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Structural evidence for the relationship between thrusts, extensional faults and granite intrusions in the Variscan belt of Galicia (Spain)

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Abstract—New structural and petrofabric data are presented from the Hombreiro pluton, a synkinematically emplaced granite located in the northern part of the Variscan belt of Spain. This pluton shows the imprint of two plastic deformations: the first is related to the motion of the Mondoñedo Nappe, with a top-to-the-east shear sense, and the later one to the Vivero Fault, an extensional shear zone with a top-to-the-west motion. These deformations initiated at high temperatures, close to the granite solidus as shown by the preservation of [*c*]-slip fabrics in quartz. This fact indicates that extensional faulting was activated soon after the thrusting of the Mondoñedo Nappe during which the Hombreiro Granite was emplaced. We propose that the position of the Vivero Fault was controlled by a crustal instability induced by the intrusion of a number of plutons that delineate the footwall block of this fault.

INTRODUCTION

FOR several years, ductile extensional faults have been recognized as a common structural feature in many convergent orogens (Burg *et al.* 1984, Platt 1986, Behrmann 1988). Much of the knowledge of this structural association comes from the Tibetan plateau, where the North Himalayan Normal Fault shows a northwards sense of shear, opposite to the overall southwards transport of the Main Crystalline Sheet (Burg *et al.* 1984, Brun *et al.* 1985). A similar case has been recognized in the French Massif Central (Mattauer *et al.* 1988).

The development of such extensional faults is usually explained by a mechanism of thinning provoked by the gravitational collapse of a crustal wedge thickened during a process of continental collision (Platt 1986, Royden & Burchfiel 1987). Nevertheless, there is evidence that some areas are faulted in preference to others. For example, the intrusion of granites into the continental crust presumably plays an active role in determining the localization of some extensional faults, as proposed for the North Himalayan Normal Fault (Burg *et al.* 1984, Mattauer & Brunel 1989) and the extensional faults of the Variscan belt of the French Massif Central (Mattauer *et al.* 1988, Faure 1989).

In this work we present a structural and kinematic study of the Vivero Fault, a ductile extensional shear zone which cuts across the Variscan belt of eastern Galicia (Spain). We intend to show here that not only the crustal thickening but also the emplacement of granite plutons have contributed to the initiation and the development of this extensional shear zone.

GEOLOGICAL SETTING

The overall structure of the Variscan belt of Galicia is the result of compressional tectonics, which led to crustal thickening by E-vergent thrusts (Marcos 1973, Martínez Catalán 1980, Bastida *et al.* 1986). Several allochthonous units that form the Cabo Ortegal Complex (Fig. 1) are interpreted as ophiolite sheets (Bayer & Matte 1979, González Lodeiro *et al.* 1982) resting on top of this nappe complex. The Vivero Fault is a major N–S-trending and W-dipping shear zone, which separates the Mondoñedo Nappe to the east from the Ollo de Sapo Anticlinorium to the west (Fig. 1). The extensional nature of this fault, strongly suggested by the fact that Precambrian rocks on the footwall side (Mondoñedo Nappe) are in contact with Ordovician and Silurian rocks on the hangingwall side (Ollo de Sapo Anticlinorium), is strengthened by kinematic criteria which consistently bring low-grade metamorphic rocks of the Ollo de Sapo Anticlinorium down onto medium- to high-grade metamorphic rocks of the Mondoñedo Nappe (Martínez Catalán 1985).

The Mondoñedo Nappe has been affected by four main phases of deformation (Bastida *et al.* 1986). The first produced megascopic isoclinal folds with a flat schistosity. The second phase produced the ductile shear zone which forms the base of the nappe. Finally, both of these structures were further deformed into two systems of open and upright folds, with a longitudinal or radial pattern of the fold axes. The region studied corresponds to the Hombreiro Granite (Fig. 1) which crops out in the core of a dome formed by the interference of the longitudinal and radial folds.

FIELD STRUCTURES

Magmatic and deformational structures in the Hombreiro Granite

Magmatic foliations can be recognized in many areas of the Hombreiro Granite (Fig. 2). They are defined by

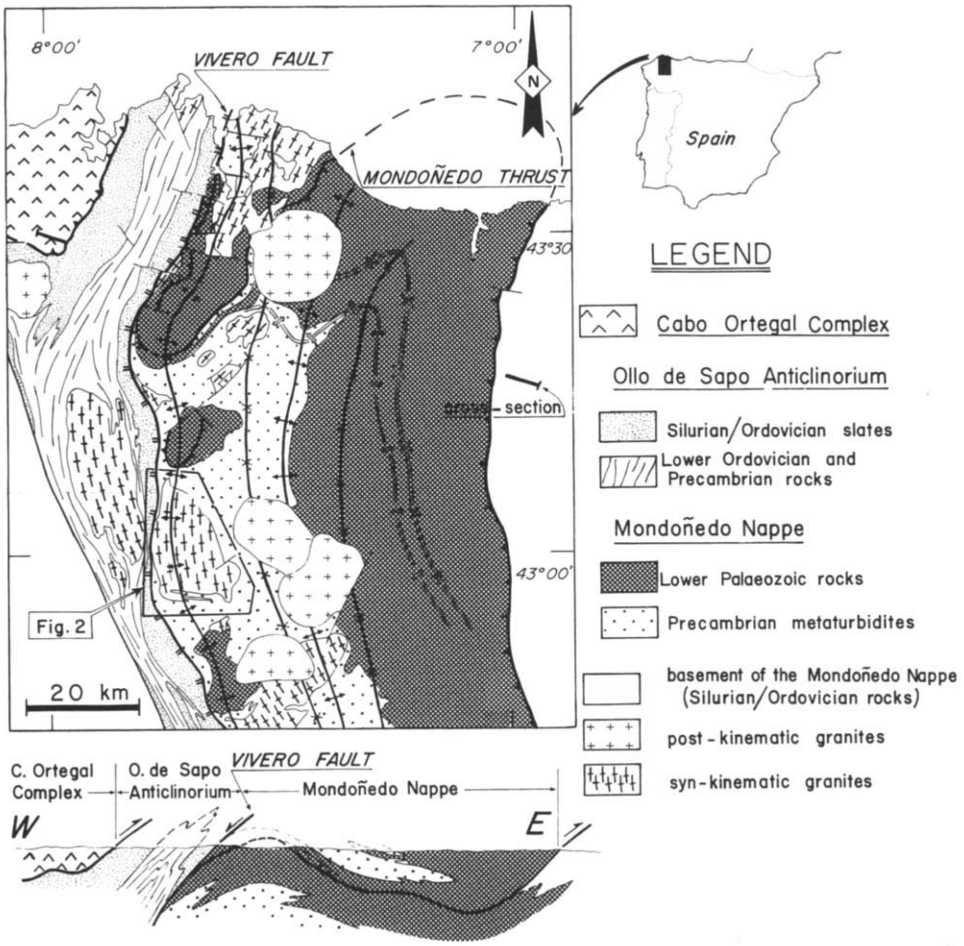

Fig. 1. Geological map of the north-western part of the Variscan belt of Spain. Some major F_1 (open symbols) and F_4 (black symbols) fold axial traces are also shown. Simplified from Bastida *et al.* (1986) and Bellido Mulas *et al.* (1987).

the preferred orientation of subhedral igneous minerals with tabular habit, like potassic feldspar, plagioclase and micas. Quartz aggregates show equiaxial shapes and are composed of a few strain-free grains. According to studies from other granites (Blumenfeld & Bouchez 1988), such microstructures are diagnostic of magmatic structures. The magmatic foliation usually strikes N–S and dips moderately to the west or east, due to the effect of late longitudinal folds (Fig. 2). Restoring these folds, the magmatic foliation would be flat-dipping, suggesting that the granite body takes the form of a sheet roughly concordant with D_1 and D_2 structures of the Mondoñedo Nappe.

The Hombreiro Granite shows the imprint of two ductile deformations. The first is concentrated around a shear zone which delineates a ring inside the massif (Fig. 2). This shear zone displays a flat foliation and locally *S–C* structures. The foliation is defined by the parallel arrangement of potassic feldspars, micas and quartz aggregates. Similar mineral orientations can be seen in adjacent undeformed granites, so that they do not by themselves provide unambiguous evidence as to the significance of this foliation. However, the dynamic recrystallization shown by potassic feldspars as well as the flattening of quartz aggregates support the action of solid-state deformations. The occurrence of myrmekite rims at potassic feldspar boundaries parallel to the foliation is a distinctive microstructure of tectonites from this shear zone with respect to the undeformed granites. On the foliation plane, a stretching lineation is clearly defined by the preferred orientation of elongated aggregates of quartz. This lineation has a N120E mean orientation (Fig. 3). From kinematic criteria, such as the asymmetry of pressure shadows around the feldspar porphyroclasts and the mica-fish geometry, a top-to-the-east sense of shear can be deduced for this shear zone. This shear sense is consistent with that of the basal thrust of the Mondoñedo Nappe (Martínez Catalán 1980, 1985, Bastida *et al.* 1986).

The second solid-state deformation of the Hombreiro Granite is expressed by the widespread presence of mylonites. These mylonites are restricted to the vicinity of the Vivero Fault, where the Hombreiro Granite develops a pervasive foliation accompanied by a prominent stretching lineation. Small new and strain-free grains along the borders of large potassic feldspar porphyroclasts are scarce in these tectonites, suggesting that much of the deformation possibly occurred outside the *P–T* field of plasticity of this mineral. In this shear zone also the lineation is concentrated around the direction N120E (Fig. 3), although here one systematically obtains a top-to-the-west shear sense (Fig. 2).

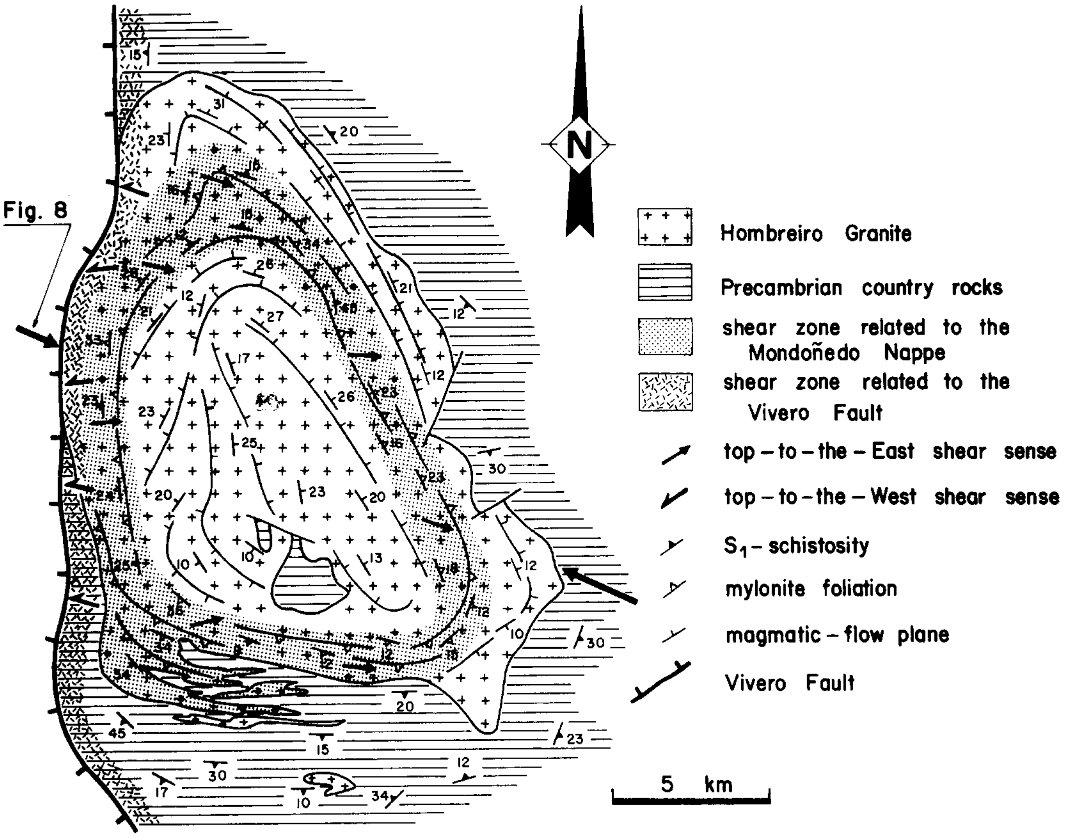

Fig. 2. Structural map of the Hombreiro Granite showing the outline of the two solid-state deformed shear zones where opposite shear senses are recorded. The pre-mylonite configuration of the granite is shown by the orientation of magmatic foliations. Trajectories of planar structures are drawn to bring out the concordance between magmatic foliations and mylonitic foliations.

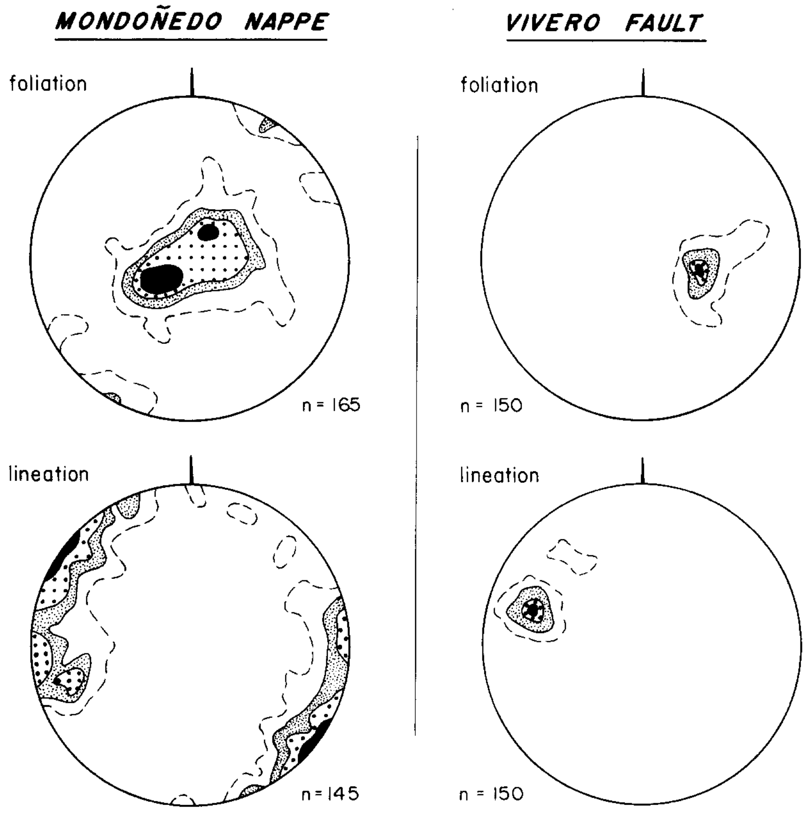

Fig. 3. Lower-hemisphere, equal-area plots of stretching lineations and poles to foliations in tectonites from the Hombreiro Granite, related to the Mondoñedo Nappe motion and to the Vivero Fault. Contours intervals: 1, 3, 5 and >10% (Mondoñedo shear zone); 5, 20 and >40% (Vivero Fault).

Metamorphic country rocks

The metamorphic country rocks are poorly exposed, so that a detailed structural analysis of these rocks could not be made. Nevertheless, relevant observations for the emplacement of the Hombreiro Granite can be made at isolated outcrops. An interesting fact is that the main schistosity of the metamorphic rocks and the magmatic foliation in adjacent granites are concordant and parallel to the granite contact (Fig. 2). This schistosity is axial planar of isoclinal folds, which even deform aplite veins intruded into biotite-bearing schists of the Mondoñedo Nappe (Fig. 4a).

Close to the Vivero Fault, the main schistosity of the Mondoñedo Nappe is overprinted by an extensional crenulation cleavage (Platt & Vissers 1980), which strikes N–S and dips to the west. It bears a N120E lineation defined by the preferred alignment of stretched porphyroclasts. Metamorphic minerals like garnet, staurolite and biotite form asymmetric porphyroclasts whereas only small biotite flakes can be found at the extensional crenulation cleavage. Senses of shear derived from these porphyroclasts or the geometry of the extensional crenulation cleavage provides a consistent top-to-the-west motion. In contrast, only a spaced and subhorizontal crenulation cleavage deforms the main schistosity of metamorphic rocks of the Ollo de Sapo Anticlinorium during the extensional motion on the Vivero Fault (Fig. 4b).

QUARTZ FABRICS

Quartz fabrics from the plastically deformed areas of the Hombreiro Granite massif have been studied with the aid of a universal stage in *XZ* sections, i.e. perpendicular to the foliation and parallel to the stretching lineation. The samples from the shear zone associated with the Mondoñedo Nappe are characterized by mosaic-like microstructures. Single grains of quartz present square or rectangular shapes and are delimitated by straight grain boundaries at right angles. Grain boundaries are oblique to the foliation trace. Quartz *c*-axis diagrams give maxima close to the stretching lineation (Fig. 5), suggesting the action of slip along the [*c*]-axis on prismatic planes.

In the Vivero Fault we have mainly obtained quartz fabrics with a single girdle oblique to the mylonitic foliation trace (Fig. 6c) or patterns with a maximum within the foliation plane and perpendicular to the stretching lineation (Fig. 6b). These tectonites frequently display a mylonitic cleavage (*C*) that may form micro-shear planes, which are oblique to and cross-cut the shape foliation (*S*) defined by the elongation of the large quartz grains outside the *C*-planes (Fig. 7a). Both the single girdle diagrams of *c*-axes and the obliquity of the mylonite cleavage (*C*) with respect to *S* point towards a non-coaxial deformation (Bouchez *et al.* 1983, Knipe & Law 1987) with a top-to-the-west sense of shear for the Vivero Fault. Less frequently, the Vivero fault zone contains fabrics in which the *c*-axes are scattered throughout the diagram, although they conserve important maxima next to the stretching lineation (Fig. 6a). In the latter case, microstructures are also characterized by mosaic-like grain arrangement (Fig. 7b) and by the presence of basal sub-boundaries within some of quartz grains. This kind of quartz fabric is usually found within lens-shaped bodies of deformed granites, surrounded by anastomosing shear zones with quartz *c*-axis patterns like that of Figs. 6(b) & (c).

The existence of optically visible basal sub-boundaries and other arguments based on TEM data led Mainprice *et al.* (1986) to interpret quartz *c*-axis diagrams similar to those of Figs. 5 and 6(a) in terms of deformation mechanisms dominated by [*c*]-slip. In contrast, diagrams of Figs. 6(b) & (c) suggest the action of slip along the ⟨*a*⟩-direction on the basal and prismatic planes, respectively. In accordance with experimental data (Kirby & McCormick 1979, Mainprice & Nicolas 1989), temperatures during plastic deformation were significantly higher for [*c*]-slip than for basal ⟨*a*⟩-slip, with those for prismatic ⟨*a*⟩-slip lying between. Most of the examples of prismatic [*c*]-slip come from tectonites deformed at high temperature (Lister & Dornsiepen 1982, Bouchez *et al.* 1985, Blumenfeld *et al.* 1986), although Garbutt & Teyssier (1991) have described quartz fabrics dominated by prism [*c*]-slip from moderate-temperature mylonitic quartzites. In our case, [*c*]-slip fabrics can be related to high-temperature deformation, as evidenced by the development of myrmekite lobes in these tectonites (Simpson & Wintsch 1989). The Mondoñedo Nappe pre-dates the birth of the Vivero Fault, as revealed by the truncation of shear zones associated with the Mondoñedo Nappe by the Vivero Fault (Figs. 1 and 2). It is worth noting that the two shear zones recognized in the Hombreiro Granite started at similar high-temperature conditions, according to the preservation of quartz fabrics dominated by [*c*]-slip in both these shear zones. On the other hand, typical quartz fabrics from the Vivero Fault strongly suggest reworking of a former high-temperature fabric as discussed below.

DISCUSSION AND CONCLUSIONS

The Vivero Fault is located in the Variscan belt of Galicia, where crustal thickening by eastward thrusting originated during continental collision. Overheating of the materials placed at the base of the thickened region (Dewey & Burke 1973, De Yoreo *et al.* 1989), would explain the generation of *S*-type granites like that of Hombreiro.

The variation of the fabric of quartz shown by the tectonites of the Vivero Fault reveals a temperature decrease, in such a way that the [*c*]-slip fabrics formed during the onset of the extensional motion of the fault are finally replaced by ⟨*a*⟩-slip fabrics. This would explain not only the scarcity of mosaic-like microstructures but also the dispersion of the quartz *c*-axes in diagrams like Fig. 6(a), since the grains deformed by [*c*]-

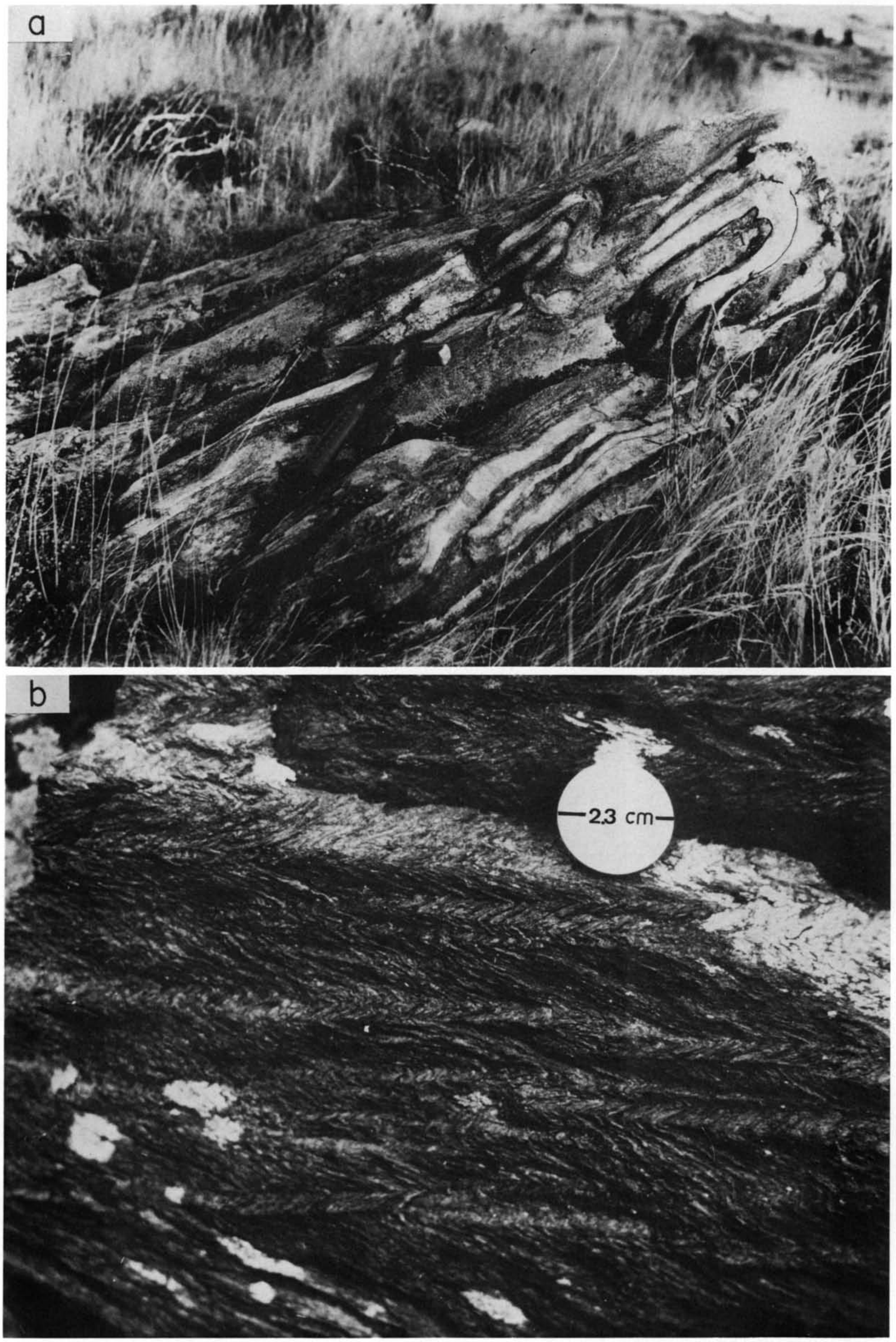

Fig. 4. (a) Isoclinal folds in aplite veins intruded into biotite-bearing schists of the Mondoñedo Nappe. The axial plane schistosity strikes N–S and dips to the west. (b) Spaced and subhorizontal crenulation cleavage in schists from the hangingwall of the Vivero Fault.

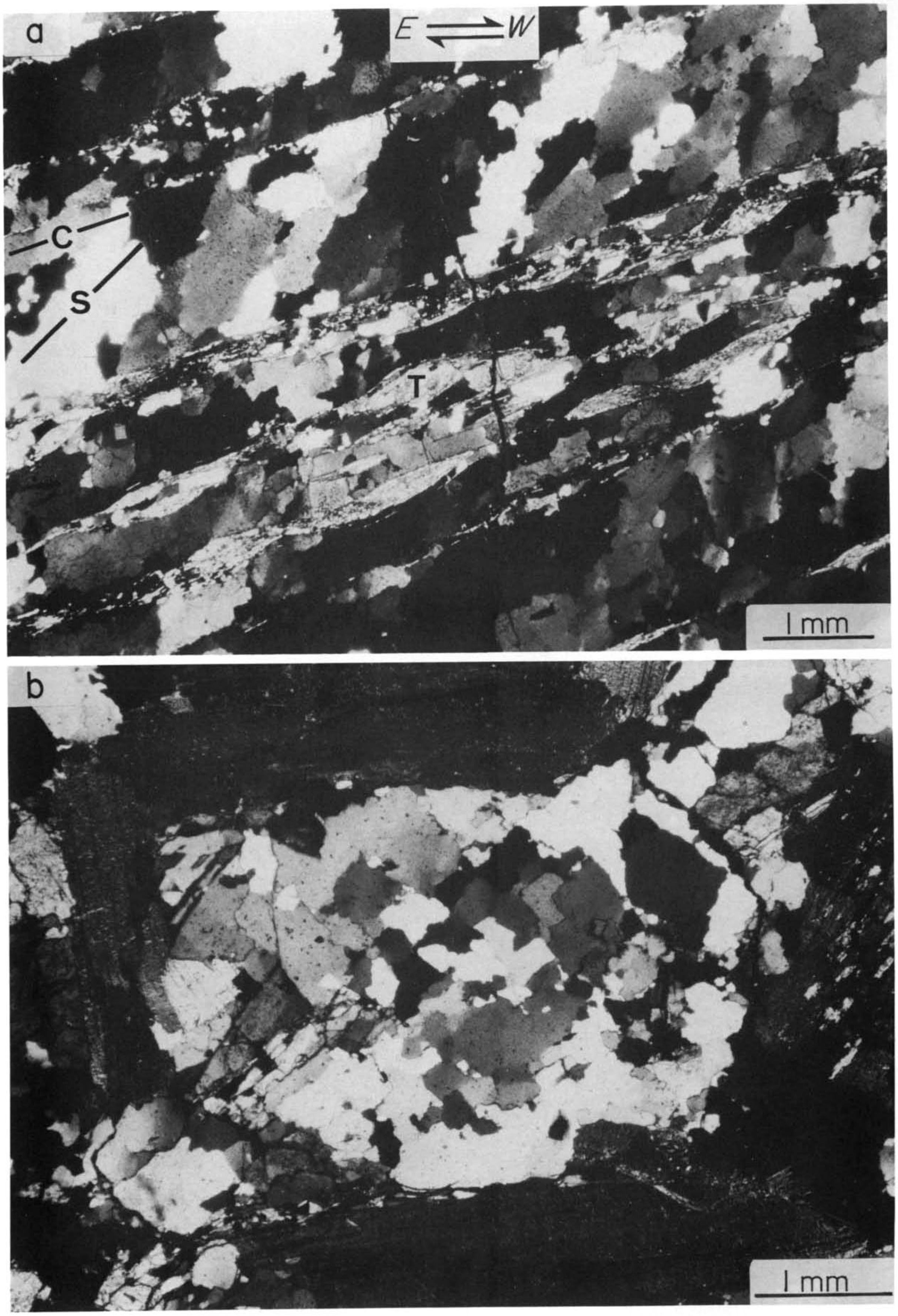

Fig. 7. (a) Shape foliation (*S*) from samples with quartz *c*-axis diagrams like those of Figs. 6(b) & (c). Obliquity of elongated quartz grains with respect to micro-shear planes (*C*) indicates a top-to-the-west displacement. Tourmaline-fish (*T*) indicate the same sense of shear. (b) Mosaic-like microstructure in quartz corresponding to the *c*-axis fabrics of Fig. 6(a).

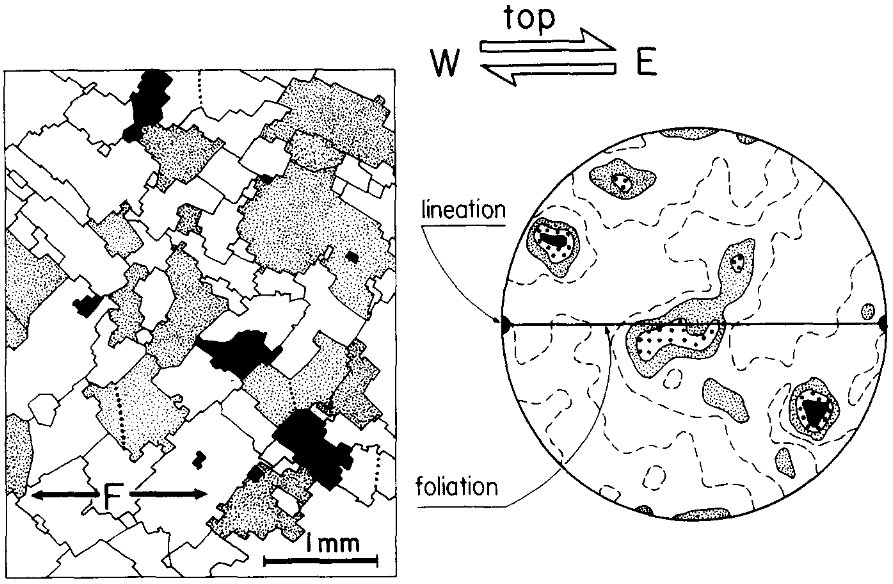

Fig. 5. Sketch of mosaic microstructure in quartz aggregates of the sample AR-3.2, a tectonite from the shear zone associated with the motion of the Mondoñedo Nappe. Quartz grains show grain-boundaries at right angles. Note the asymmetry of grain-boundaries in respect of the foliation trace (F). Diagram shows the preferred orientation of quartz c-axes (100 measurements; contours intervals: 1, 3, 5 and >7%). This diagram implies [c]-glide in quartz.

slip only represent a transient episode of the deformation history associated with the Vivero Fault. This interpretation is supported by the preservation of quartz fabrics due to [c]-slip in lens-shaped bodies surrounded by shear zones with fabrics due to ⟨a⟩-slip (Fig. 6).

Our structural data demonstrate the syntectonic character of the Hombreiro Granite. This granite was intruded into the Mondoñedo Nappe when the thrusts were still active, as revealed by the ductile shear zone with a top-to-the-east motion which cuts the massif

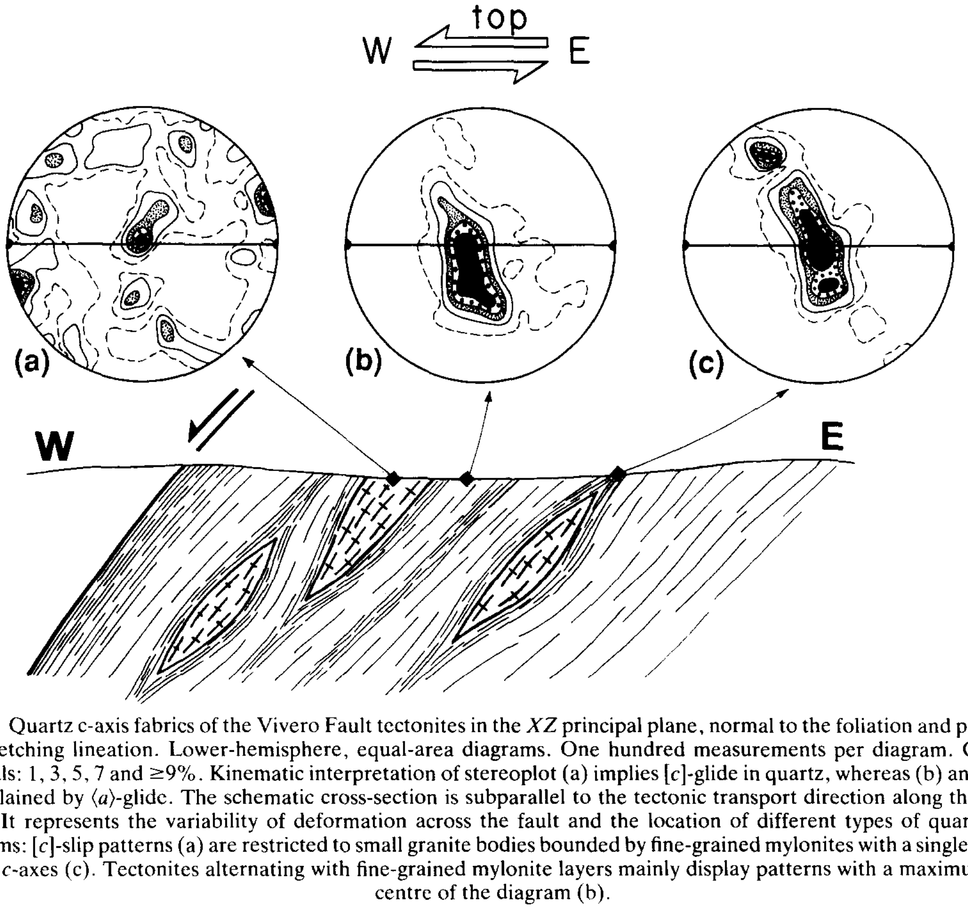

Fig. 6. Quartz c-axis fabrics of the Vivero Fault tectonites in the XZ principal plane, normal to the foliation and parallel to the stretching lineation. Lower-hemisphere, equal-area diagrams. One hundred measurements per diagram. Contours intervals: 1, 3, 5, 7 and ≥9%. Kinematic interpretation of stereoplot (a) implies [c]-glide in quartz, whereas (b) and (c) can be explained by ⟨a⟩-glide. The schematic cross-section is subparallel to the tectonic transport direction along the Vivero Fault. It represents the variability of deformation across the fault and the location of different types of quartz fabric diagrams: [c]-slip patterns (a) are restricted to small granite bodies bounded by fine-grained mylonites with a single girdle of quartz c-axes (c). Tectonites alternating with fine-grained mylonite layers mainly display patterns with a maximum at the centre of the diagram (b).

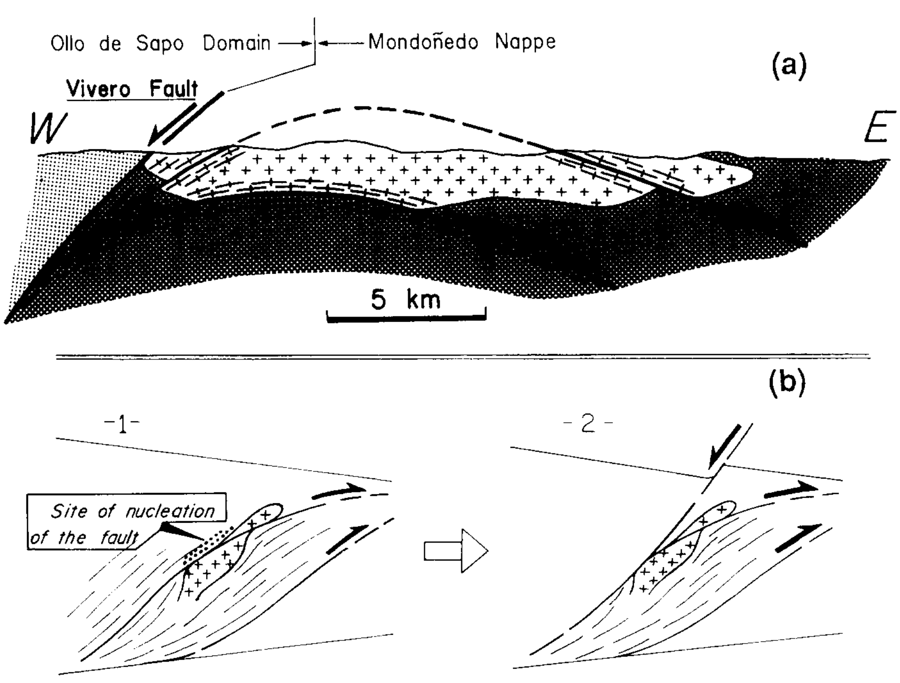

Fig. 8. (a) Cross-section through the Hombreiro Granite, illustrating the truncation of the shear zone associated with the Mondoñedo Nappe (D_2-phase) by the extensional Vivero Fault. (b) Schematic model showing the development of a crustal wedge thickened by thrusts. The intrusion of granites when thrusts are operating and thickening is still in progress, induces a crustal instability (1), which nucleates the gravitational collapse of the wedge (2).

(Figs. 2 and 8). This interpretation is also supported by gravity data from the Lugo Dome (Aranguren unpublished data) which clearly show that the granite takes the form of a sheet extending down to a depth of only 2 km. On the other hand, the western border of the Hombreiro Granite has later been affected by the Vivero Fault, but still at high temperatures as attests the conservation of quartz *c*-axis fabrics due to [*c*]-slip (Mainprice *et al.* 1986). The existence of high-temperature fabrics in deformed granites related to the Mondoñedo Nappe and to the Vivero Fault indicates that both these deformations occurred close to the granite solidus. This suggests that the extensional motion of the Vivero Fault overlapped in time the thrusting of the Mondoñedo Nappe as well as the intrusion of the Hombreiro Granite.

Apart from the Hombreiro Granite, several other synkinematic granite plutons have been intruded into the Mondoñedo Nappe (Bellido Mulas *et al.* 1987). These plutons crop out in the footwall side of the Vivero Fault. They have also been deformed in the same fashion by the fault and define as a whole a N–S line, roughly parallel to that of the fault (Fig. 1). Restoring erosion, the fault trace would be more directly over the line of plutons. It is worth noting that the Vivero Fault is an important structure more than 125 km long, of which no less than 80 km correspond to granites (Fig. 1). Therefore, it appears that the location of the Vivero Fault has been controlled by the intrusion of granite bodies along this N–S axis. We propose that these granites served as the nucleation site for the gravitational collapse of the crustal wedge previously thickened during the process of continental collision (Fig. 8). This nucleation effect would be favoured both by the thermal softening of the crust adjacent to the granites and by the localization of strain in the granite, triggered by the mechanical weakness of the granite in relation to the host rocks.

In conclusion, the structural and kinematic relationships between thrusting and normal faulting in the Variscan belt of Galicia (northwestern Spain) has basic similarities with those documented for the Tibetan plateau (Burg *et al.* 1984, Mattauer & Brunel 1989), since thrusts and extensional faults along the same direction were active during the emplacement of a set of granitic plutons. Our results on the Hombreiro Granite suggest that the intrusion of granites played a major role in controlling the localization of the Vivero Fault; some data on radiometric ages of stretching lineations associated to the Mondoñedo Nappe and the Vivero Fault are needed to constrain this interpretation, but our structural and petrofabric data clearly show that cooling of the Hombreiro Granite was coeval with the extensional motion on the Vivero Fault.

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