bulletin 83, 2449–2474.

Loomis, T.P., 1972b. Diapiric emplacement of the Ronda high-temperature intrusion, southern Spain. Geological Society of America Bulletin 83, 2475–2496.

Means, W.D., 1990. Kinematics, stress, deformation and material behaviour. Journal of Structural Geology 12, 953–971.

Platt, J.P., Vissers, R.L.M., 1980. Extensional structures in anisotropic rocks. Journal of Structural Geology 2, 397–410.

Platt, J.P., Vissers, R.L.M., 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and the Gibraltar arc. Geology 17, 540–543.

Platt, J.P., Behrmann, J.H., Cunningham, P.C., Dewey, J.F., Helman, M., Parish, M., Shepley, M.G., Wallis, S., Weston, P.J., 1989. Kinematics of the Alpine arc and the motion history of Adria. Nature, London 337, 158–161.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology, Volume 1: Strain Analysis. Academic Press, London.

Ring, U., Ratschbacher, L., Frisch, W., Biehler, D., Kralik, M., 1989. Kinematics of the Alpine plate-margin: structural styles, strain, and motion along the Penninic–Austro-alpine boundary in the Swiss–Austrian Alps. Journal of the Geological Society of London 146, 835–849.

Torres-Roldán, R.L., 1979. The tectonic subdivision of the Betic Zone (Betic Cordilleras, southern Spain): its significance and one possible scenario for the westernmost Alpine belt. American Journal of Science 279, 19–51.

Urai, J.L., Williams, P.F., van Roermund, H.L.M., 1991. Kinematics of crystal growth in syntectonic fibrous veins. Journal of Structural Geology 13, 823–836.

Vissers, R.L.M., Platt, J.P., Van der Wal, D., 1995. Late orogenic extension of the Betic Cordillera and the Alboran Domain: A lithospheric view. Tectonics 14, 786–803.

Westerhof, A.B., 1977. Contact relations of high-*T* Peridotites in the Serrania de Ronda, Southern Spain. Tectonophysics 39, 579–591.

Wilson, C.J.L., Will, T.M., 1990. Slickenside lineations due to ductile processes. In: Knipe, R.J., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics. Geological Society Special Publication 54, pp. 455–460.