Large extensional structures developed during emplacement of a crystalline thrust sheet: the Mondoñedo nappe (NW Spain)

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Abstract

The Mondoñedo nappe is a crystalline thrust sheet characterized by large recumbent folds, regional intermediate-pressure metamorphism, synkinematic intrusion of granitoids during nappe emplacement, and an extensional ductile shear zone developed within the nappe during thrusting. A large tectonic window permits the study of the footwall unit, revealing another extensional shear zone contemporaneous with thrusting and a low-pressure metamorphic evolution, in contrast to that of the hanging wall unit. The two main extensional shear zones produced E–W extension parallel to the direction of orogenic shortening and normal to the orogenic structural trend. Furthermore, subordinate N–S longitudinal extension was accommodated by normal faults in the footwall, and some of these faults were used as lateral ramps in late stages of thrusting.

The role of the extensional shear zones and faults described is discussed in the context of an evolving orogenic wedge dominated by plate convergence but characterized by large-scale rheological heterogeneities within it. Deep-seated viscous flow, triggered by heat accumulation, seems to account for the horizontal stretching and probable tapering of the orogenic wedge, which was induced by gravitational instabilities due to partial melting and underplating by buoyant continental crust.

Keywords: Crystalline nappe; Syn-orogenic extension; Orogenic wedge; Iberian Massif

1. Introduction

Studies of thrust sheets within the internal zones of orogenic belts are important in assessing crustal convergence, and estimating the long-term rheological behaviour of continental lithosphere. However, the emplacement history of crystalline thrust sheets is usually complex and difficult to ascertain, partly because they involve large portions of the crust (Hatcher and Hooper, 1992), and even the upper mantle, and include a wide range of rheological behaviours along a single allochthonous unit. Descriptions of large-scale thrust geometry and associated macrostructures less commonly focus on the internal zones of orogenic belts than in the external zones. Difficulties arise because crystalline thrust sheets involve rocks previously folded, so that the bedding cannot be taken as a horizontal reference surface, in order to establish original fault dips or make estimates of displacement and shortening. Furthermore, many internal nappes are very large (larger than the largest foreland thrust sheet; Hatcher and Williams, 1986) and their outcrop is obscured by plutonic intrusions and late structures. Due to these problems, large associated structures are typically assumed to pre- or post-date thrusting, instead of investigating the possibilities of being coeval with it.

Structures whose kinematics do not fit the expected compressional dynamic framework, or omit parts of the normal stratigraphic sequence or metamorphic succession appear often associated to crystalline nappes. In some cases, they could be structurally induced by the geometry of the thrust fault (Dahlstrom, 1970; Coward, 1982; Wibberley, 1997), linked to the development of imbricates, out-of-sequence thrusts or tear faults (Butler, 1982; Morley, 1988; Mueller and Talling, 1997), or be equivalents to Riedel shears oblique to the basal thrust (Yin and Kelty, 1991). But, in other cases, their size, in relation to the nappe to which

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they are associated, and their imprint in its metamorphic evolution point to large-scale phenomena, related to the dynamics of the whole orogenic belt rather than to the individual allochthonous units.

In particular, extensional structures have been found in a number of large crystalline thrust sheets in the Scandinavian Caledonides (Fossen, 1992, 2000; Milnes et al., 1997), the European Variscides (Burg et al., 1994; Pitra et al., 1994), the North American Cordillera (Hodges and Walker, 1992) and the Himalayas (Burg et al., 1984; Hodges et al., 1996), among others orogenic belts. There, much attention has been paid to the syn- or postorogenic character of the extensional structures. For instance, Fossen (2000) pointed out that whereas in the Caledonides, extension is essentially postorogenic, the Himalayas offer good examples of synorogenic extension.

The problem with synorogenic extension is how a local stress field can develop opposite to the regional or distant convergence-related stress field. Commonly invoked explanations are the upwelling of some hot and buoyant material, such as the asthenosphere or molten crust and mantle rocks (Van Den Driesche and Brun, 1991–1992; Vanderhaeghe et al., 1999), and the creation of a high topographic relief, which may develop vertical stresses high enough to make unstable and collapse a large portion of the mountain belt (England, 1983; Burg et al., 1984; Burchfiel and Royden, 1985; Dewey, 1988; Molnar and Lyon-Caen, 1988). In the latter case, the relief may simply result from crustal or lithospheric thickening due to convergence, or be a consequence of the removal of the mantle lithospheric root either by detachment or by convective erosion (Platt and Vissers, 1989; Platt, 1993).

Much of the discussion on synorogenic extension in mountain belts is linked to that of exhumation of deep-seated structural units, often showing evidence of high-pressure metamorphism. The quick exhumation rates required for the preservation of high-pressure parageneses is difficult to explain by erosion only, and has been linked to tectonic denudation in many cases (Davies and Warren, 1988; Jolivet et al., 1998). To account for the synchronism often observed between exhumation and convergence, Platt (1986) discussed the mechanics of orogenic wedges consisting of viscous material, typical of the internal zones of orogenic belts. Although inspired in the well-established mechanics of accretionary wedges with Coulomb behaviour (Davis et al., 1983; Dahlen et al., 1984), he avoided choosing a particular bulk rheology, and carried out a merely qualitative analysis. From it, he suggested that transitions from local convergence to local extension could be driven by changes in wedge geometry, and showed how extension may occur in parts of the wedge during continuous convergence.

Platt's conclusions pertaining to tectonic denudation do not differ essentially from the models relating extension with gravitational collapse, but provide mechanisms by which the wedge can be thickened and turned unstable, namely changes in its internal rheology or in the rate of convergence, and underplating by continental slices. Obviously, the generation of molten, buoyant material represents a drastic rheological change inside the wedge (which may modify the local stress field), and the addition of mantle material may be a kind of magmatic underplating.

The idea that adjustments inside the orogen, including extensional structures, is related to viscous flow in its deep parts, is gaining adepts progressively. Although primarily seen as a post-convergence phenomenon (Sandiford, 1989; Block and Royden, 1990; Van Den Driesche and Brun, 1991–1992; Costa and Rey, 1995), it can overlap with orogenic shortening if convergence continues after the middle and/or lower crust have had enough time to develop a low-viscosity hot layer (Clark and Royden, 2000; Beaumont et al., 2001; Shen et al., 2001).

The aim of this article is to demonstrate that large extensional structures in the Mondoñedo nappe and its autochthon formed while Variscan convergence was active and, mostly, during the emplacement of the nappe itself. Extension was mainly transversal to the structural trend; that is, it took place in the direction of nappe emplacement—although in two opposite senses—but subordinate extension occurred also longitudinally. Extensional and compressive structures interfered during nappe emplacement, and cross-cutting structural criteria, together with overprinting metamorphic relationships, information extracted from synkinematic granitoids, and published age data, permit a detailed reconstruction of the evolution of this area of the Iberian Massif. The deduced tectonothermal history is then discussed in the context of the Variscan orogenic wedge and its kinematics, which includes the role of viscous flow associated with high-grade metamorphic rocks developed below the nappe.

2. Setting and previous work

The Mondoñedo nappe is a large crystalline thrust sheet occurring in the internal zones of the NW Iberian Massif, and made up of low to high-grade metasediments and several massifs of synkinematic granitoids (Figs. 1 and 2). It was first described by Matte (1968) as a large recumbent anticline, and then by Marcos (1973), who mapped its frontal thrust and stated its importance as a first-order allochthonous unit of the Variscan internal zones. The southern branch of the nappe was mapped by Pérez-Estaún (1978), and further research along the coastal section showed the existence of a 3–3.5-km-thick basal ductile shear zone (Figs. 3 and 4) in its internal parts (Bastida and Pulgar, 1978). Martínez Catalán (1980) identified the basal thrust outcropping in these internal parts and mapped the thrust and associated shear zone, showing the existence of two tectonic windows, named Xistral and Monte Carballosa (Fig. 1). The thrust front can be traced for 200 km and a

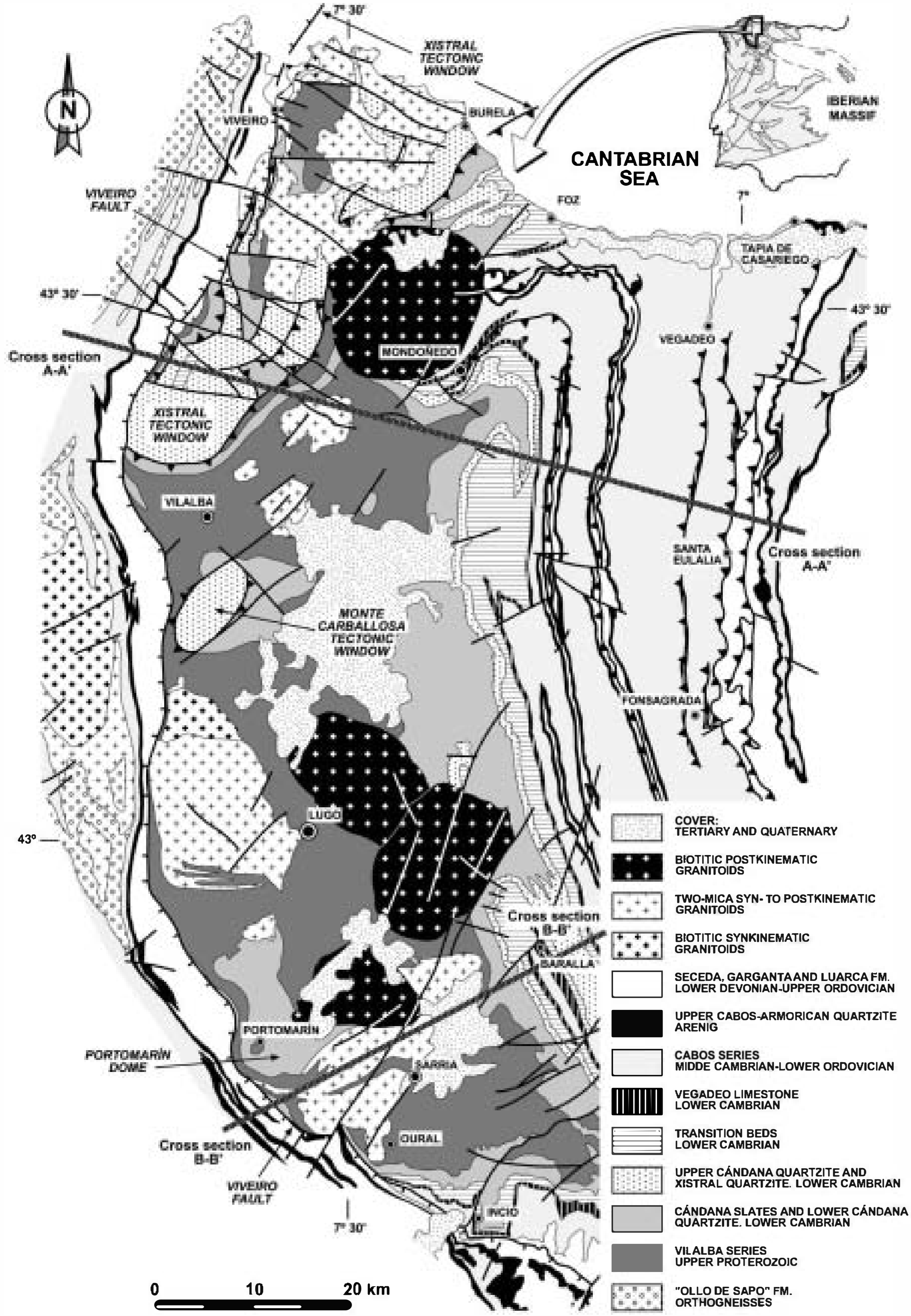


Fig. 1. Geological map of the northern and central parts of the Mondoñedo nappe.

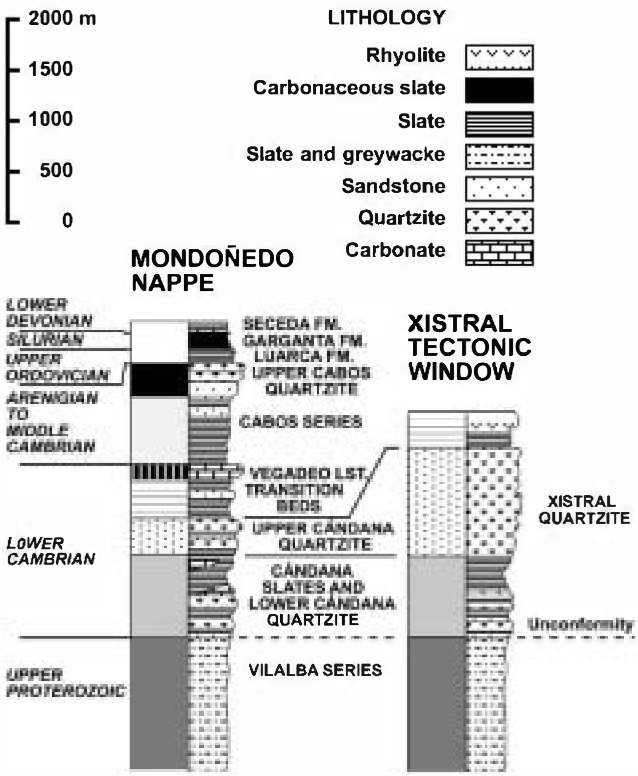


Fig. 2. Stratigraphy of the Mondoñedo nappe and its autochthon (Xistral tectonic window). The key to the stratigraphic divisions (left hand columns) is given in Fig. 1.

width of 65 km is measurable for the thrust sheet between its frontal thrust and the western limit of the tectonic windows. Displacement cannot be measured because of the absence of correlatable cut-offs between the hanging wall and the footwall. However, correlation between two Lower Cambrian quartzite formations (Upper Cándana and Xistral quartzites; Fig. 2), permits a minimum estimate of 45 km (see cross-section A–A′ in Fig. 4).

The nappe consists of 3000 m of Upper Proterozoic slates and greywackes, the Vilalba Series, and another 3000 m of Lower to Middle Paleozoic clastics and carbonates of shallow-water platform facies, locally reaching the Lower Devonian (Fig. 2). Slates are the most common lithologies, followed by quartzites. The Paleozoic is thicker in the footwall unit (7000–10000 m), but appears incomplete in the tectonic windows. A strongly competent horizon of Lower Cambrian sandstones, the Xistral Quartzite, occupies most of the windows, reaching a structural thickness of 5000 m after having been folded and locally repeated by thrusting.

The sedimentary succession was deformed during the Variscan orogeny. A first deformation episode of east-verging recumbent folding was followed by ductile and brittle thrusting toward the east (Figs. 3 and 4). Subsequent open steep folding allowed the present-day preservation from erosion of around 10 km of the Mondoñedo thrust sheet in an open synform. The basal parts of the thrust sheet outcrop at its front and also surrounding the tectonic windows. To the west, the thrust sheet is bounded by the Viveiro fault, a west-dipping normal fault cutting across the nappe and its autochthon (Figs. 1, 3 and 4).

Detailed structural analyses of the hanging wall unit and the basal ductile shear zone can be found in Martínez Catalán (1985), Bastida et al. (1986) and Aller and Bastida (1993). These contributions deal with the geometry of the allochthonous unit, its macro-, meso- and microstructures, the synkinematic metamorphism, and the geometry and kinematics of the basal shear zone. The significance of the Mondoñedo nappe in the structural evolution of the Variscan belt of NW Spain is discussed in Pérez-Estaún et al. (1991).

In previous works, the only contractional ductile shear zone identified was at the base of the hanging wall unit (the Mondoñedo nappe itself), the only extensional structure identified was the post-nappe Viveiro fault, and the structure of the tectonic windows was poorly known. Nappe emplacement was simply viewed as an allochthonous sheet moving without much internal deformation over the basal ductile shear zone and sliding along a brittle thrust fault once relatively high crustal levels were reached. Contemporaneous erosional denudation was assumed to account for decompression indicated by the metamorphic evolution, and extensional deformation was considered to have occurred essentially in a post-nappe stage (Martínez Catalán, 1985).

After a careful review of the hanging wall unit, new mapping of the footwall unit in the tectonic windows, and a petrological study of the metamorphic evolution, a complex picture of ductile shear zones (Figs. 3 and 4), with different kinematics and partially overlapping in time, has emerged. The petrological study has been carried out in representative domains of the nappe and its footwall unit, but these results are presented in a companion paper (Arenas and Martínez Catalán, 2003).

3. Shear zones in the hanging wall unit

The structure of the Mondoñedo nappe is dominated by east-verging recumbent folds. The geometry of these large folds suggest a strong flattening, which is corroborated by a pervasive axial planar cleavage (S_1). The overturned limb of the main recumbent fold, the Mondoñedo–Lugo–Sarria (MLS) anticline, reaches 15 km in the upper parts of the stratigraphic section (Fig. 4). The recumbent folds reflect an episode of crustal shortening and thickening, and were affected by a regional metamorphism of intermediate pressure, as defined by Miyashiro (1961), with kyanite–sillimanite, common in midcrustal levels of many orogenic belts (Thompson and England, 1984). The metamorphic zoning, of Barrovian type, includes chlorite, biotite, garnet, staurolite–kyanite, sillimanite and sillimanite–orthoclase

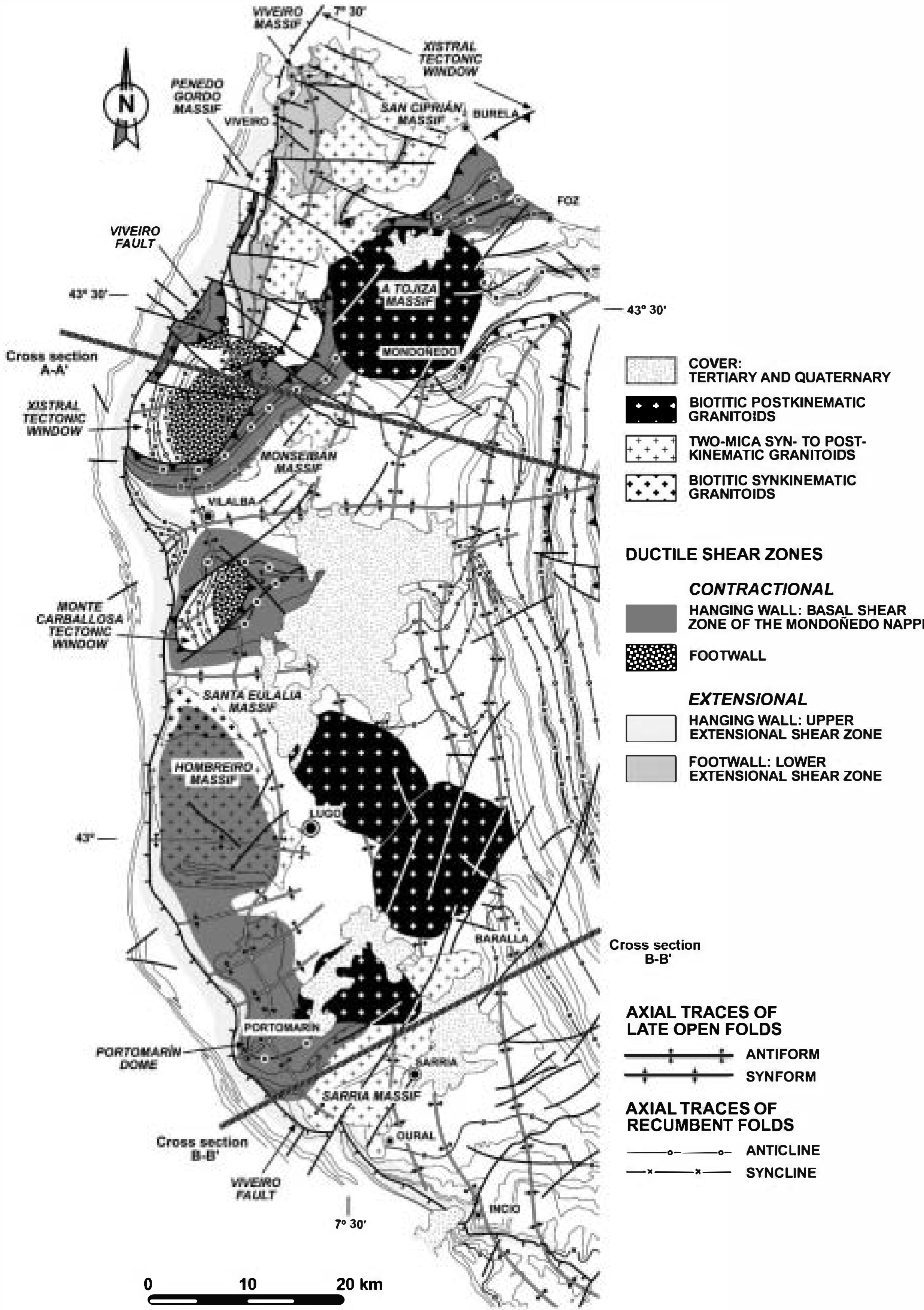


Fig. 3. Map showing the distribution of ductile shear zones in the hanging wall and footwall to the Mondoñedo thrust and the axial traces of major folds. Faults and unit boundaries allow a comparison with Fig. 1. Stratigraphic and lithological keys are used only for cover and granite massifs.

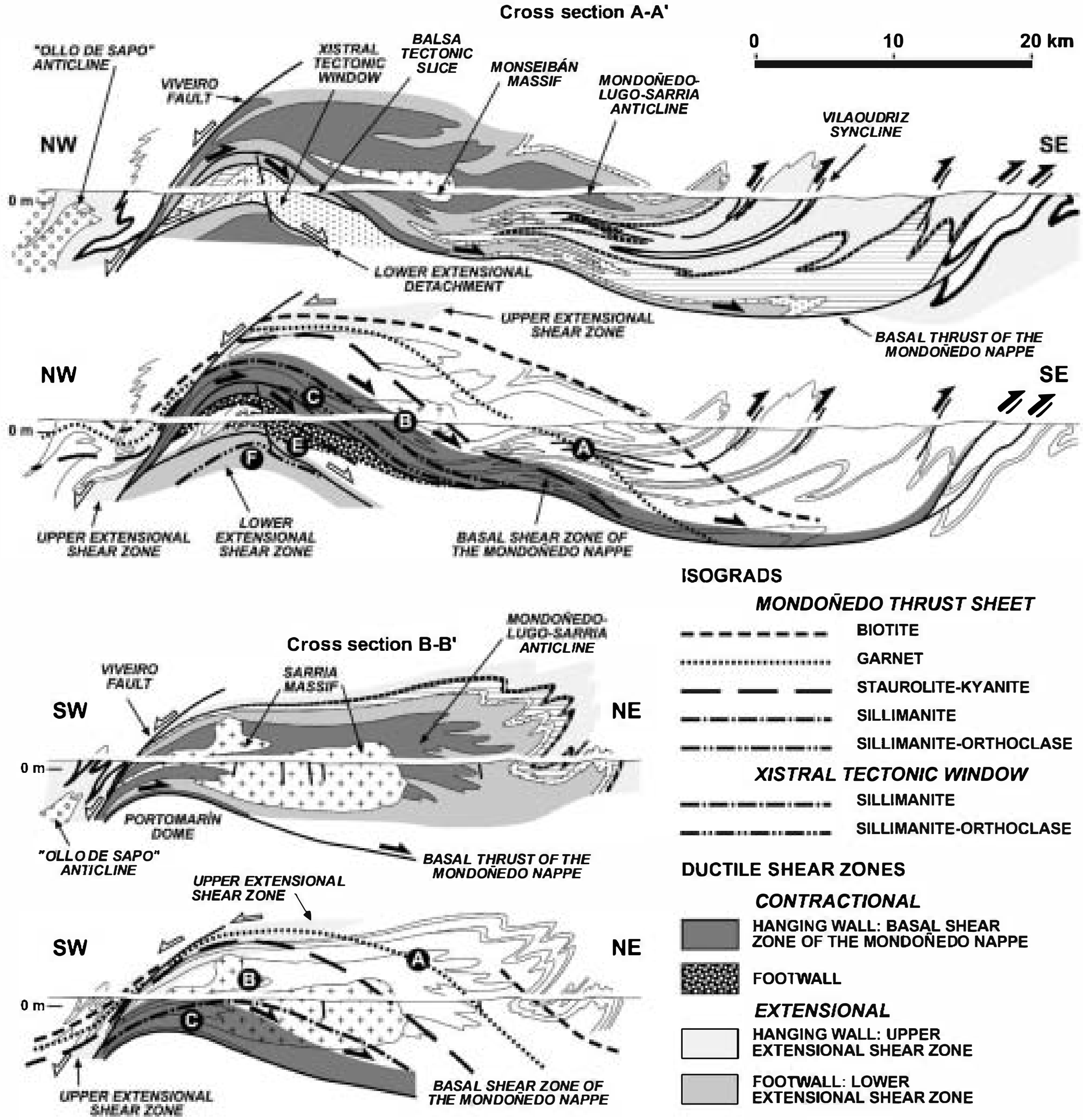


Fig. 4. Two general sections across the Mondoñedo nappe, each shown in two versions. The first depicts the lithostratigraphic units (see legend in Fig. 1), and the second, the shear zones and the metamorphic isograds. Arrows show movement of contractional (black) and extensional (white) shear zones and faults. For location, see Figs. 1 and 3. Letters A–F refer to the location of the P–T paths shown in Fig. 6.

(Fig. 5). The isograds crosscut the recumbent folds (Capdevila, 1969), and were deformed by the subsequent ductile shear zones and cut by the thrust and normal faults (Fig. 4).

The Upper Proterozoic core (Vilalba Series) of the MLS anticline has a mean thickness of 6 km along most of the fold, as deduced from cross-sections constructed by down-plunge projection of the hinges and limbs of the second-order folds. To the W and SW, however, the Vilalba Series becomes progressively thinner, and the fold core is less than 1 km thick (Fig. 4). The thinning of the fold nappe toward its internal parts is not only reflected in the core of the anticline, but also in the thickness of the Paleozoic formations on both limbs and in the width of the metamorphic zones (Figs. 4 and 5). Thinning is due to the superposition of two ductile shear zones with opposite senses of movement. One of these

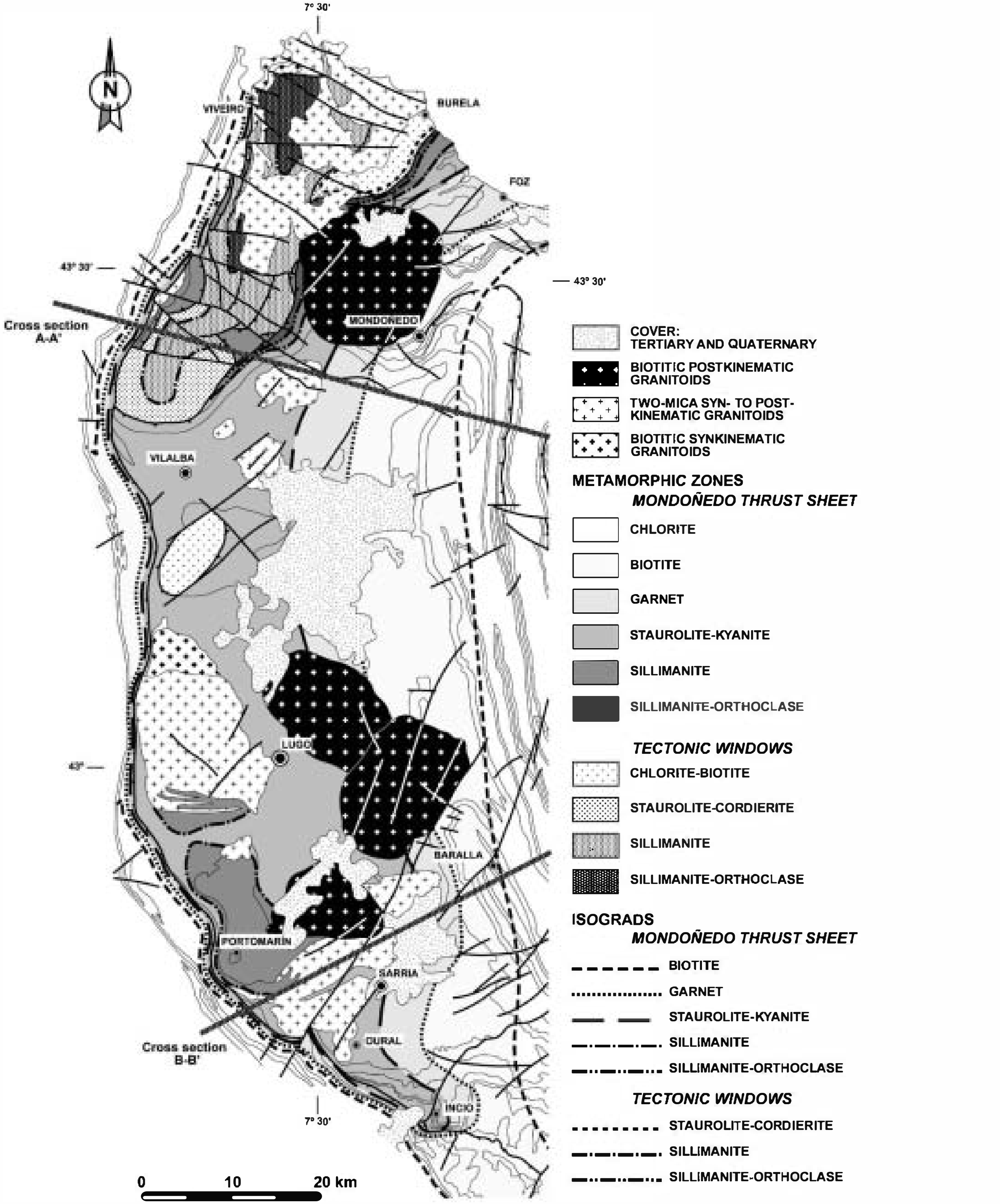


Fig. 5. Map of metamorphic zones and isograds. Note how the zones narrow in the western part of the nappe, due to the superposition of the upper extensional shear zone and the Viveiro fault.

is the top-to-the-east basal shear zone of the Mondoñedo nappe, which sheared and thinned the overturned limb of the MLS anticline, doubling its cross-sectional length in its deep parts, where it attains more than 30 km (compare units deformed in the shear zone with units in less deformed parts above in cross-section A–A′ of Fig. 4). The other shear zone is a shallow-dipping extensional ductile structure with top-to-the-west motion, developed in the upper parts of the MLS anticline (Fig. 4; cross-sections A–A′ and B–B′).

This section describes both the basal (reverse) and the upper (normal) shear zones, and demonstrates their temporal overlapping. The tectonothermal evolution of the nappe will be outlined along with the structural description. A detailed petrological description of the metamorphism is provided elsewhere (Arenas and Martínez Catalán, 2003). Here, only the key aspects emerging from our study of the regional and local distribution of metamorphic zones (Fig. 5), and the P–T conditions and evolution will be mentioned. Three P–T trajectories corresponding to upper, intermediate and lower parts of the Mondoñedo thrust sheet are shown in Fig. 6, paths A, B and C, respectively. Little control is available for the prograde paths (dashed), but the pressure peaks vary from 6 to 11–12 kbar, indicating that the pile of recumbent folds reached a depth of 38–45 km, and what

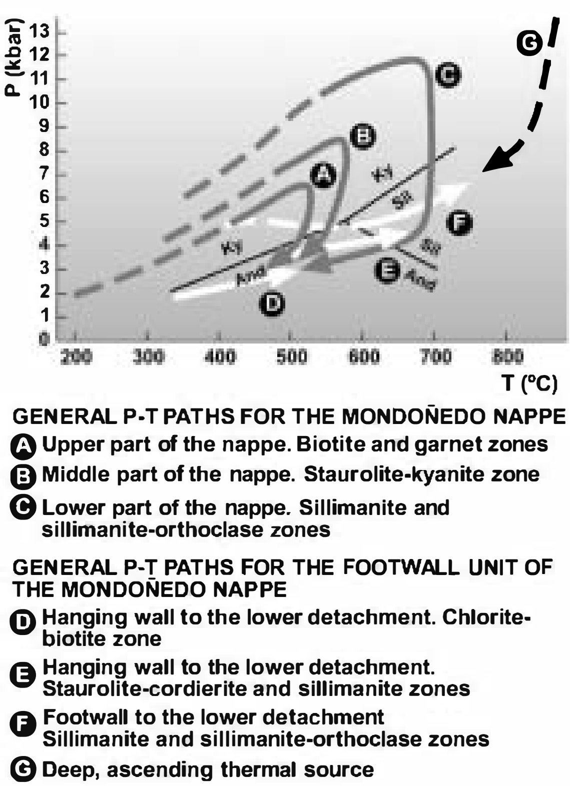


Fig. 6. P–T paths for the Mondoñedo thrust sheet (grey arrows), its footwall unit (white arrows), and deeper crustal rocks underlying the lower extensional shear zone (black arrow). The paths are representative of different parts of the nappe and its autochthon, which are indicated with capitals in the cross-sections of Figs. 4, 8 and 13. Based on Arenas and Martínez Catalán (2003). Dashed lines represent parts of the paths not based on petrological data.

presently constitutes the nappe was initially around 20 km thick. Temperature peaks are close to pressure peaks and vary from 500 to 700 °C.

3.1. Basal shear zone of the Mondoñedo nappe

The basal shear zone is narrow at the frontal parts of the nappe, where no more than 200 m of sheared rocks crop out. The shearing overprints earlier structures and developed a crenulation fabric in slates, very low-grade phyllonites and cataclasites (Marcos, 1973). Conversely, the thickness of the basal ductile shear zone attains 3–3.5 km in the internal parts of the nappe, where it crops out surrounding the two tectonic windows and also in two domes formed by interference of orthogonal late open folds in Portomarín and to the west of Lugo (Figs. 3 and 4). The shear zone is characterized by a generalized crenulation cleavage or a new medium-grained schistosity (S_2) in the pelites, a mylonitic foliation in the quartzites (Bastida and Pulgar, 1978), and a mineral lineation roughly striking E–W. Minor folds with curved hinges, including sheath folds, and S–C structures are also common. The kinematic indicators consistently give a top-to-the-east sense of shear. A few metres of ultramylonites have been found locally at the thrust surface.

Aller and Bastida (1993) described in detail the basal shear zone along the coast, to the east of the Xistral tectonic window, establishing a threefold subdivision according to microstructural criteria. In the lower levels, mylonites and ultramylonites are common, and quartz *c*-axis fabrics are of the small-circle type (Schmid and Casey, 1986). This indicates strong shearing at low temperature conditions, and represent late stages of thrusting, contemporaneous with greenschist facies retrogradation. The middle part of the shear zone contains blastomylonites, and the quartz *c*-axis fabrics are of the monoclinic incomplete single girdle and type I crossed girdle, suggesting deformation at higher metamorphic conditions, mostly in the amphibolite facies. The upper part includes non-mylonitic quartzites and quartzites with small-circle type and type I crossed girdle which, together, suggest lower temperatures than in the central parts.

The internal parts of the basal zone suffered the highest P–T conditions, and also the most intense retrogradation. After the Barrovian-type metamorphic event, nappe emplacement began along the ductile shear zone. Sillimanite grew synkinematically in the deeper parts of the nappe, while andalusite porphyroblasts developed in its upper parts. All the P–T paths show a decompression, which was greater in the deeper parts (compare paths A and B with path C in Fig. 6 and their locations in Fig. 4). The decompressive paths were, at an initial stage, close to isothermal for the lower parts (Fig. 6, path C), suggesting a quick exhumation (Thompson and England, 1984), a feature commonly associated with tectonic denudation. Conversely, the late stage shows cooling accompanied with slight decompression. This corresponds to a relatively thin thrust sheet (roughly 12 km, indicated by the 3 kbar at its base; see path C in Fig. 6) being emplaced at relatively shallow levels and undergoing only slight denudation.

The presence of deformed Variscan granitoids is another important feature of the basal shear zone. The Sarria, Hombreiro, Santa Eulalia, Monseibán (Fig. 3) and other minor massifs partly intruded into the shear zone, and were sheared toward the east (Fig. 4). Martínez Catalán (1983) and Aranguren and Tubía (1992), described the microstructures and estimated the temperature conditions of deformation, which were close to the solidus temperature for granite. The fact that shearing closely followed their emplacement points to their synkinematic character.

3.2. Upper extensional shear zone

In the western region of the nappe, the stratigraphic sequence, the recumbent folds and the metamorphic zones thin gradually to the west (Figs. 4 and 5). This is a region where a subhorizontal crenulation cleavage or a new schistosity was developed, as well as an E–W mineral lineation. This region contrasts with wide areas to the east, which are structurally lower, and where only the first cleavage (S_1) is present. There is clearly a zone of deformation superimposed on the normal limb of the MLS anticline. Its maximum thickness is estimated at 2 km, and decreases progressively to the south of Oural (Fig. 3). Asymmetric pressure shadows, developed around pre- and synkinematic porphyroblasts, indicate a top-to-the-west sense of shear.

The shear zone deforms the recumbent folds and the Barrovian metamorphic zones, and is considered to post-date them. However, porphyroblasts of kyanite, staurolite and andalusite grew in the shear zone synkinematically with the second cleavage. This implies that the P–T conditions were still high, and suggests that motion in the shear zone began during the early stages of nappe emplacement. Because the P–T conditions were greater there than at the base of the thrust sheet in later stages of emplacement, the upper shear zone probably finished its activity before the end of the thrusting process.

An additional criterion for the relatively early timing of the upper shear zone is provided by the Sarria massif: its upper part intruded the shear zone after shearing had ceased, because the granite is undeformed there. However, the massif intruded in the nappe while it was still being emplaced, and was deformed within the basal shear zone (Figs. 3 and 4).

The thinning of the metamorphic zones and the apparently down-dip motion (top-to-the-west) suggest a normal character for the shear zone, being equivalent to a broad extensional detachment. In terms of thermobarometry, this is reflected in the isothermal, decompressive portion of the P–T paths followed by the deep parts of the Mondoñedo nappe (Fig. 6, path C). Its kinematics might imply the tectonic extrusion of the MLS anticline from the root zone, in a way comparable with that proposed by Dietrich and Casey (1989) for the Helvetic nappes. However, the MLS anticline is different to the Helvetic case, as the upper shear zone has a sense of motion opposite to that of the basal one. Alternatively, the upper extensional shear zone may be a consequence of gravitational collapse, in response to gravitational gradients created by orogenic topography.

The upper shear zone was later overprinted by the Viveiro normal fault. Because of the spatial coincidence of both structures (Fig. 3), they have been considered associated (Martínez Catalán, 1985; Martínez et al., 1996). However, in the light of the new data, they are considered here to be separated in time: the upper ductile shear zone moved during nappe emplacement, whereas the Viveiro fault cuts the Mondoñedo thrust sheet and its autochthon.

4. Shear zones in the footwall unit

In the western part of the Mondoñedo nappe, two families of open folds, longitudinal (N–S to NE–SW) and transverse (NW–SE to E–W), interfere allowing the footwall unit to crop out (Fig. 3). A longitudinal antiform is essentially responsible for the large northern tectonic window (Xistral), and the same, when interfering with an E–W transverse antiform, causes the southern small window (Monte Carballosa). This section describes the different structural units exposed in these tectonic windows, together with the main ductile shear zones identified (Fig. 7). Focusing on the Xistral window (except when specifically stated), this section uses longitudinal and transverse cross-sections (Fig. 8) to study the complex pattern of compressional and extensional structures contemporaneous with thrusting. A three-dimensional sketch showing the relationships between the main compressional and extensional structures is shown in Fig. 9.

The Xistral Quartzite (Fig. 2) was strongly folded prior to nappe emplacement. When not affected by additional deformation, cross-bedding indicates the way-up direction, permitting the mapping out of the large folds. In these cases, the S_1 foliation is axial planar to the folds, a stretching lineation is not thoroughly developed and textures are not mylonitic. Conversely, when affected by subsequent shear zones, the quartzites were mylonitized, a pervasive elongation of quartz grains developed, commonly striking E–W (Fig. 7), and cross-bedding is poorly preserved and difficult to interpret. In addition, new minor folds developed locally.

Relics of the basal shear zone of the Mondoñedo nappe have been preserved in the footwall unit, and several tectonic slices exist close to the thrust fault. Furthermore, a strain gradient to the SE is identified in the Xistral Quartzite in the south, and interpreted as a contractional shear zone converging upward into the Mondoñedo basal thrust.

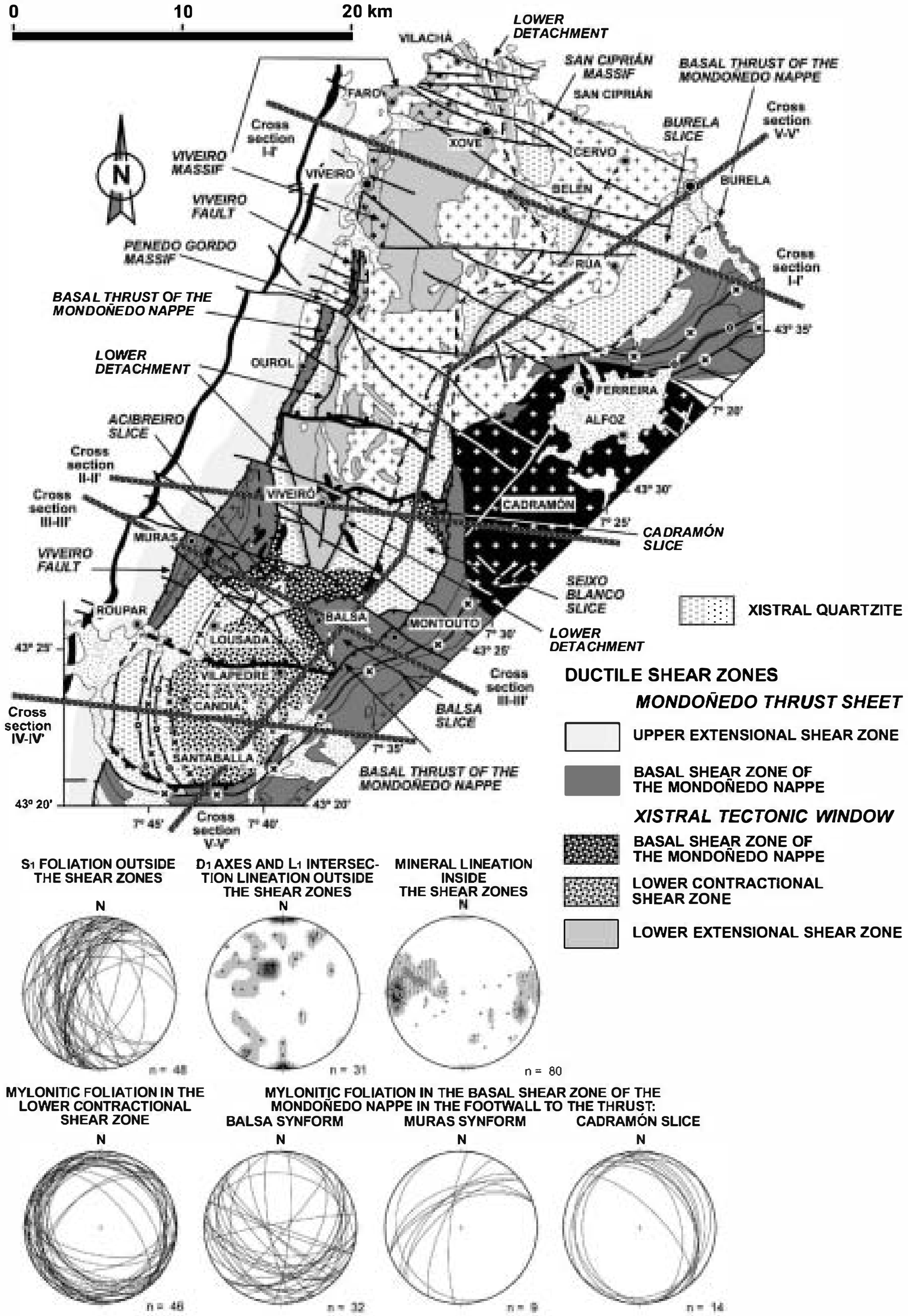


Fig. 7. Map showing the distribution of ductile shear zones in the Xistral tectonic window, and diagrams depicting the attitude of foliation and lineation (lower hemisphere, equal area stereographic projection).

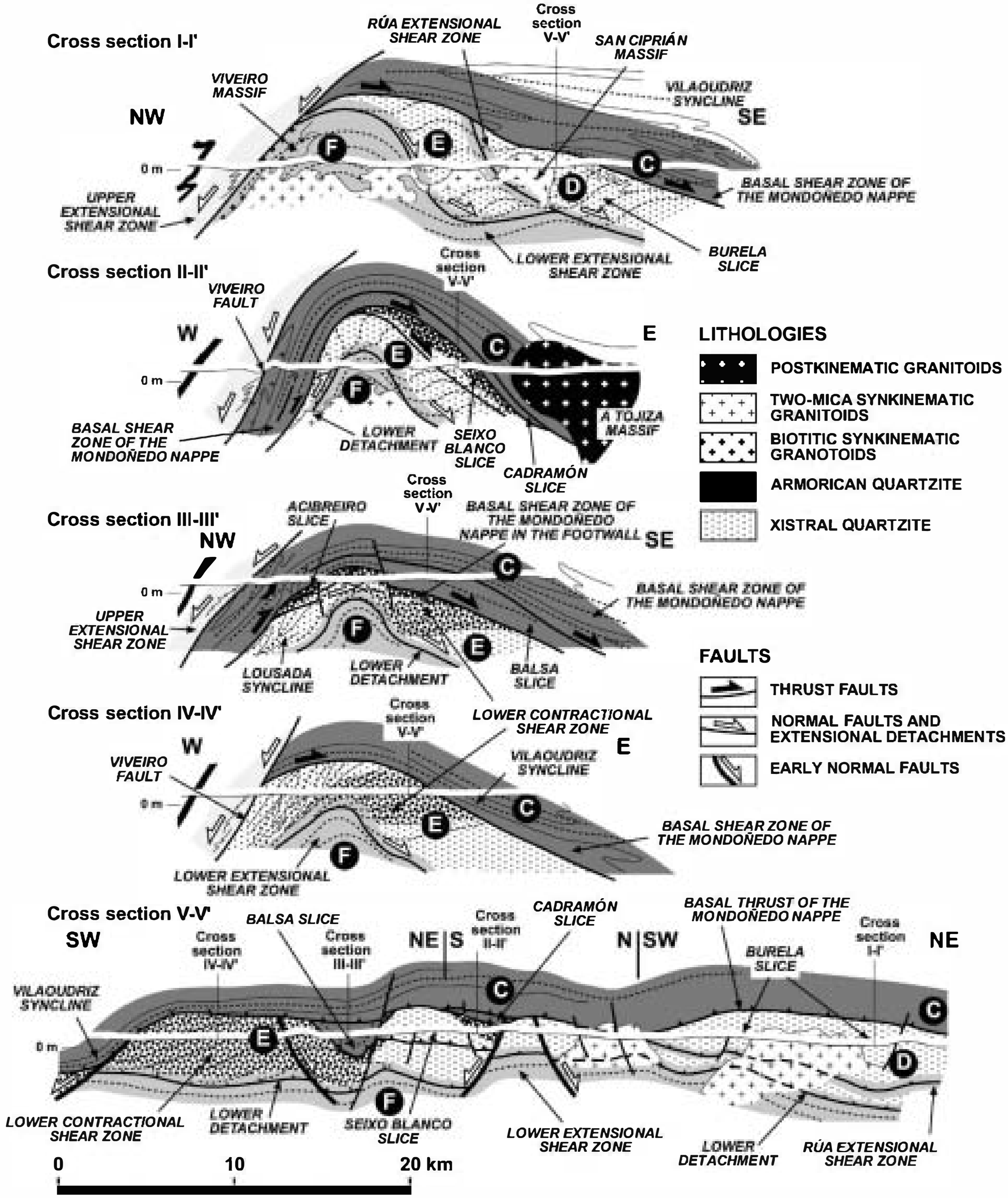


Fig. 8. Geological sections across the Xistral tectonic window showing the ductile shear zones and faults. For location, see Fig. 7. For legend of the shear zones, see Figs. 3 and 4. Letters C–F refer to the location of the P–T paths depicted in Fig. 6. Thin dashed lines show the attitude of the main foliation: S_1 outside the shear zones, and (S_1 +) S_2 in the shear zones.

The main extensional structure is a detachment situated at the bottom of the quartzitic formation and below it (Figs. 7–10). In addition, horizontal extension affected the quartzite in both longitudinal and transverse directions. The E–W extension created faulted blocks that underwent domino-style rotation (Fig. 8, cross-section I–I′). The N–S extension gave rise to transverse normal faults cutting across the footwall unit (Fig. 8, cross-section V–V′, and

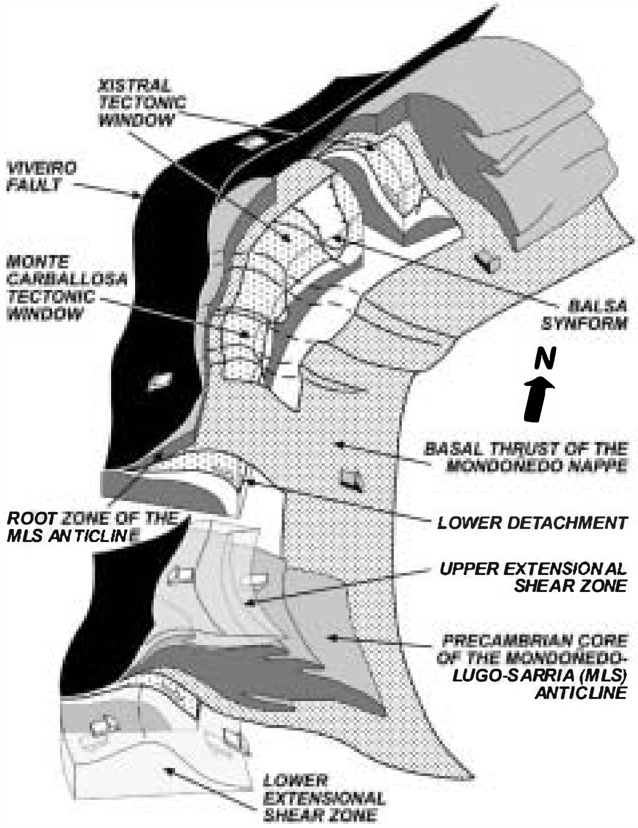


Fig. 9. Three-dimensional sketch showing the relationships between the main contractional and extensional structures. The upper part of the figure depicts the crosscutting relationships between folds and faults, whereas the lower block shows the two main extensional ductile shear zones (light grey, 'transparent'). The contractional ductile shear zones are not shown.

Fig. 9). All these structures were active during different stages of nappe emplacement.

The metamorphic evolution of the footwall unit is very different from that of the hanging wall. It is better described by its low-pressure conditions and by a strong thermal gradient (Fig. 6, white arrows), and is similar to the low-P intermediate type of Miyashiro (1961), characterized by parageneses with andalusite–staurolite–cordierite. An episode of vigorous heating affected most of the Xistral window and is clearly identified in the quartzites, where it gave rise to a pronounced grain growth, initiated in the advanced stages of deformation (Fig. 11).

4.1. Basal shear zone of the Mondoñedo nappe in the footwall unit

Remnants of a ductile shear zone have been found in the upper parts of the Xistral Quartzite, in two contiguous outcrops that surround a NW–SE-trending synform between Muras and Balsa (Figs. 3 and 7). The structure here is defined by a saddle-fold geometry formed by interference between the transverse synform and the large longitudinal antiform. A third outcrop, a few kilometres to the north, west of Cadramón (Fig. 7), also occurs on the southern limb of another very open transverse synform.

The mylonitic foliation in the shear zones defines the saddle form of the fold and is at a low angle to thrust faults within the window, which are also affected by the fold interference. This contrasts with the S_1 foliation below, which is at nearly 90° to these thrust faults (Fig. 8, cross-section II–II′). Stretching lineation, marked by elongation of quartz grains, varies from E–W to NW–SE, and shear criteria indicate top-to-the-east kinematics. The quartzite shows a late-kinematic generalized grain growth (Fig. 11c) and a quartz *c*-axis fabric (Fig. 12, sample PG-77) discussed in a separate section.

The structural position, always directly underneath slices of the Mondoñedo nappe (see below), suggests that the mylonitic remnants are relics of the Mondoñedo basal shear zone, preserved in its footwall. In contrast to the hanging wall unit, the maximum thickness of the shear zone is 1 km in the footwall, a value attained only in the hinge zone of the Muras–Balsa radial synform and decreasing progressively to zero in the limbs (Fig. 8, section V–V′). It seems as if the shear zone was being folded in the radial synform and, at a given moment of the folding process, was cut by the Mondoñedo thrust fault (Fig. 10). The shear zone itself was cut and repeated by late-stage thrust faults, giving rise to two quartzitic imbricates (the Acibreiro and Seixo Blanco slices; Figs. 7 and 8). We will turn back to these points later, when describing the N–S extension.

4.2. Lower contractional shear zone

In the south of the Xistral window and in the Monte Carballosa window, the quartzite became mylonitized to the east, below a less-deformed zone where the recumbent folds can be easily mapped (see Figs. 3 and 7). In the Xistral window, the mylonitic foliation is folded in an interference dome (see stereographic projection in Fig. 7), but is oblique to the Mondoñedo basal thrust (Fig. 8, cross-section IV–IV′) in such a way that unfolding the late longitudinal antiform, it would dip some 30° more to the west than the thrust itself. In fact, both shear zones converge to the south of Balsa (Fig. 7). This feature, together with the kinematic criteria indicating top-to-the-east shearing, supports the interpretation of the shear zone as having been a wide ductile thrust.

The mylonitic texture of the quartzites is well marked by quartz ribbons bounded by flat and parallel muscovite crystals. The quartz grains show a late- to post-kinematic generalized grain growth typical of high temperature annealing (Wilson, 1973; Bouchez and Pêcher, 1981) in the lower and middle parts of the shear zone in the Xistral window (sample PG-62; Fig. 11b), but not in the upper part (sample PG-59; Fig. 11a), nor in the Monte Carballosa window where the metamorphic grade remained low through the entire history of deformation. Paths E and D of Fig. 6, depict the metamorphic evolution of points of the

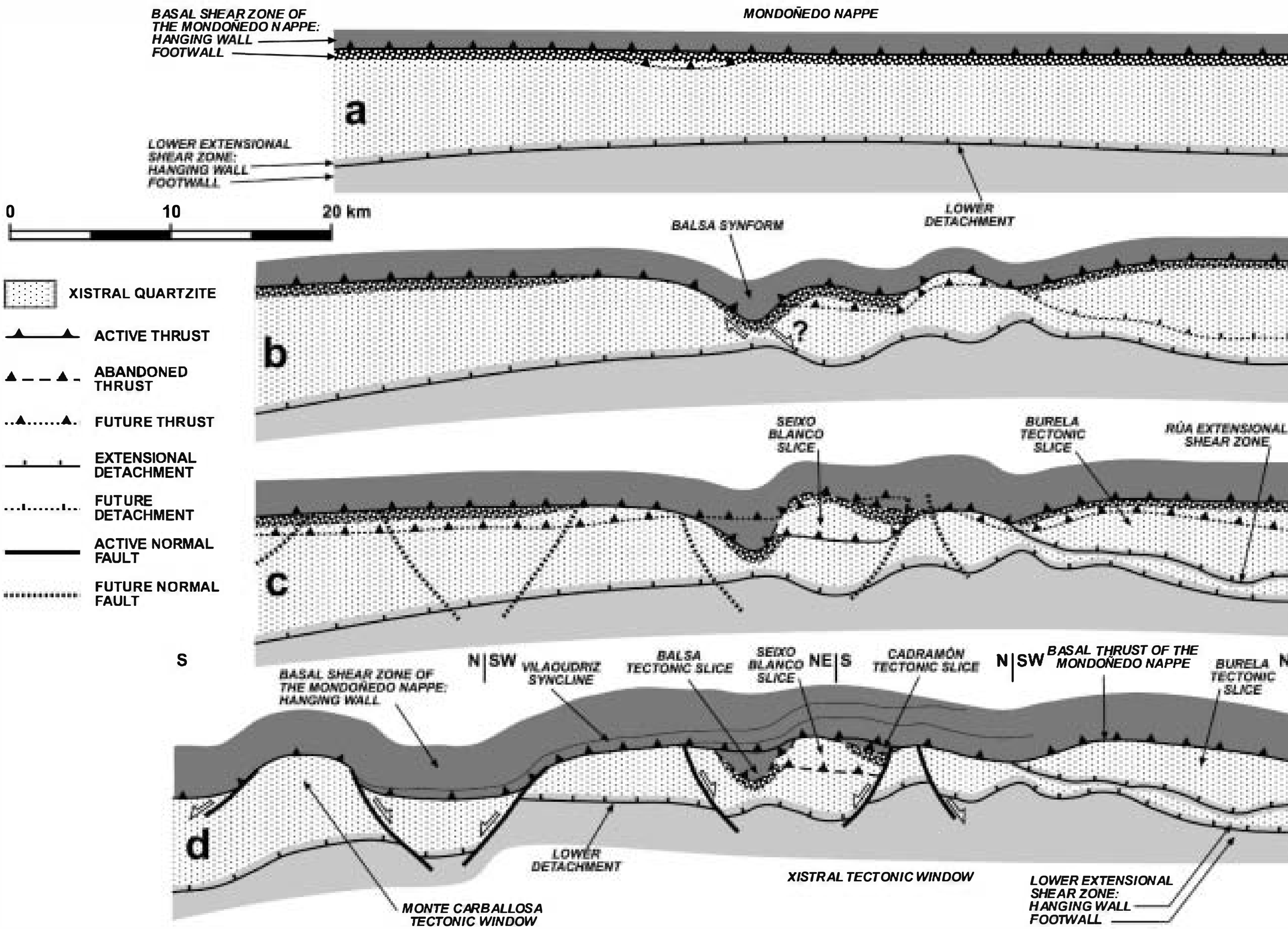


Fig. 10. Footwall sequence diagram showing the evolution of the lower unit of the Mondoñedo thrust in a section normal to the transport direction (section V–V′ of Fig. 8). The progressive thickening of the basal shear zone of the Mondoñedo nappe (dark grey) from (a) to (d) tries to reflect the fact that more internal parts of the nappe (where the basal shear zone was wider) were reaching the section, thus reflecting thrust motion contemporaneous with the N–S extension.

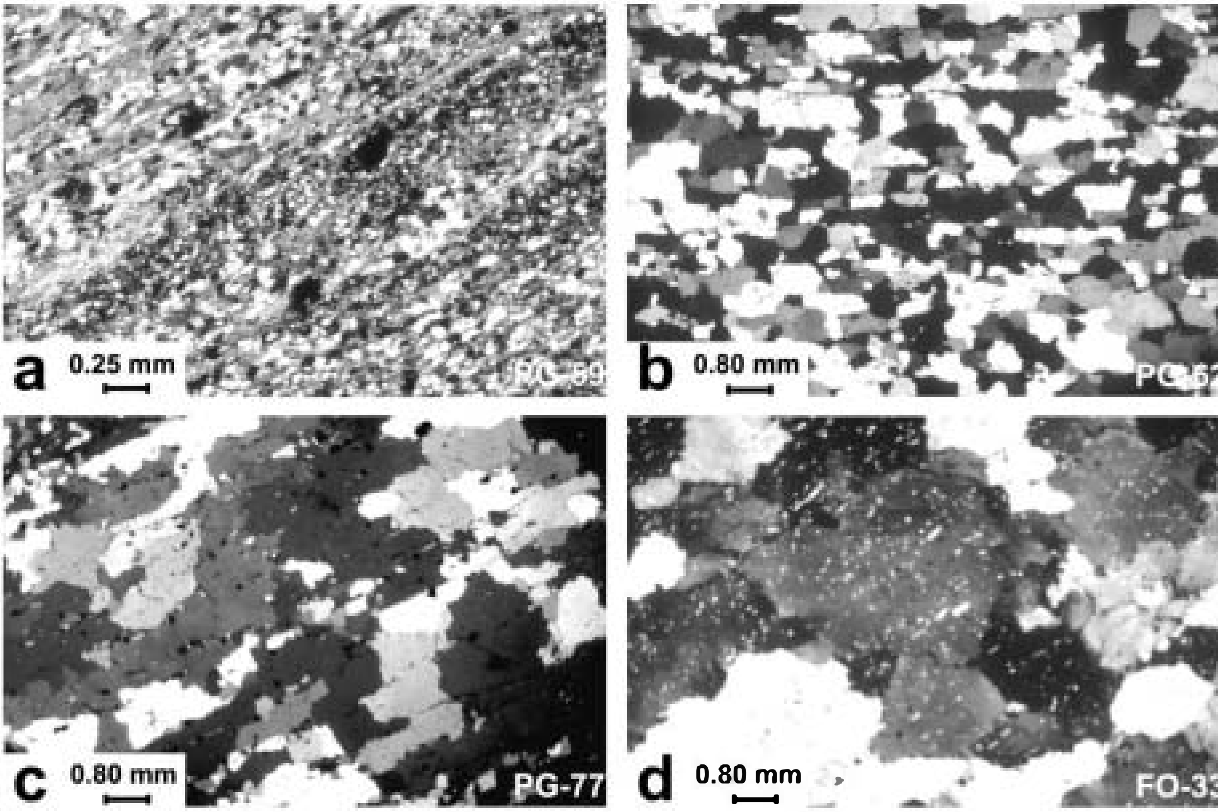


Fig. 11. Microphotographs of mylonitized quartzites in the shear zones of the Xistral tectonic window, showing the effect of heating on grain size. (a) Original fine-grained fabric of the lower contractional shear zone preserved around Vilapedre, in the southern part of the Xistral window (Fig. 7), and corresponding to the upper part of the staurolite–cordierite zone. (b) Mylonitic fabric of the lower contractional shear zone at the limit between the sillimanite and staurolite–cordierite zones. Grain growth is very pronounced and evident when comparing with the previous photograph (note the different scales). (c) Fabric of the basal shear zone of the Mondoñedo nappe in the footwall unit inside the sillimanite zone. (d) Fabric of the quartzites adjacent to the lower detachment and to the sillimanite–orthoclase zone, showing generalized and exaggerated grain growth. Note the parallel inclusions of white mica corresponding to an older, fine-grained foliation. Crossed polarizers. The structural position of the samples is shown in Fig. 12.

footwall unit equivalent to the sampling sites of PG-62 and -59, respectively, and Fig. 12 (cross-section IV–IV′) shows the structural position and quartz *c*-axis fabric of both samples.

4.3. Lower extensional shear zone and detachment

The base of the Xistral Quartzite delineates a N–S antiform around Viveiró, a hamlet in the centre of the tectonic window (not to be confused with the village of Viveiro, 20 km to the north, on the coast, and which gives its name to the Viveiro fault; see Fig. 7). The limit is very smooth, when one considers the fact that the quartzites are strongly folded. This basal contact is not a stratigraphic one, but a detachment fault, associated with which there is a 100–350-m-thick mylonitic shear zone affecting the base of the quartzites above. The mylonites include a new generation of minor recumbent folds with east vergence. These and the asymmetry of sigmoidal boudins indicate a top-to-the-east shearing. As is usually found in the Xistral tectonic window, the quartz–mylonites underwent grain growth, though here it is even more exaggerated (sample FO-33 in Fig. 11d). Individual quartz grains may attain 10 mm along their long axis, which commonly (but not always) is parallel to the apparent mineral lineation of the rock, marked statistically by the long axes of the quartz grains. The mylonitic foliation is parallel to the detachment, but the layering and the S_1 foliation in the Xistral Quartzite above the shear zone are inclined between 30 and 90° to it (Fig. 8, cross-sections I–I′ to IV–IV′).

High-grade paragneisses of the sillimanite and the sillimanite–orthoclase zones occur below the detachment, constituting its footwall. A high-temperature and low-pressure penetrative foliation, roughly parallel to the detachment, characterizes its footwall, which is also penetratively deformed. Numerous granitic injections evidence partial melting, and the metamorphic associations, characterized by the absence of kyanite and the scarcity of garnet, indicate that high temperatures were associated with relatively low pressures (Fig. 6, path F). No low-T relics are found in the footwall to the detachment, whereas they are common in the quartzites above, where parallel inclusions of very small size (mostly white mica) in large new quartz grains, point to a first mylonitic stage developed at low grade conditions (Fig. 11d). Also, pelitic horizons inside the hanging wall quartzites are low- to medium-grade schists,

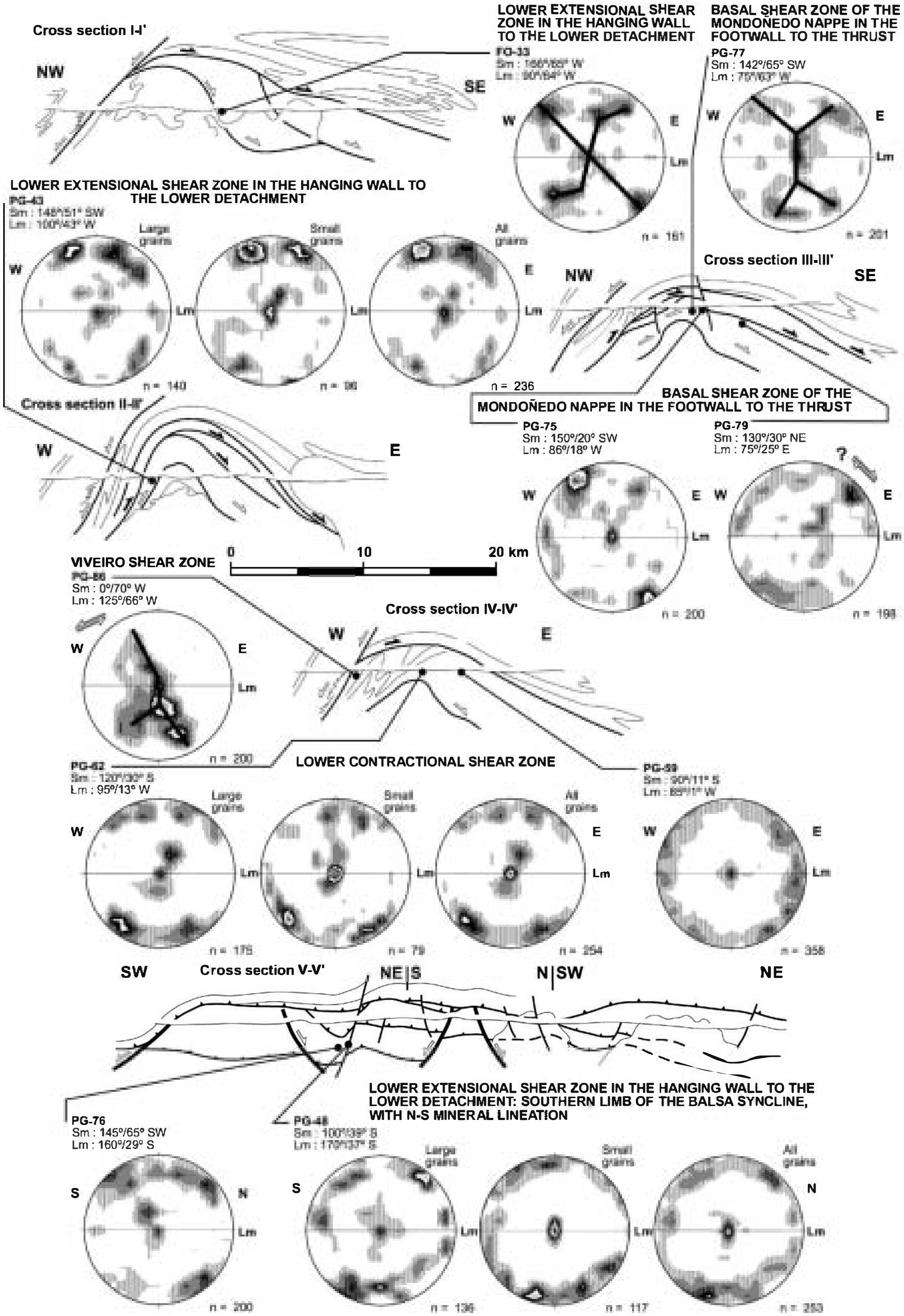


Fig. 12. Quartz *c*-axis fabrics from the Xistral Quartzite mylonitized in the different shear zones. Cross-sections of Fig. 8 are used to locate the analysed samples.

which were later heated to the sillimanite zone (Fig. 6, path E), but never transformed into paragneisses.

These petrological constraints are used as evidence indicating a jump in metamorphic grade across the detachment, with the omission of part of the metamorphic zoning, pointing to an extensional movement (Wheeler and Butler, 1994), coupled with heating of its upper unit with heat transmitted from the lower unit. Yet the P–T paths for the upper and the lower units (Fig. 6, paths E and F, respectively) run almost parallel. Both are nearly isobaric prograde trajectories, of the type commonly developed in the hanging wall to large extensional detachments (Escuder Viruete et al., 1994, 1997). Considering the P–T path of the lower unit (Fig. 6, path F), the possibility arises that this footwall represents in fact the upper part of a deeper zone of crustal thinning and stretching, whose lower part consist of hot material ascending inside the crust.

A series of synkinematic granites, granodiorites and locally, tonalites, associated with ultramafic rocks, intruded the northern part of the Xistral tectonic window (Figs. 1, 3, 7 and 8), and are collectively described as the Viveiro massif (Galán, 1987). These rocks were deformed, acquiring a low-dipping foliation parallel to the regional high-T and low-P foliation of their country rocks. Galán (1987) and Galán et al. (1996) studied these rocks, concluding that the ultramafics have a mantle provenance, and the tonalites and granodiorites include mantle components.

The geological map NW of Viveiró (Fig. 7) shows that the lower detachment joins the Mondoñedo basal thrust to the west (Fig. 8, section II–II′). We assume that the thrust was inclined to the west, but depending on how much, the lower detachment would have had an original dip either to the east or west. On purely geometrical grounds, it might be equivalent to either a normal or a reverse fault. However, because the omission of part of the metamorphic zoning suggests it is an extensional detachment, and shear sense was to the east, we infer it to have originally dipped to the east.

The lower detachment, the associated narrow hanging wall shear zone and the widely deformed paragneisses and igneous rocks below are collectively termed the lower extensional shear zone (Fig. 8). A related structure occurs in the northern part of the Xistral window, west of Rúa, where two blocks with west-dipping foliation, are cut by an east-dipping ductile shear zone with top-to-the-east movement (Fig. 8, section I–I′). Even though both blocks are made up of the Xistral Quartzite, the lower one is in the sillimanite zone, whereas the upper one is greenschists facies (Fig. 5). This points to the extensional character of the Rúa shear zone, which joins the Mondoñedo thrust fault to the south (Fig. 7).

The Rúa extensional shear zone seems dynamically linked to the lower detachment. Its throw is not necessarily large, as the thermal gradient associated with the lower detachment is high and the sillimanite and chlorite–biotite zones were probably not far from each other. The most striking feature of this shear zone is the high angle it makes to the foliation in the two blocks it separates. In both the Mondoñedo thrust sheet and its footwall unit below the Xistral Quartzite, the bedding and the foliation dips are generally low and, more important, at low angles to the attitude of the thrust fault (Fig. 4). This is not the case in the Xistral Quartzite, however, where the bedding, the S_1 foliation and the axial surface of first-phase folds dip between 45 and 90°, except inside the ductile shear zones (Fig. 8). In most of the eastern part of the Xistral window, the first foliation makes an angle of nearly 90° to the thrust fault (Fig. 8, sections I–I′ to III–III′). Also, in both flanks of the N–S antiform at Viveiró, the planar fabric in the Xistral Quartzite is parallel to its lower limit only close to it, but above the shear zone, bedding and foliation quickly rotate, becoming perpendicular to the lower detachment (Fig. 8, section II–II′).

If the high angle between the foliation and either the thrust or the lower detachment is an original feature, the first folds, usually recumbent, would have been vertical in the Xistral Quartzite. The other possibility is that this angle resulted from subsequent rotation, and the Rúa extensional shear zone may have allowed the rotation to proceed by domino-style boudinage. This type of boudinage needs weak, ductile layers on both sides to accommodate the rotation of the rigid blocks. The hot footwall unit of the lower detachment may have worked as the lower one of such ductile layers, whereas the basal shear zone of the Mondoñedo nappe would have been the upper one. At least two blocks, separated by the Rúa extensional shear zone, rotated counterclockwise. Another block may have existed to the west of Viveiró if the antiform there was nucleated by boudinage. Because folds form at the neck of boudins, the antiform may have resulted from the E–W individualization of a new block during E–W extension. This would explain its nearly N–S attitude, somewhat different from the NE–SW strike of the tectonic window and of the late open folds in the northern part of the Mondoñedo nappe (Fig. 3).

4.4. N–S extension and the thrust slices

Megaboudins other than the blocks described in the previous section also developed during nappe emplacement, but related to longitudinal stretching of the Xistal Quartzite. The lower detachment and the basal shear zone of the Mondoñedo nappe are commonly 2000 m apart, but north of Balsa, they join each other (Fig. 7), and this occurs in the only area where N–S stretching lineations are seen in the Xistral Quartzite (Fig. 7; N–S maximum in the stereoplot showing mineral lineation inside the shear zones). Elongation is normal to the fold axis in the inner arc of the Balsa syncline, a feature compatible with the syncline being the neck of a megaboudin. This interpretation explains why the shear zones that developed in the upper and lower parts of the Xistral Quartzite, approach each other in this area (Fig. 8, section V–V′, below the Balsa slice), and is illustrated in Fig. 10b.

The subsequent development of E–W-trending normal faults confirms the N–S extension. Inside the Xistral window, three of these faults (thick lines in Figs. 7 and 8, section V–V′) crosscut the footwall unit but not the Mondoñedo thrust sheet. The most prominent of these faults, west of Cadramón, cuts the Seixo Blanco slice (preserved only in the downthrown southern block) but is cut by the Mondoñedo thrust fault. The E–W fault appears folded by late longitudinal folds, a feature that can be appreciated in the map (Fig. 7) and in an outcrop where a fault-related cataclasite appears folded with a steep axis. Many other faults have been mapped, but most of them are late structures, post-dating the longitudinal folds. Conversely, these three are early normal faults pre-dating the latest stages of thrusting.

The N–S extension, though of limited extent, had an important imprint in the present configuration of the Mondoñedo nappe and its footwall unit. The necks of the boudins and the fault-related grabens have preserved slices of the Mondoñedo nappe that were abandoned in these structural depressions by newly formed faults above. This is the case of the Balsa and Cadramón tectonic slices (Figs. 7–9). Conversely, boudins and horsts were truncated and quartzitic slices, such as Seixo Blanco, were incorporated into the thrust sheet.

It has been a common practice in thrust tectonics to use hanging wall sequence diagrams (e.g. Harris, 1970; Elliott and Johnson, 1980) to show the evolution of allochthonous units. The diagrams are successive longitudinal cross-sections showing how different units are being incorporated into the hanging wall unit of thrust systems propagating sequentially in a piggy back mode. In the case of the Mondoñedo nappe, several imbricates were abandoned below the currently active thrust fault, so that a footwall sequence diagram (Fig. 10) seems appropriate to show the development of thrust slices in relation to N–S extension.

Fig. 10 illustrates both the creation of the Balsa slice after development of the Balsa synform, and how the Seixo Blanco slice developed by truncation of a megaboudin North of the Balsa synfom (a–c), itself then being truncated by an early normal fault (c and d) and lately overprinted by the latest Mondoñedo basal thrust fault (d). In addition, to show how the slices developed sequentially and how they were preserved by the creation of new faults above, Fig. 10 explains the origin of the transverse open folds: they correspond either to the necks of megaboudins, or are 'forced' folds above horsts and grabens bounded by the early E–W normal faults in the footwall unit. The southern limit of the Xistral window and the original north and south boundaries of the Monte Carballosa window, were probably early normal faults, affecting the Xistral Quartzite but not penetrating up into the Mondoñedo nappe. The thrust sheet adapted to this evolving footwall structural topography, and the normal fault planes became part of the thrust surface, acting as lateral ramps during the last stages of thrusting.

4.5. Quartz c-axis fabrics

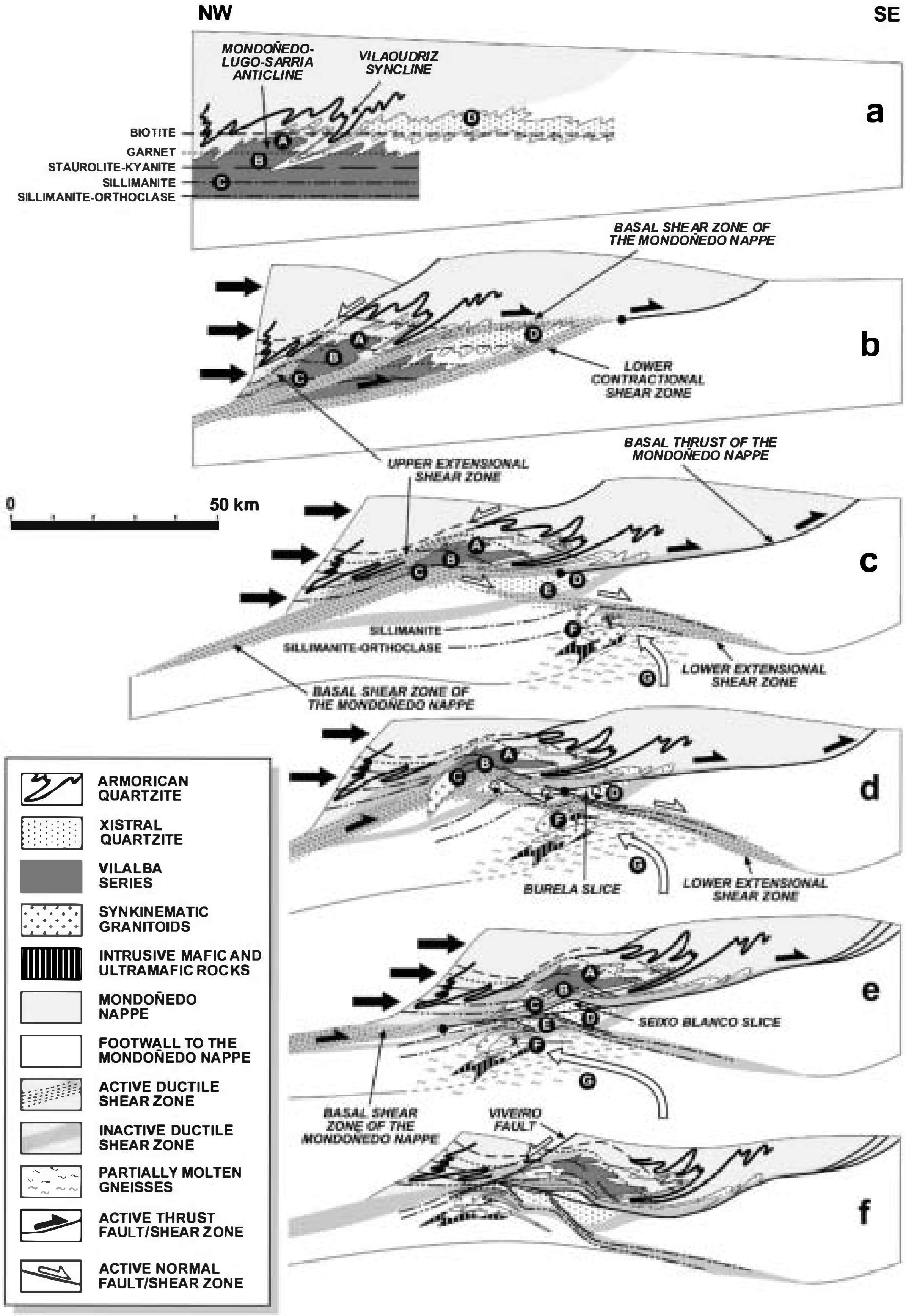
The shear zones of the Xistral window share a common quartz *c*-axis fabric: a type I crossed girdle (Lister and Williams, 1979; Schmid and Casey, 1986), usually orthorhombic (Fig. 12). Often, there is a central part oblique to the mylonitic foliation and sometimes, the oblique central part of the crossed girdles, or the more populated of the two girdles, may be taken as kinematic indicators. In all the cases, however, shear sense has been checked with macroscopic kinematic criteria, such as sigmoidal boudinage and fold vergence.

The fabrics are similar to those modelled by Lister and Williams (1979) for simple shear sometimes combined with coaxial deformation, and correspond to plane strain ellipsoids according to Lister and Hobbs (1980). Samples taken outside the shear zones do not show clear crystallographic fabrics.

To test the influence of the grain growth recorded by the quartzites inside the sillimanite zone, separate diagrams were plotted for small and large grains of the same thin sections. Large quartz grains show microinclusions, mostly of white mica grains, parallel and closely spaced (Fig. 11d). They are relics of an earlier fine-grained foliation and, when the grain growth is not exaggerated (Wilson, 1973), that is, not all of the grains reach large sizes, small quartz grains do not include white mica (Fig. 11c) and are viewed either as preserved relics of the pre-heating stage or as recrystallized new grains.

As can be seen in Fig. 12, crystallographic fabrics are similar for both grain sizes, which suggests that this type of *c*-axis fabric existed before the quartz grains grew. Behrmann and Platt (1982) obtained similar diagrams in rocks deformed at low-grade conditions, between 300 and 400 °C. It is quite clear that mylonites developed at relatively low temperatures and were subsequently heated. But it seems that heating was accompanied with further ductile deformation. The largest grains post-date mylonitization in the lower detachment (Fig. 11d) so that, there, grain growth continued after mylonitization had ceased. However, the large quartz grains often define the mineral lineation. This is the case of the lower contractional shear zone (Fig. 11b), the basal shear zone of the Mondoñedo nappe in the footwall unit (Fig. 11c), the lower detachment and the hinge zone of the Balsa syncline, the supposed megaboudin neck of the N–S extension. In these cases, the shape fabric of large quartz grains fits the *c*-axis fabric, suggesting that deformation was active during heating.

In sections where the Xistral Quartzite can be traced from low-grade to the sillimanite zone (Fig. 5), the metamorphic grade increases downward, and grain growth occurs only in the staurolite–cordierite and sillimanite zones, being generalized and pronounced only in the latter. For instance,



NW
SE
MONDOÑEDO-LUGO-SARRIA ANTICLINE
VILAOUDRIZ SYNCLINE
BIOTITE
GARNET
STAUROLITE-KYANITE
SILLIMANITE
SILLIMANITE-ORTHOCLASE
a
BASAL SHEAR ZONE OF THE MONDOÑEDO NAPPE
LOWER CONTRACTIONAL SHEAR ZONE
b
UPPER EXTENSIONAL SHEAR ZONE
BASAL THRUST OF THE MONDOÑEDO NAPPE
0
50 km
c
SILLIMANITE
SILLIMANITE-ORTHOCLASE
LOWER EXTENSIONAL SHEAR ZONE
BASAL SHEAR ZONE OF THE MONDOÑEDO NAPPE
d
BURELA SLICE
LOWER EXTENSIONAL SHEAR ZONE
e
SEIXO BLANCO SLICE
BASAL SHEAR ZONE OF THE MONDOÑEDO NAPPE
VIVEIRO FAULT
f
ARMORICAN QUARTZITE
XISTRAL QUARTZITE
VILALBA SERIES
SYNKINEMATIC GRANITOIDS
INTRUSIVE MAFIC AND ULTRAMAFIC ROCKS
MONDOÑEDO NAPPE
FOOTWALL TO THE MONDOÑEDO NAPPE
ACTIVE DUCTILE SHEAR ZONE
INACTIVE DUCTILE SHEAR ZONE
PARTIALLY MOLTEN GNEISSES
ACTIVE THRUST FAULT/SHEAR ZONE
ACTIVE NORMAL FAULT/SHEAR ZONE

the original fine-grained fabric of the lower contractional shear zone (Fig. 11a) has been preserved around Vilapedre, in the southern part of the Xistral window (Fig. 7). This indicates that grain growth was induced by heat transferred from below, and we have seen that heating was coeval with the activity of the lower detachment, which we suggest is an extensional structure. Furthermore, the simultaneous shearing and grain growth in the Mondoñedo shear zone (Fig. 11c) demonstrates temporal overlapping (or alternance) between ductile thrusting and motion of the lower detachment, that is between contractional and extensional structures.

5. The Viveiro fault

A normal fault limits the Mondoñedo thrust sheet to the west, crosscutting its hanging wall and footwall units (Figs. 1, 4, 7 and 9). The brittle fault dips between 40 and 60° west, and has an associated ductile shear zone, a few hundreds of metres thick, that has not been shown in the maps and cross-sections for the sake of clarity. There, the previous regional foliation, either the S_1 or the S_2 of the Mondoñedo basal or upper extensional shear zones, appears crenulated by a new, subhorizontal cleavage. Minor recumbent folds with west vergence and weakly curved hinges, and S–C or ECC microstructures (Platt, 1984), indicate a top-to-the-west motion, with a slight right-lateral component (Martínez Catalán, 1985; Martínez et al., 1996). Where the Xistral Quartzite was involved in the shear zone, a mylonitic foliation developed, whose *c*-axis fabric shows a main girdle oblique to the foliation, supporting the top-to-the-west sense of shearing (Fig. 12, sample PG-86).

The upper extensional shear zone and the Viveiro fault coincide spatially (Fig. 3), but the metamorphic evolution of the Mondoñedo thrust sheet demonstrates that they were not simultaneous. The upper shear zone developed during early stages of nappe motion, when the thrust sheet was thick and glided above the ductile basal shear zone, whereas the Viveiro fault cuts the thinned thrust sheet, the brittle thrust fault, and the footwall unit, indicating that it formed when nappe motion had ceased. The Viveiro fault overprints the earlier shear zone, which was dragged downward to the west by the more steeply-dipping fault (Figs. 4 and 9). It is possible that the fault used parts of the pre-existing weak shear zone to nucleate and develop.

The shear zone associated with the Viveiro fault developed under low-grade metamorphic conditions. Kyanite and staurolite presently found around the fault grew during motion of the upper extensional shear zone, when the preserved upper levels of the Mondoñedo nappe were deep enough to fall into the kyanite field, and their decompressive P–T path went through this field for a large part of its trajectory (Fig. 6, path A). Martínez Catalán et al. (1990) suggested a throw of 10–12 km for the Viveiro fault, considering the metamorphic gap: it separates the chlorite zone to the west, from the sillimanite zone to the east (Figs. 4 and 5). A more precise estimation of the vertical offset, based on thermobarometry, was given by Reche et al. (1998) as between 4 and 5 kbar, roughly equivalent to 15–19 km. This throw is viewed as the result of the two dip-slip motions: that of the upper extensional shear zone and that of the Viveiro fault itself. A dip-slip of 5–6 km is more reasonable for the Viveiro fault alone in the north (Fig. 4, cross-section A–A′). To the south, the fault slip decreases progressively, being less than 1 km in the area of Incio (Fig. 3).

6. Absolute and relative timing and structural evolution

The structural history of the Mondoñedo nappe and its footwall is graphically shown in Fig. 13. The different stages are based on overprinting criteria and crosscutting relationships described in previous sections, which will be recalled to justify the structural evolution. The relative chronology, bracketed by published isotopic age data discussed below, is summarized in Fig. 14.

The age of the first deformation phase is constrained by $^{40}Ar/^{39}Ar$ whole-rock geochronology on the S_1 foliation in adjacent areas (Dallmeyer et al., 1997). Toward more internal zones, the first cleavage was dated at 359.3 ± 0.2 Ma in the western limb of the 'Ollo de Sapo' anticline (Fig. 15) to the south of the Mondoñedo nappe. Toward the foreland, an age of 336.5 ± 0.3 Ma was obtained near La Espina thrust, at the limit with the external zones to the east (Fig. 15). From these data, the development of recumbent folding in the Mondoñedo nappe can be approximately placed somewhere in the interval between 360 and 335 Ma.

Two samples intended for dating the S_1 and S_2 foliations in the Mondoñedo nappe gave ages of 300.0 ± 1.0 ($^{40}Ar/^{39}Ar$ whole rock) and 298.2 ± 0.6 Ma ($^{40}Ar/^{39}Ar$ muscovite), respectively (Dallmeyer et al., 1997). However,

Fig. 13. Structural evolution of the Mondoñedo nappe and its footwall unit showing the development of major extensional structures during thrusting. A black dot at the rear edge of the Mondoñedo thrust marks the suggested propagation of the fault into the basal ductile shear zone. The metamorphic isograds have been included. (a) After recumbent folding and equilibration of Barrovian metamorphism. (b) Early stages of emplacement of the Mondoñedo nappe and coeval extension, related to the upper extensional shear zone. (c) As before, but extension begins to affect the footwall unit, associated with the ascent of igneous rocks and partially molten gneisses. (d) and (e) Westward motion of the hot, partially molten rocks induces continued activity of the lower extensional shear zone and detachment, and heating of its hanging wall unit. Note the ascent of the sillimanite isograd into the previous low-grade Xistral Quartzite, the extension of this unit accomplished by domino-style boudinage, and the truncation of one of the boudins by the thrust fault, forming the Seixo Blanco slice. (f) The Viveiro normal fault post-dates the last increments of thrusting.

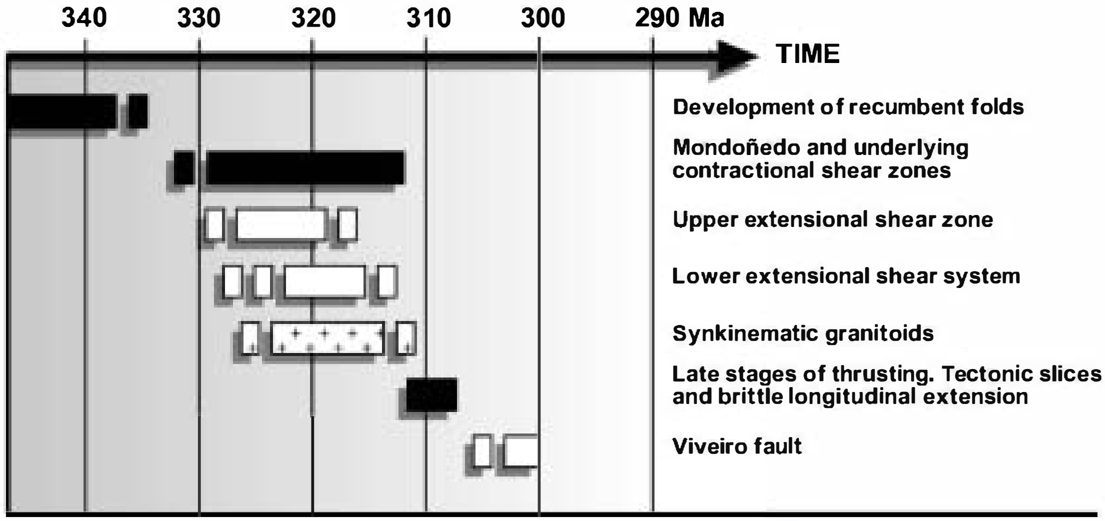


Fig. 14. Timing of contractional and extensional structures across the study area. Chronology is based on Dallmeyer et al. (1997) and Fernández-Suárez et al. (2000).

synkinematic granitoids gave U–Pb zircon and monazite ages ranging between 310 and 330 Ma for the massifs of Sarria, Viveiro and Penedo Gordo (Fernández-Suárez et al., 2000). This would suggest that both the S_1 and S_2 foliations are more than 10 m.y. younger than the granitoids synkinematic with nappe emplacement. A more feasible explanation is that, rather than dating fabric development, the two $^{40}Ar/^{39}Ar$ ages represent cooling ages related to unroofing, and perhaps date the uplift of the nappe by motion on the Viveiro fault.

The Sarria massif is a two-mica granite intruded in the southern part of the Mondoñedo nappe (Fig. 3) and deformed in its basal shear zone (Martínez Catalán, 1983, 1985). The intrusion also reached the upper extensional shear zone, but is undeformed there (Figs. 3 and 4, section B–B′) and assumed to post-date this shear zone. Consequently, the age of crystallization of the granite, 313 ± 2 Ma (Fernández-Suárez et al., 2000), establishes an upper limit for the upper extensional shear zone, whose motion pre-dated this age, and also a lower limit for the final emplacement of the thrust sheet (Fig. 14), which continued moving after the granite intrusion. The Penedo Gordo massif, dated at 317^{+9}_{-5} Ma (Fernández-Suárez et al., 2000), also intruded into the upper extensional shear zone, but was only deformed by the Viveiro fault (Figs. 3 and 7), establishing a lower limit for its motion and, as the Sarria massif, an upper age limit for the upper extensional shear zone. The Viveiro massif (Figs. 3, 7 and 8) was deformed in the lower extensional shear zone, so that the 323^{+9}_{-5} Ma age of crystallization obtained by Fernández-Suárez et al. (2000) represents a lower limit for the late activity of this structure.

Postkinematic granitoids have been dated between 285 and 295 Ma (U–Pb method, Fernández-Suárez et al., 2000) and 275 and 285 Ma ($^{40}Ar/^{39}Ar$ method; Dallmeyer et al., 1997). U–Pb data are more reliable for crystallization ages, and provide an upper limit for thrust tectonic activity: the A Tojiza massif (295 ± 2 Ma) and the San Ciprián massif (286 ± 2 Ma) overprinted the basal shear zone and thrust fault of the Mondoñedo nappe (Fig. 8, sections I–I′ and II–II′). These same massifs also yielded $^{40}Ar/^{39}Ar$ muscovite ages of 284 and 274 Ma, respectively, suggesting a time lapse of 10 m.y. between crystallization and cooling to the closure temperature of argon in muscovite.

Taking together these data and the mutual relationships between the different structures described in the previous sections, a picture of the structural evolution can be traced.

After a first episode of recumbent folding, crustal thickening and burial, loosely constrained between 360 and 335 Ma, a Barrovian metamorphic zoning was established and equilibrated (Fig. 13a and Fig. 6, paths A, B and C, prograde part of grey arrows, mostly dashed). The Xistral Quartzite occupied, at that time, a relatively shallow position.

In the next 30 million years, the contractional ductile shear zones developed. The more internal parts of the thrust sheet initiated their exhumation along the basal shear zone of the Mondoñedo nappe (Fig. 13a and b) from a depth of 38–45 km (Arenas and Martínez Catalán, 2003). While thrust motion induced crustal thickening, the thrust sheet became thinned by the upper extensional shear zone, and the lower extensional detachment developed in the footwall unit (Fig. 13c). An upper age limit for the extensional activity in the nappe is provided by the Sarria and Penedo Gordo massifs (313 ± 2 and 317^{+9}_{-5} Ma, respectively; Fernández-Suárez et al., 2000), which were not affected by the upper extensional shear zone.

Heat accumulation due to crustal thickening and,

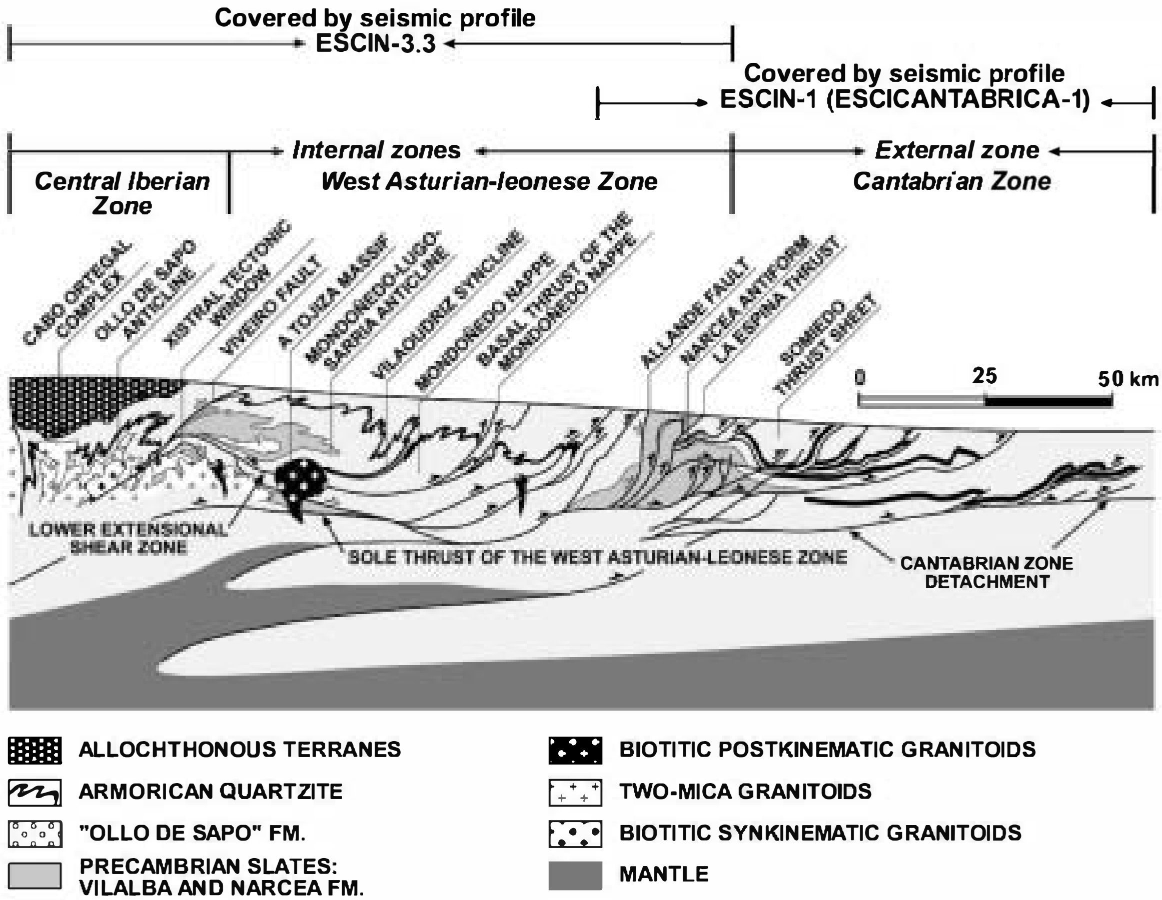


Fig. 15. The structure of the Variscan wedge, as suggested at the end of convergence, based on surface geology and geophysics.

probably, to advention of mantle-derived rocks, may have triggered the development of the lower extensional shear zone, which juxtaposed deep-seated hot rocks against the overlying and relatively cold Xistral Quartzite. The thick and competent quartzitic layer might have acted as a screen, channelling the viscous flow of ascending buoyant material. Partially molten crustal and subordinate mantle rocks trying to open their way upward (Fig. 6, path G) would have been obliged to flow near horizontally, giving rise to the lower extensional detachment (Fig. 13c–e). Heating was very strong in the footwall to the Mondoñedo nappe (Fig. 6, paths E and F), and synkinematic igneous rocks intruded in the footwall to the lower detachment.

The heat transmitted from below annealed the mylonitic quartzites of the hanging wall to the detachment, and also those of the two contractional shear zones in the Xistral tectonic window, that had previously developed low-grade mylonites (Fig. 11). Consequently, we assume that the lower detachment post-dated part of the ductile shearing in the Mondoñedo and lower contractional shear zones. However, it seems that heating was accompanied with further ductile deformation, so that all of the shear zones in the footwall to the Mondoñedo thrust fault were heated while being still active. Furthermore, as long as the Mondoñedo thrust and associated tectonic slices cut the annealed mylonites, we infer that thrust movement continued after the activity along the lower detachment had ceased.

Once thinned, the Mondoñedo nappe moved as a relatively cold thrust sheet, less than 20 km thick, overthrusting its present footwall unit, which registered a moderate heating and pressurization until the P–T conditions at the bottom of the hanging wall (Fig. 6, path C) were equal to those at the top of the footwall (Fig. 6, path D). The thrust developed as a discrete fault close to the ductile-brittle transition, propagating into the previous ductile shear zone and preserving most of it in the hanging wall (Fig. 13c–e), but also a portion in the footwall (Fig. 7).

The Xistral Quartzite underwent E–W and N–S extension coeval with the late stages of nappe emplacement. Ductile extension in the E–W direction included domino-style rotation of individual blocks (Fig. 13d). N–S extension was locally ductile but most generally brittle (Fig. 10). In both cases, asperities created by the individual blocks, equivalent to megaboudins, were cut by the late thrust fault, giving rise to lens-shaped tectonic slices (Figs. 10 and 13e). However, this was not always the case, because the faults bounding horsts and grabens created by the N–S extension acted as lateral ramps, giving rise to the transverse E–W-trending open folds in the thrust sheet (Figs. 3, 7, 9 and 10).

Once thrust motion had ceased, the Viveiro fault developed, crosscutting the Mondoñedo thrust sheet and its autochthon (Fig. 13f).

7. Implications for the dynamics of the Variscan orogenic wedge

The Mondoñedo nappe occupies the western part of the West Asturian-leonese Zone, which is one of the internal zones of the Variscan belt in the NW Iberian Massif (Julivert et al., 1972). To the east, the Cantabrian Zone is a foreland thrust belt representing an external zone of the massif. Fig. 15 sketches the final stage of the orogenic evolution in the Mondoñedo nappe and surrounding areas, as deduced from deep seismic reflection profiles (Pérez-Estaún et al., 1994; Ayarza et al., 1998), and structural information from surface geology after Marcos (1973), Bastida et al. (1982, 1986), Pérez-Estaún et al. (1988, 1991), Martínez Catalán et al. (1990), Gutiérrez-Alonso (1996), and this work.

A deep reflection seismic profile acquired on land in the Cantabrian Zone (ESCIN-1) shows a wedge geometry and a relatively shallow sole thrust, confirming the thin-skinned style of deformation in this zone (Pérez-Estaún et al., 1994). In another deep seismic profile (ESCIN-3.3) acquired offshore north of the study area, a crustal-scale thrust is suggested by a series of reflections below the Mondoñedo nappe, which continue west, down-dip into the lower crust and the Moho discontinuity (Ayarza et al., 1998). These structures, called, respectively, the Cantabrian Zone detachment and the sole thrust of the West Asturian-leonese Zone, have been incorporated into Fig. 15. Furthermore, the ESCIN-3.3 profile shows two or three bands with high reflectivity in the lower half of the crustal section underlying the Mondoñedo nappe. Ayarza et al. (1998) interpreted them as lower crust-mantle imbrications, because refraction seismics and a magnetic anomaly suggest the existence of mafic and ultramafic rocks relatively close to the surface (Aller et al., 1994; Córdoba et al., 1987; Ayarza et al., 1998).

All the geological and geophysical data can be readily integrated with the structural evidence to draw an image of the orogenic belt as a wedge, and also to gain insights into its evolution. The fact that the structural style of the Cantabrian Zone is thin-skinned suggests that its basement must have been underthrust beneath the West Asturian-leonese Zone. For the 90-km-long ESCIN-1 profile, the accumulated displacement of the thrusts faults has been estimated as 150 km (Pérez-Estaún et al., 1994), implying that another 60 km should have been moved to the west. The Cantabrian Zone continues at least 80 km eastward of the end of the seismic profile, so that the total length of the underthrust basement should be more. Thin-skinned tectonics were active in the Cantabrian Zone until Kasimovian times (Pérez-Estaún et al., 1988), i.e. until 300 m.y. ago, and this is the age suggested for the Viveiro fault by $^{40}Ar/^{39}Ar$ cooling ages in the Mondoñedo nappe (Dallmeyer et al., 1997). Furthermore, the lowermost band with high reflectivity in profile ESCIN-3.3, situated at a depth of 34–41 km, can be followed to approximately the vertical of the Viveiro fault.

According to these data, a wedge shape is quite reasonable for this area of the Variscan belt. The innermost part of the original basement of the Cantabrian Zone would have acted as the lower boundary of the wedge during the late stages of convergence, and its underthrusting would have been active until around 300 m.y. ago. In spite of being subjected to continuous (or episodic) shortening (Fig. 14), two extensional shear zones developed inside the wedge, probably to compensate gravitational gradients (Hodges et al., 1996) created by its internal dynamics and thermal evolution. The fact that the lower extensional shear zone developed beneath the Mondoñedo nappe during its emplacement confirms that its basal thrust was a contractional fault inside the wedge, and not its basal boundary.

Underplating probably played a role in the extensional activity, as frontal accretion to the east occurred in a thin-skinned mode; that is, involved only the sedimentary prism. Westward underthrusting of part of the the external basement seems to have occurred partially beneath the lower continental crust and the subcontinental mantle of the internal zones (Fig. 15). Buoyancy due to this density inversion may be responsible for increasing the vertical stress and creating topographic relief. The same effect would have been induced by partial melting deep in the crust. In addition, prolonged heating, mostly due to orogenic thickening but possibly with a magmatic contribution from the mantle (Galán et al., 1996), would have lowered the viscosity of the middle and lower crust, preparing it to flow easily in response to the internal stress field. If vertical stresses were dominant in the deep parts of the wedge, the viscous flow would have extended it, mostly transversally, i.e. in the E–W direction (although some longitudinal extension also took place), inducing a decrease in the wedge taper.

The lower extensional shear zone may represent a transition between a low-viscosity, flowing crustal layer and a stronger crust above. In fact, this broad structure, whose lower limit does not outcrop, might have accommodated much of the internal strain needed to extend and sharpen the wedge. Conversely, the upper extensional shear zone probably developed in the relatively strong part of the wedge to reduce topographic relief and/or to accommodate the E–W extension undergone by deeper parts. Extension in both shear zones took place while convergence continued, as demonstrated by crosscutting relationships of the late Mondoñedo thrust (Figs. 13 and 14). The Viveiro fault, post-dating nappe emplacement, could reflect the latest stages of convergence in the Cantabrian Zone.

8. Conclusions

Vertical shortening and extension occurred in both the hanging wall and the footwall to the Mondoñedo thrust fault synkinematically with thrusting, as shown by crosscutting structural relationships and overprinting metamorphic criteria from two extensional shear zones. Extension was mostly transversal to the orogenic trend, but subordinate longitudinal extension induced normal faulting in the footwall unit to the Mondoñedo nappe, and some of these faults were used as lateral ramps in the latest stages of thrusting.

Using published geological and geophysical data, the complex 3D structural evolution deduced for the Mondoñedo nappe and its autochthon is viewed in a wider regional context, as forming part of an orogenic wedge active during most of the Carboniferous in the NW Iberian Massif. In its late stages, gliding of the wedge could have taken place over the presently missing part of the original basement of the foreland thrust belt, which should have been carried beneath the internal zones while its sedimentary cover was being peeled off and imbricated in the front of the wedge.

Heterogeneity characterize the internal deformation of the wedge, with the strain partitioned into structures of different significance. In the case examined in this paper, a major thrust led the local kinematics, overprinting all the extensional structures developed, except the last. This seems to reflect the regional stress field, clearly dominated by plate convergence. However, heat accumulation resulting from crustal thickening and magmatic underplating weakened the deep parts of the wedge, giving rise to a viscous flow that accommodated its extension, induced by gravitational instabilities. The lower extensional shear zone probably represents the transition between a low-viscosity flowing mass and an overlying, more viscous structural level, with the strain being concentrated in an important lithological boundary, the base of the competent Xistral Quartzite. The upper extensional shear zone, developed in relatively higher and stronger parts of the wedge, would result from E–W stretching, gravitational collapse or both.

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