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The Malpica–Lamego Line: a major crustal-scale shear zone in the Variscan belt of Iberia

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Abstract

The Malpica–Lamego Line (MLL) is a deformation zone in the Variscan belt of NW Iberia (NW Spain and N Portugal) that runs parallel to the chain for at least 275 km, bearing I-type granodiorite plutons along most of its length. The MLL affects previous structures by which high pressure and ophiolitic rocks were exhumed and emplaced on the Iberian plate during earlier deformation phases. Correlation and reconstruction of the stratigraphy of these sheets or tectonic units at both sides of the shear zone allows a preliminary estimate of the accumulated vertical and horizontal offsets after the tectonic activity of the fault. The value of the separations, of crustal-scale proportions, reaches a maximum 15 km of vertical offset that decreases gradually to the south. The structural record found in the rocks indicates a strike-slip regime that, in general, does not fit the geometry of the offsets. We suggest that the MLL went through two different stages during the same orogenic cycle: a first dip-slip episode, a reverse faulting event, overprinted by a later strike-slip reactivation. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Most of the crustal-scale shear zones in the hinterland of collisional belts are described in the literature as wide, high-strain zones that may cut the whole crust and that juxtapose tectonic elements with very different tectonometamorphic histories (Moores and Twiss, 1995). Movements along such shear zones generally span several million years and form an integral part of the tectonic evolution of orogenic belts. It commonly represents an important tectonic style after continental stacking (Coward, 1994; Woodcock and Schubert, 1994; Moores and Twiss, 1995). This is because during the later tectonic evolution of an orogen, the older shear zones, with earlier dip-slip history, could have been reactivated as major strike-slip shear zones to produce movement of continental masses parallel to the orogen, a process known as *tectonic escape* (Tapponnier and Molnar, 1976; Burke and Sengör, 1986). These overprinting relations in high-strain zones at orogen scale have been studied in recent alpine collisional belts like the Himalayas, the Alps, and Turkey (Dewey et al., 1986; Tapponnier et al., 1986; Ratsbacher et al., 1991), but also in ancient collisional belts like the Variscan belt in Europe (Matte and Burg, 1981; Matte, 1986; Dias and Ribeiro, 1995) and the Caledonides (Gilotti and Hull, 1993). Most of the major crustal-scale shear zones in such belts show a clear pervasive strike-slip event, which post-dates a previous and, to a certain extent, more obscure dip-slip episode(s).

We present herein a study of the northern portion of the Malpica–Lamego Line (MLL) in the Variscan belt of Iberia (Fig. 1). This deformation corridor runs parallel to the mountain chain for over 275 km and is delineated along 200 km of strike length by I-type granodiorite plutons. The present level of exposure shows several types of structures, from micro- to macro-scale, formed at mid-crustal levels in a tectonic strike-slip regime. The restoration of the lithostratigraphy and the previous structure at both sides of the shear zone implies a significant dip-slip displacement to fit the distribution of geological markers and suggests a tectonic event prior to the strike-slip deformation, and thus a poly-phase history for the MLL.

In this paper, internal stratigraphies of the sheets that represent the allochthonous complexes of NW Iberia, emplaced prior to formation of the MLL are first presented, and will be used in the restoration of the geometry prior to movements along the MLL. Secondly, the structural record found in the rocks in relation to the tectonic activity of the MLL is described. Neither of these approaches to the tectonic history of the MLL support a

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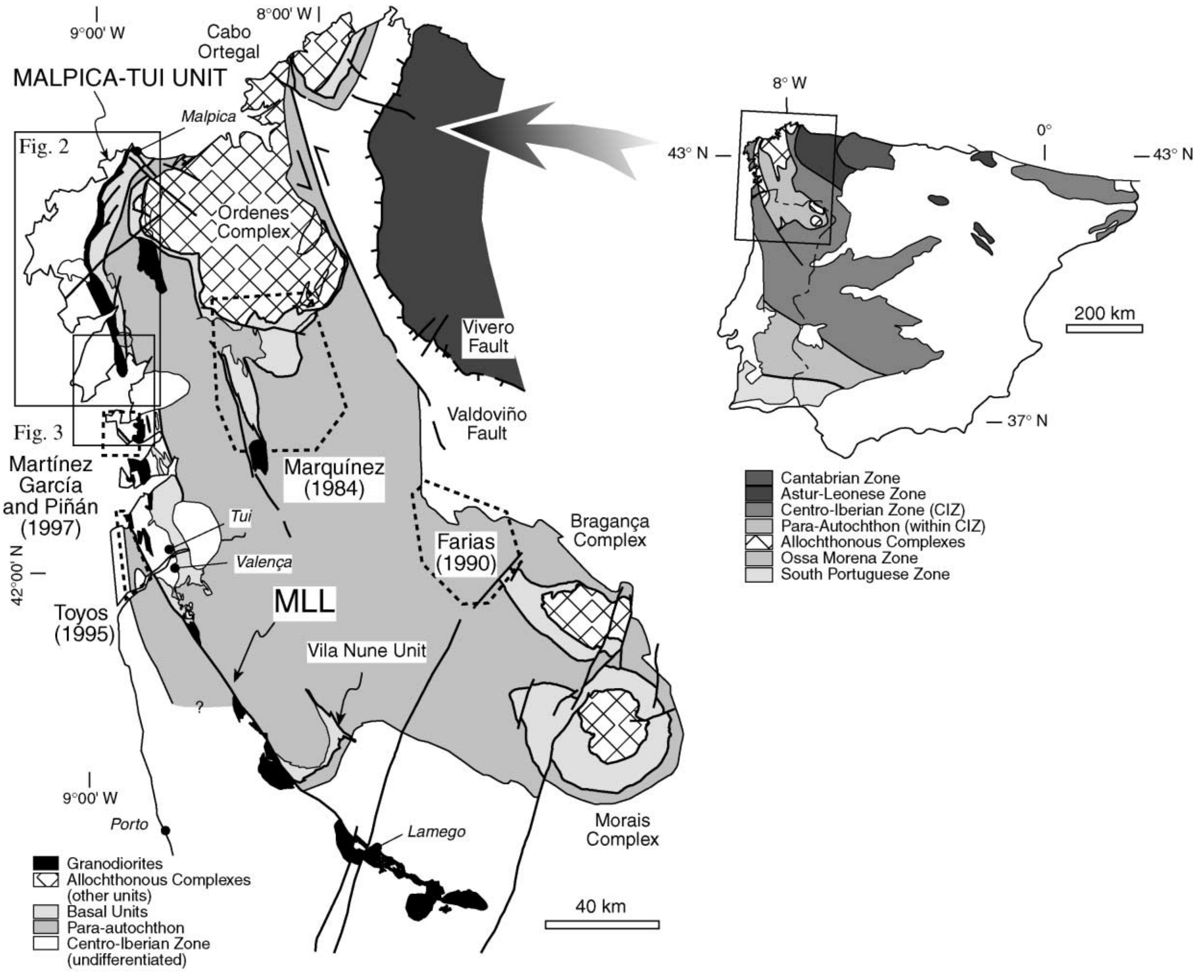

Fig. 1. Sketch map of the Variscan belt of NW Iberia. Special reference is made to the main tectonic units and structures. Geology is mainly based on maps in Parga Pondal (1982) and Ferreira et al. (1987). The boxed areas are mentioned in the text. Inset represents the Variscan Massif of Iberia, based on Julivert et al. (1972) and Martínez Catalán (1990). (Spanish–Portuguese border is shown for reference by a discontinuous line.)

unique tectonic event, and thus a poly-phase evolution is suggested.

The MLL started to operate in a period of tectonic style transition from tangential or nappe tectonics to a more vertical tectonic style of intracontinental deformation or post-nappe tectonics, during continent–continent collision. This kind of poly-phase structure is not an isolated phenomenon in collisional orogens (Coward, 1994; Woodcock and Schubert, 1994), and its recognition might help us to understand areas with the same problematic structure in this or in other orogenic belts.

2. Tectonic Setting

2.1. Nappe tectonics in the Variscan belt of Iberia: exhumation and emplacement of high-pressure rocks

The present level of exposure of the basement in the NW of the Iberian Peninsula allows the mapping of rocks belonging to the Middle Palaeozoic middle crust of the Variscan orogen. On the earlier geological maps, several flat-lying units with high-pressure rocks were clearly differentiated from the variably metamorphosed, underlying Palaeozoic sequence of Iberia (Arps et al., 1977; Parga Pondal, 1982). The upper rocks were grouped in the complexes of mafic and related rocks of NW Iberia (Arenas et al., 1986), more commonly known as the allochthonous complexes of NW Iberia. It is widely accepted that these rocks are relics of major nappes (Ries and Shackleton, 1971) that were emplaced during early Variscan times (Dallmeyer et al., 1997) as a consequence of the collision of a thinned continental margin (of exotic provenance) against the Iberian plate (Martínez Catalán et al., 1996, 1997). From bottom to top, they consist of: (i) basal units, with early HP–LT metamorphic record (Martínez Catalán et al., 1996); (ii) a unit with ophiolitic affinities (Williams, 1983; Arenas et al., 1986; Díaz García, 1990); (iii) a lower continental crustal sheet, with HP–HT metamorphic record (Ribeiro et al., 1990; Fernández Rodríguez, 1997; Galán and Marcos, 1998); and (iv) an upper sheet made of terrigenous sequences with a general low grade metamorphic and deformation imprint (Díaz García, 1990; Ribeiro et al., 1990).

The footwall to the allochthonous complexes is characterised in NW Iberia by two other broad tectonic elements: (1) an allochthonous sheet formed by metasedimentary rocks of uncertain age, overlying (2) the autochthonous sequence, the Precambrian and Lower Palaeozoic sedimentary rocks of the Central–Iberian Zone (according to the zonal subdivision by Julivert et al., 1972). The upper element rests tectonically upon the second and is variably named as Schistose Domain of Galicia–Tras-os-Montes (Marquínez, 1984; Arenas et al., 1986; Farias et al., 1987) or Para-autochthon (Ribeiro et al., 1990), the latter being preferred in this contribution. The presence of the lower element, the autochthon, in NW Iberia is the target of recent work in this particular part of the chain, although it was not previously recognised because of strong later H*T* metamorphism and granitization (Toyos, 1995; Martínez-García and Piñán, 1997; Llana Fúnez, 1999). It constitutes a fundamental key in the understanding of the MLL geometry and eventually of other structures with the same significance.

The term 'allochthonous' is used in the regional literature (see, for example, Dallmeyer and Martínez-García, 1990, and this study) with regard to the allochthoneity of the different tectonic units that form the nappe pile of NW Iberia. With regard to the MLL, the terms hanging wall and footwall refer to the blocks at both sides of the main deformation zone and will be used to avoid confusion.

The suture zone of the Variscan collision in NW Iberia is situated within the allochthonous complexes (Matte and Burg, 1981; Pérez-Estaún et al., 1991) above the basal units (Martínez Catalán et al., 1996) and is defined by the ophiolitic relics (Williams, 1983; Arenas et al., 1986; Marcos and Farias, 1999). The suture separates the Iberian plate, belonging to the underlying Gondwana rocks from an overlying exotic terrain, thought to be the Meguma Terrane (Martínez Catalán et al., 1997). The kinematics of the exhumation and emplacement of the allochthonous complexes is not yet established with certainty; however, it is assumed that the direction of transport of nappes was basically east, towards the foreland (see cross-sections in Bastida et al., 1984; Burg et al., 1987; Ribeiro et al., 1990; Pérez-Estaún et al., 1991; Martínez Catalán et al., 1996, 1997, 1999).

During the exhumation of the allochthonous complexes, a penetrative tectonic fabric was developed in the rocks; the dominant tectonic feature preserved in the different rock units is the decompressive part of the metamorphic *PT*-path (Fernández Rodríguez and Marcos, 1996; Fernández Rodríguez, 1997; Matte, 1998; Galán and Marcos, 1998; Llana-Fúnez, 1999). The heterogeneity of the deformation allowed the preservation of this tectonometamorphic history in pods, surrounded by the tectonic fabric, or within the foliation itself. The different allochthonous units, tectonic sheets and slices, for instance, were finally emplaced in the present configuration by thrusting at greenschist facies conditions (Bastida et al., 1984; Arenas et al., 1986; Marcos and Farias, 1999), although some late extensional readjustments have been inferred in certain areas (Burg et al., 1994; Martínez Catalán et al., 1996; Díaz García et al., 1999). The structures and mineral assemblages associated with the main fabric in these rocks, i.e. foliation and lineation, mostly predate the tectonic history of the MLL, and will be treated from here onwards as an inherited feature of the rocks.

2.2. Major subvertical shear zones in NW Iberia

Another remarkable feature of the Variscan orogen exposed in NW Iberia is the presence of an anastomosing system of subvertical high-strain zones bounding and crosscutting the allochthonous complexes and related structures (Fig. 1). The structures present in these shear zones were predominantly formed during strike-slip movements and are associated with the intrusion of various granitoid plutons (Iglesias and Choukroune, 1980; Courrioux, 1983, 1984; Ferreira et al., 1987). The steeply dipping high-strain zones separate domains where foliation was originally subhorizontal (e.g. allochthonous complexes). Prior to late upright folding, slight changes in the dip of these subhorizontal domains, on map-scale, indicate that in certain cases large strike-slip displacements are accompanied by significant vertical offsets, enhancing at the same time the apparent strike-slip offsets.

The tectonic style at this stage of the evolution of the Variscan belt would be that of intracontinental tectonics, in the sense given by Coward (1994) and Woodcock and Schubert (1994) for collisional orogens. Some of the Variscan high-strain shear zones have been related to tectonic escape processes in this part of the belt (Aranguren and Tubía, 1994) and to the development of the Ibero–Armorican Arc. The arc structure, of orogenic scale, is thought to have formed as a consequence of the indentation of Iberia into the microcontinents between Gondwana and Laurentia caused by a strongly irregular continent–continent collision (Matte, 1986; Dias and Ribeiro, 1995). In the northern branch of the arc, in Brittany, the intracontinental deformation is much better developed than in Iberia (see Rolet et al., 1994).

2.3. Synthetic review of metamorphic events in the Variscan belt of NW Iberia

Two major and widespread orogen-scale metamorphic events are highlighted during the evolution of the Variscan orogen in NW Iberian: an early Variscan episode, characterised by a high-pressure and barrovian metamorphism, and a Variscan, or late Variscan, high temperature metamorphism, spatially and temporally associated with a marked phase of granite formation/intrusion (Martínez et al., 1990). The main differences between both are their relative timing and the tectonic setting where they developed.

The early Variscan episode is probably related to the duplication of the continental crust at the beginning of the collision, i.e. to the nappe emplacement briefly described in the previous section. The metamorphic mineral assemblages found are varied but are intimately associated with penetrative and extensive tectonic fabrics (main foliation in rocks), their metamorphic record being dependent on their location within the tectonic pile. In general, the *P*/*T* ratio is high, especially in the overridden plate, below the suture zone (Iberia). The emplacement of exotic lower continental crust, the hot rocks of Cabo Ortegal, Órdenes and Morais–Bragança, produced inverted metamorphic gradients in the underlying colder rocks of the Iberian plate (Arenas et al., 1995), described as well in other parts of the chain (Burg et al., 1989).

This complex regional metamorphism is partly overprinted by high-temperature metamorphism (Martínez et al., 1990). In flat-lying domains the H*T*-metamorphism is rarely related to penetrative ductile deformation; this is the case only in discrete shear zones (it bears some relation with two-mica granite intrusions and with extensive migmatization at orogen scale).

3. The Malpica–Lamego Line

The MLL has a north–south orientation parallel to the trend of the orogen for 275 km. It was previously described in terms of two different dextral strike-slip shear zone segments: the Malpica–Vigo Shear Zone, in the northern part (Iglesias and Choukroune, 1980; Iglesias and Ribeiro, 1981), and the Vigo–Régua Shear Zone, in the southern part (Ferreira et al., 1987). Both shear zones are continuous and represent the same structure, and are joined herein into a single structure.

The shear zone is characterised by a regionally consistent subvertical foliation and a sub-horizontal lineation (plunging 8° S). The shear zone separates rocks of different tectonic levels in the nappe pile already outlined. The apparent vertical offset is larger in the northern segment of the MLL, diminishes to the south towards Portugal, and practically dies out before reaching the Tertiary unconformity that covers the Variscan Massif in central Iberia (Fig. 1). This vertical offset exceeds 10 km and can be considered crustal in scale.

The MLL is intimately associated with several elongated I-type granodiorite plutons (Capdevila et al., 1973) that align with the shear zone (Ferreira et al., 1987). The granodiorites formed by partial melting of the lower crust, (Capdevila et al., 1973; Gallastegui, 1993) with mafic melts derived from the upper mantle. The orientation of large K-feldspar megacrysts in the granodiorites, floating in an undeformed matrix, define a foliation that has been interpreted as magmatic (Avè Lallemant, 1965; Gallastegui, 1993). The foliation, which has a constant orientation along the MLL (it dips ca. 70° to the west and strikes parallel to the main shear zone), is considered useful as a strain marker. Younger, two-mica granite intrusions are partially deformed by the shear zone (Iglesias and Choukroune, 1980). These granites are of S-type and originate from crustal melting (Capdevila et al., 1973).

3.1. Hanging wall rocks

The hanging wall to the west of the MLL is formed by rocks that belong to the autochthonous sequence of the Central–Iberian Zone (CIZ), from Precambrian to Lower Palaeozoic age (Julivert et al., 1972). The sequence is dipping to the west. The widespread intrusion of two-mica granites and its associated migmatization (see, for example, Gil Ibarguchi, 1982), increases to the north and obliterates the characteristic features of the original lithostratigraphic sequence, partially preserved in a few localities. The MLL is in contact with different lithostratigraphic units along the shear zone; the lithological contacts are oblique in some segments (Fig. 3). The lower lithostratigraphic units are exposed in the north, while to the south the apparent lithostratigraphic separation with regard to the footwall of the MLL, diminishes considerably (Fig. 1).

The northernmost and relatively best preserved exposure of this autochthonous sequence in contact with the shear zone is in the Barbanza peninsula (Figs. 2 and 3). Here it composes scattered microconglomerates, coarse-grained sandstones and black pelites, included in a monotonous series of pelites and fine-grained sandstones (Llana-Fúnez, 1999). These rocks are typical of the Douro Group (Sousa, 1982; Toyos, 1995) which forms the lower parts of the autochthonous succession in the CIZ (Cabral et al., 1992). Ductile deformation affecting the rocks is restricted to discrete subvertical shear zones (Llana-Fúnez, 1999) while extensive metamorphism is associated with the intrusion of granodiorites and two-mica granites (von Raumer, 1962; Cuesta, 1993). No clear evidence of previous barrovian metamorphism is preserved. Towards the south, the next exposure of the autochthonous sequence occurs in the area surrounding the town of Portonovo (Fig. 3) where the lithostratigraphic units overlying the Douro Group crop out (according to Martínez-García and Piñán, 1997). They are mechanically roofed by the Para-autochthon. A tectonic fabric is observed in the upper rocks from the autochthonous, as well as mineral growth, probably caused by barrovian metamorphism, but again it is strongly affected by the metamorphism associated with the granitic intrusions (Martínez-García and Piñán, 1997).

To the south of the latter exposure, the rock units that are in contact with the MLL belong to the Para-authocthon. Notwithstanding this, the existence of a semi-tectonic window in the Tomiño area (Toyos, 1995) allows the autochthonous sequence to outcrop (Figs. 1–3). The allocththonous sheet is formed by the Nogueira Group at the base, and by the Paraño Group at the top. These groups were defined below the Órdenes Complex by Marquínez (1984) but are also found below the other allochthonous complexes of NW Iberia: Cabo Ortegal (Marcos and Farias, 1999), Morais and

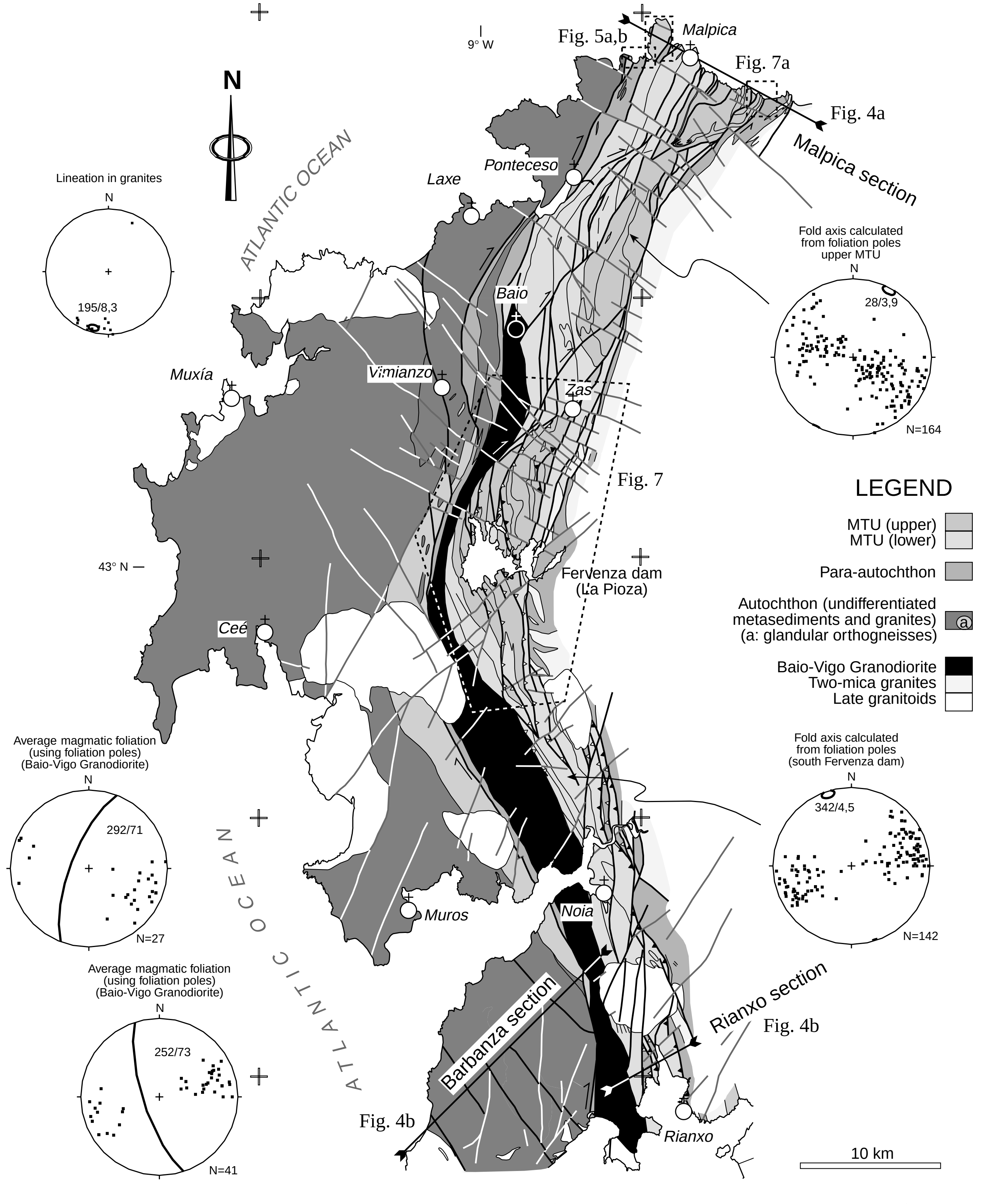

Fig. 2. Tectonic elements in the study area (crosses indicate the boundaries of Spanish 1:50,000 topographical sheets). Detailed zones of Figs. 4, 5, 7 and 8 are indicated with boxes. The hanging wall rocks, formed by the autochthonous sequence of the CIZ and two-mica granites, are shown with the same pattern. The geology of MTU is part of the Ph.D. thesis of S.L-F.

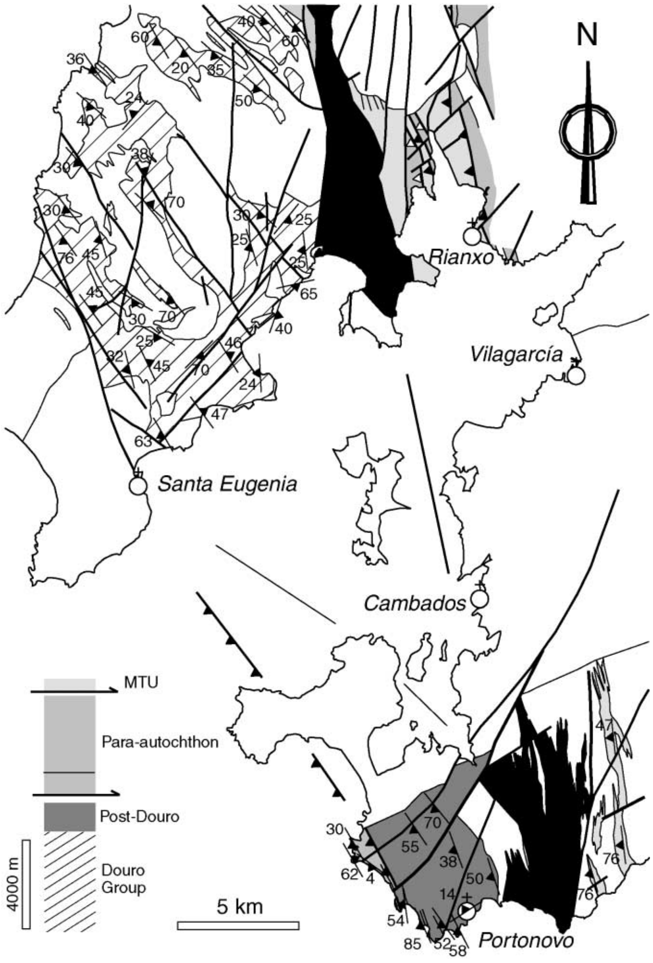

Fig. 3. Map from the particular segment of the MLL where oblique lithological boundaries in the autochthonous sequence in the hanging wall (to the west) are oblique with the main shear zone. Geology in the Portonovo area has been reinterpreted from the original map of Martínez-García and Piñán (1997). Legend as in Fig. 2.

Bragança (Arenas et al., 1986) and Malpica-Tui Unit (Llana-Fúnez, 1999). The grade of metamorphism and the development of a tectonic fabric increases to the top of this sequence, Arenas et al. (1995) have described an inverted metamorphic gradient in these rocks, among other tectonic sheets above them.

3.2. Footwall rocks

To the east of the MLL, along 150 km, is the Malpica–Tui Unit (MTU), which forms the lower terms of the allochthonous complexes. The general synformal structure of this unit (Gil Ibarguchi and Ortega, 1985) plunges slightly to the north (average 4° deduced from cross-sections in sequence and from pole projection of foliation data: Llana Fúnez, 1999; also in Fig. 2) allowing the outcropping of upper units towards the north. The fold axes are parallel to the MLL and are probably related to the tectonic activity of the main shear zone, which might explain the extremely elongated shape of this unit in comparison with other allochthonous complexes (150 by 5–10 km, see Fig. 1).

The lower boundary of the MTU, the basal shear zone (Fig. 4), is an approximately 100-m-wide high-strain zone that separates this unit from the underlying rocks of the Para-autochthon. Only the Paraño Group is seen below the MTU (Díaz García, 1993; Llana-Fúnez, 1999). The basal shear zone is preserved in very few places as the eastern boundary of the MTU (see Fig. 2), but in general is obliterated and reworked by later vertical faults.

4. Geometry and kinematics of associated structures

The shear zone that marks the MLL is defined by a belt of schistose tectonites (Fig. 6a) intruded by the I-type granodiorites. The shear zone has a steep, west-dipping foliation and associated sub-horizontal lineation, plunging 8° S. Several structures associated with the strike-slip deformation in both the hanging wall of the shear zone and the footwall, are described below.

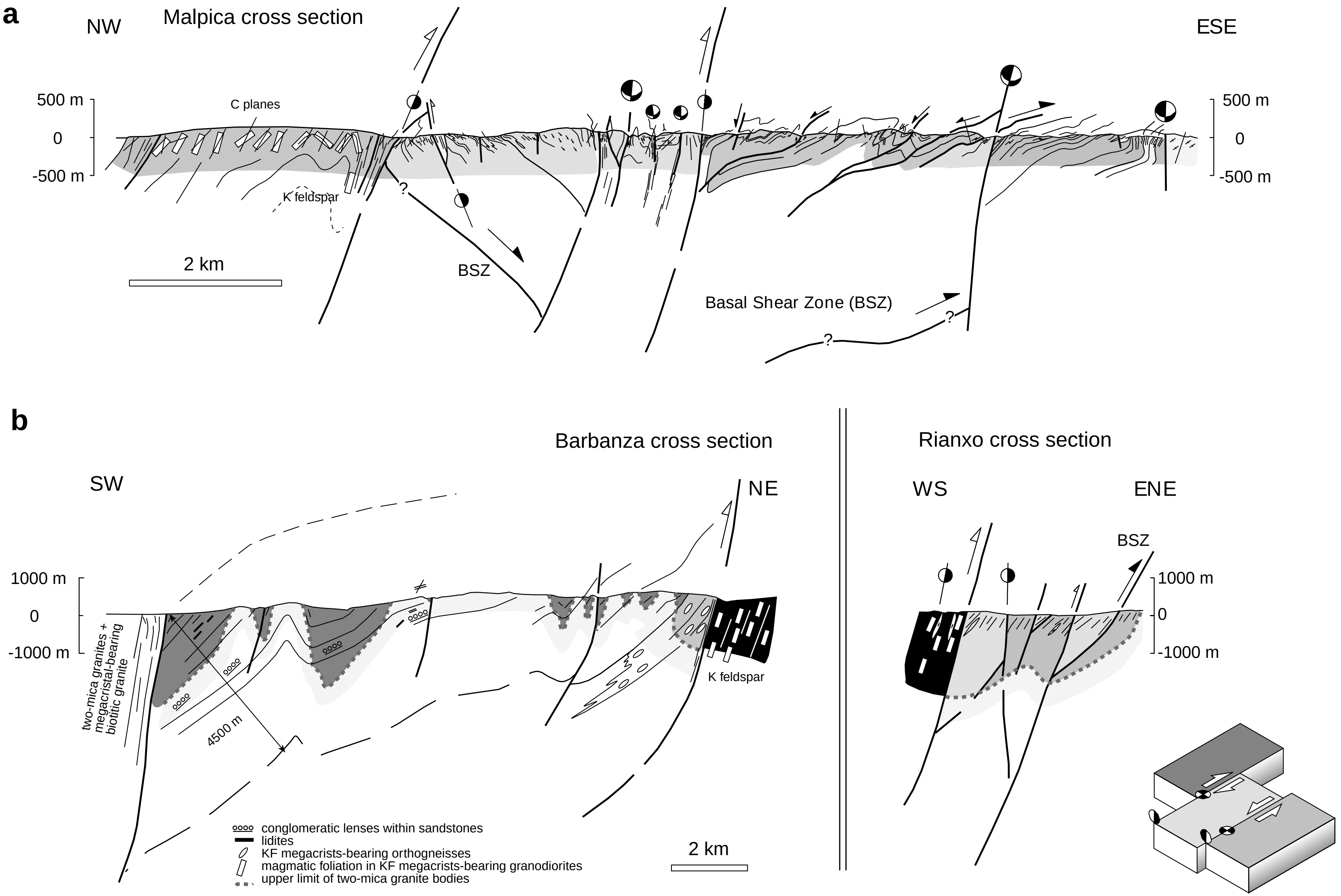

Fig. 4. NW–SE cross-sections showing the relations between different tectonic elements at both sides of the MLL. Legend and location for cross-sections are in Fig. 2. Notation used in the sections for faults with a strike-slip component of movement is represented in the small sketch at the bottom right.

4.1. Structures in the hanging wall rocks

The two-mica granites affected by the deformation of the MLL show pervasive SC fabrics in different localities within the study area (Parga Pondal, 1956; Avè Lallemant, 1965; Iglesias and Choukroune, 1980; Iglesias and Ribeiro, 1981; Gallastegui, 1993). These granites are widespread and constitute the dominant rock type in the hanging wall. In low-strain domains outside the main shear zone, the granites show a pervasive but coarse magmatic foliation of feldspar megacrysts. Hence, emplacement for these magmatic rocks under tectonic stresses should be inferred (Paterson et al., 1989).

Dextral SC fabrics in S-type granites develop progressively from the hanging wall towards the main shear zone in a 500-m-wide asymmetric shear zone, which is seen to the north of the locality of Ponteceso (Fig. 2). Discrete and planar surfaces, or C-planes, shear the coarse foliation dextrally (Fig. 6b, see also Iglesias and Choukroune, 1980). The angle between S- and C-planes and the spacing between C-planes diminish towards the main shear zone. The C-planes are defined by muscovite, chlorite and, in the mylonites of the main shear zone, quartz, showing dynamic recrystallization. K-feldspar and plagioclase show cataclasis and disappear progressively towards the main mylonitic band.

The magmatic foliation in I-type granodiorites defined by orientation of K-feldspar laths is deformed at the centimetre scale by later dextral shear zones, south of the previous locality (Avè Lallemant, 1965; Gallastegui, 1993). Mechanical twinning in plagioclase, undulose extinction in K-feldspar and development of ribbons in quartz indicate solid-state ductile deformation of the granodiorites during development of the shear zones (Gallastegui, 1993). Recrystallization of biotite and growth of chlorite in the same discrete bands are some of the mineral changes related to deformation. The orientation of these shear bands, oblique at map-scale to the magmatic foliation and to the general trend, and the millimetre-to-centimetre space between shear planes make them resemble the geometry of C–C′ fabrics (according to the relative orientation of each shear plane with regard to the main shear zone, which would represent the 'C-plane').

The last remarkable structure found in the hanging wall of the MLL is found in the San Adrián peninsula (Fig. 5), where glandular orthogneisses similar to the lower parts of the autochthonous sequence outcropping in this part of the belt, define an antiform (cross-section a in Fig. 4). The blastomylonitic foliation in these rocks is unrelated to the MLL, and is then folded and overprinted by the C-planes (Figs. 5 and 6c and d). These planes occupy the axial position in cyclographic figures of the foliation and also indicate a dextral shear with regard to that foliation (Fig. 5a).

4.2. Structures in the footwall rocks

In contrast to the hanging wall, in which granites predominate, the footwall is composed of very varied foliated rocks of the MTU in the northern portion; these rocks are fundamental to understanding the heterogeneity of deformation and structures observed to the east of the main shear zone. A complex system of anastomosing discrete sub-vertical shear zones has formed in these rocks. Some of the latter are oriented obliquely to the main shear zone (Figs. 2 and 7) forming angles between 30 and 50° with it, which are consistent with synthetic Riedel shears. The angles of 30–50° for Riedel shears are high in comparison with the theoretical values for this type of shear bands, estimated around 8–16° (Tchalenko, 1970), 10–15° (Ramsay and Huber, 1987) or 15–20° (Blenkinsop and Treloar, 1995). Thus, we interpret the increase in the angle between the oblique shears and the main shear zone to be related to a transpressive deformation regime (Woodcock and Schubert, 1994). The shear zones separate the rocks into isolated, quasi-lensoid bodies that show open, upright folds (Fig. 7). The open folds have steeply west-dipping axial planes and fold axes that are commonly parallel to the regional trend of the main shear zone in schists and paragneisses, or slightly oblique in more competent lithologies like orthogneisses and metabasites (Fig. 7).

The eastern boundary of the deformation band that affects the MTU, to the north of the Fervenza dam (Fig. 2), is composed of an array of sub-vertical or steep northwest-dipping faults characterised by cataclastic deformation and left-lateral shear sense. These faults obliterate the lower tectonic boundary of the MTU, the basal shear zone (Figs. 2, 4 and 8). In the coastal section (Fig. 8) the fault is associated with some northwest-dipping chloritic bands with sinistral C′ surfaces (Fig. 6f). There are also some quartz tectonites that show sygmoidal fracture or rock cleavage, consistent with a sinistral shear sense (Fig. 6e), indicating brittle deformation. The fault rocks, with fragments of fine-grained cataclasite floating on even finer-grained cataclasite, reveal repeated fracturing during this event. Contemporaneous with this brittle deformation are the intrusion of pegmatites, hydrothermal activity and related mineralization (Castroviejo, 1990).

The same left-lateral structures are seen in the main shear zone of the MLL at Xeiruga. Here, left-lateral shear zones overprint earlier ones as well as wrap dextral folds that plunge steeply to the north (see Fig. 8b and c). Although no clear cross-cutting relations are seen on a wider scale, we interpret the movements to post-date the dextral deformation. They are characterized by a discontinuous deformation style and hydrothermal activity. The association of upright folding with dextral shearing suggests their occurrence during the same contractional event, where coexistence of folding and shearing can be understood as the effect of deformation partitioning (Bell, 1981) at mid-crustal depths. Upright folding in rocks within the pseudo-lensoid domains produce vertical thickening and horizontal thinning, and stretching parallel to the MLL, the latter being facilitated by displacement accumulated in an anastomosing system of high-strain zones.

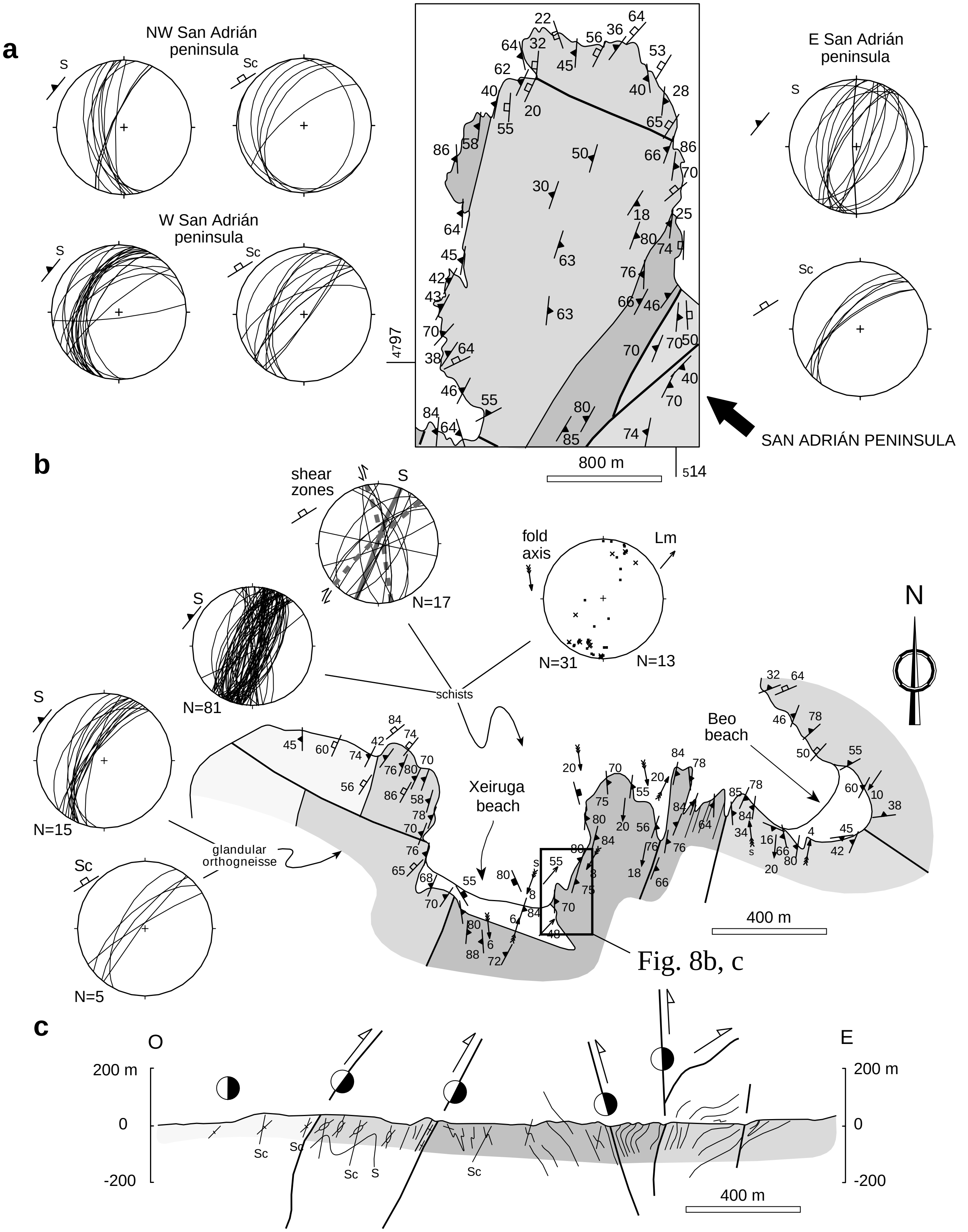

Fig. 5. Detailed maps of the MLL: (a) showing the relation between the crenulation cleavage and the previous tectonic foliation at San Adrián peninsula, (b) from the main shear zone in the Xeiruga beach. A cross-section through the MLL parallel to the coast has been made in the latter area. Reverse faulting and strike-slip symbols in the faults indicate likely separate events. Regional locations for (a) and (b) are boxed in Fig. 2.

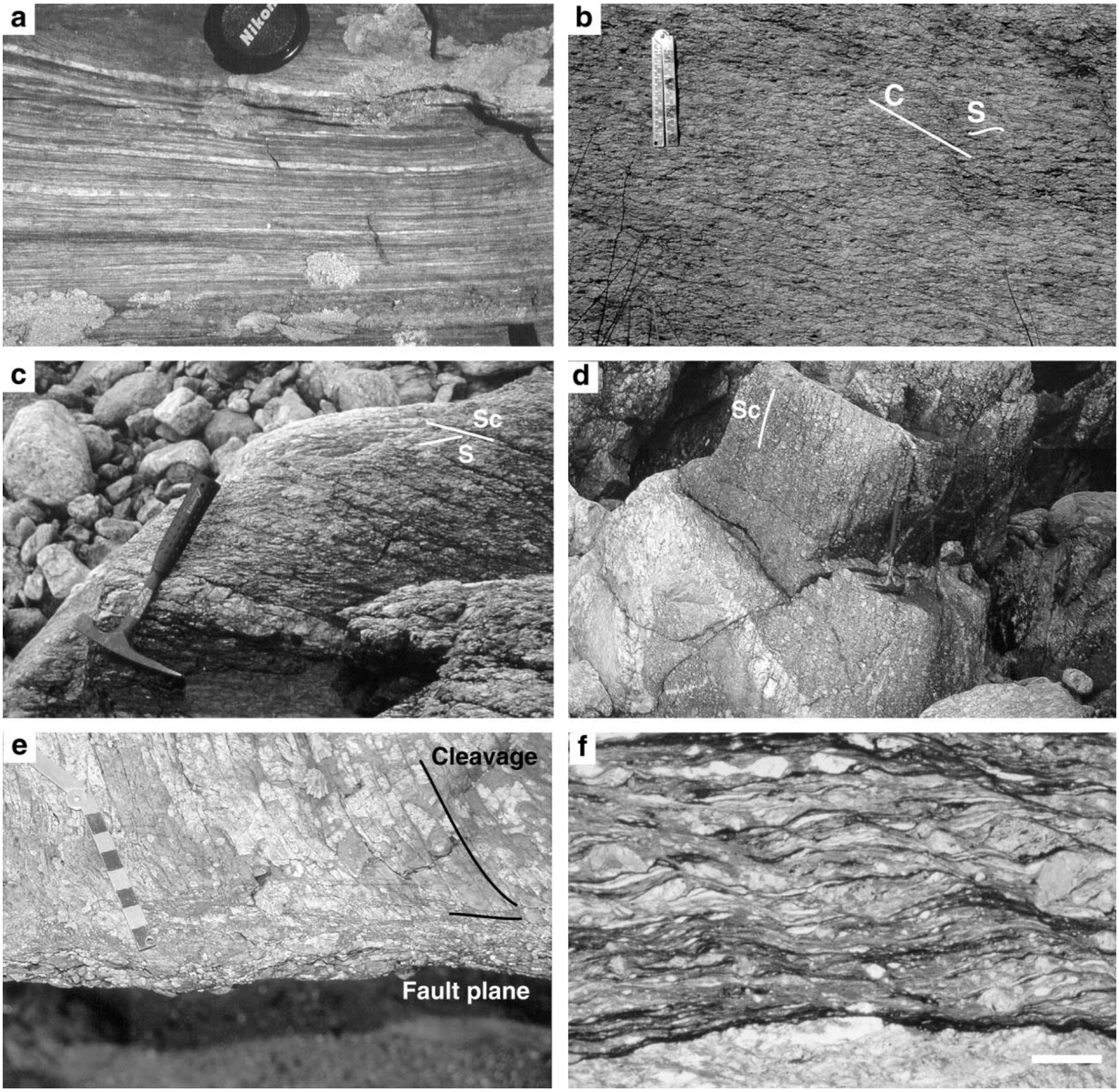

Fig. 6. (a) Mylonitized schists in the main shear zone; (b) S–C fabrics in two-mica granites; (c, d) crenulation cleavage in glandular orthogneisses at San Adrián, (e) horizontal section, and (f) W–E cross-section looking north; (e) fracture or rock cleavage in tectonites in the Riás Fault; and (f) S–C′ fabrics in schists in the same fault. In (a), (b), (c) and (e) north is to the right. The ruler and hammer for scale are 8 and 30 cm, respectively, and the scale bar in (f) is 200 μm.

5. Discussion

5.1. Separation of geological markers: scale of the structure

A preliminary estimate of the finite displacement accumulated in the MLL can be made using the apparent offsets on the maps defined by the differences in the stratigraphy of the allochthonous complexes and underlying tectonic units along both sides of the deformation zone.

To constrain the vertical offset, a transverse cross-section was constructed at the Barbanza peninsula where the lowest part of the exposed autochthonous sequence is exposed (Fig. 3b and c). Restoration of the overlying units in the hanging wall at the Barbanza peninsula implies an accumulated vertical separation of approximately 15 km (the measure in the cross-section in Fig. 9b). Towards the south of this locality, the vertical separation of the geological markers diminishes progressively until it disappears such that: (1) upper parts of the autochthonous sequence are in contact with the MLL, and (2) the Para-autochthon (Paraño Group) occurs in contact with the MTU. As indicated previously, the lithological contacts are oblique to the MLL in some portion of the shear zone (Fig. 3). The ideal thicknesses used to restore the sequence of rock units below the allochthonous complexes were taken from neighbouring areas: from Marquínez (1984); and Farias (1990)

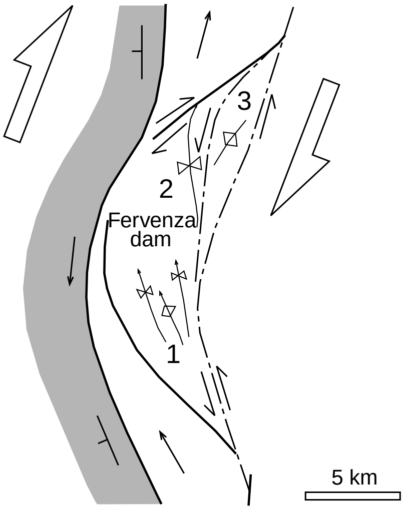

Fig. 7. Oblique shear zones, taking up most of the deformation, isolate quasi-lensoid bodies with little internal deformation in the footwall of the MLL, to the east of the main shear zone. The cartoon represents, synthetically, the case around the Fervenza dam. Number 1 indicates the axial traces of folds approximately parallel to bounding shear zones (in schists) and numbers 2 and 3, axial traces slightly oblique to the same boundaries (in orthogneisses and mafic rocks, respectively).

for the Para-autochthon below the Órdenes and Bragança Complex, and from Toyos (1995) for the autochthonous sequence in the Tomiño area (see boxes in Fig. 2).

The apparent strike-slip offset is estimated assuming that the separation (interpreted to be produced by boudinage) of a body of orthogneisses situated at the base of the autochthonous sequence is produced by stretching parallel to the MLL (Fig. 9a). The horizontal separation of approximately 28 km is then taken as a minimum; however, internal deformation within the orthogneisses cannot be disregarded. In this particular segment of the MLL (see Fig. 2), this apparent strike-slip offset cannot be explained by an apparent offset associated with a subsequent vertical movement because the lithological contacts in the hanging wall are parallel to the shear zone, in contrast to what happens further to the south.

5.2. Proposal of tectonic history for the MLL

The structural record within the MLL indicates that deformation is related to a dextral strike-slip regime (later minor left-lateral movements would produce only local overprinting relations). The stretching lineation associated with this strike-slip regime plunges 8° to the south. Assuming that the lineation is parallel to the tectonic transport direction (i.e. monoclinic simple shear flow) a right-lateral displacement of ca. 70 km would be necessary to achieve an apparent 15 km vertical offset in the Barbanza peninsula, using simple mathematical calculations. Considering the strike-length of 275 km of the MLL, such an offset is not easily absorbed so a complementary dip-slip component is needed. In addition to this, a progressive reduction of the apparent vertical offset towards the south would be necessary. This would imply a more complicated displacement pattern for the MLL, assuming it was produced in one single event.

The development of pervasive strike-slip structures may have obliterated the microstructure record of any earlier dip-slip episode. We propose the following order of events: (1) a reverse movement during which the hanging wall is elevated, and (2) a later strike-slip episode. The only structure that could be associated with the reverse faulting event is the antiform defined by orthogneisses, which has been deduced in the cross-section in Fig. 4a, and subsequently

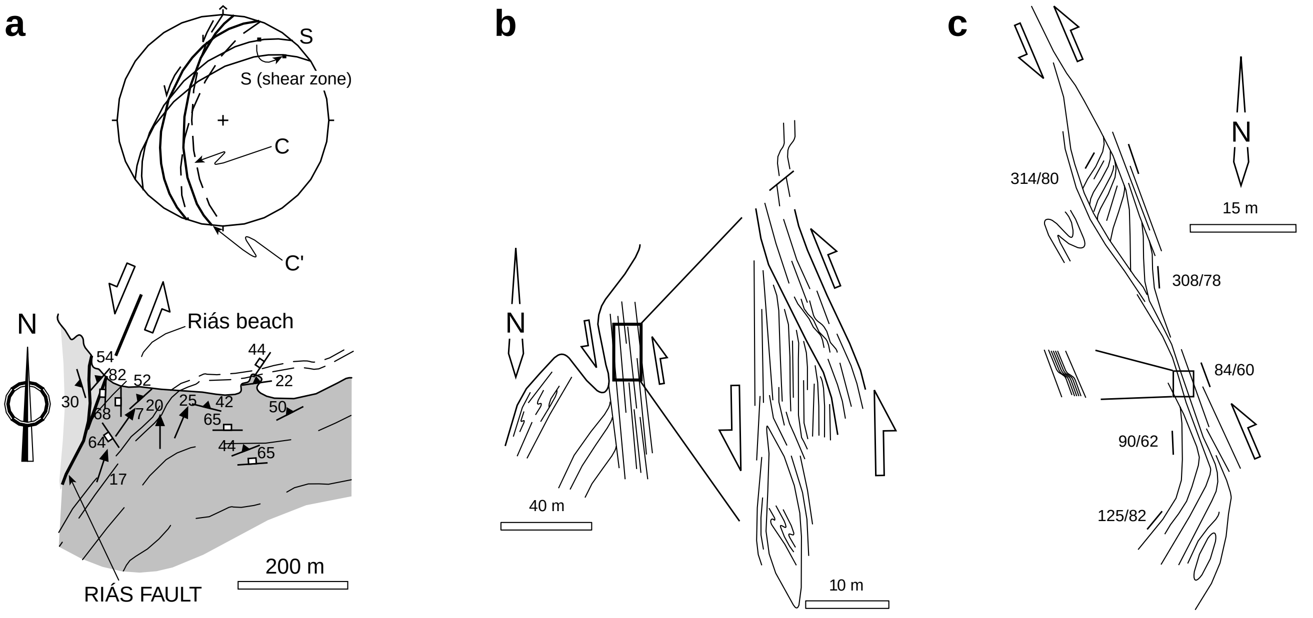

Fig. 8. Left-lateral structures in the footwall of the MLL: (a) eastern limit of the MTU, the Riás Fault; (b) and (c) field drawings showing left-lateral shear zones overprinting earlier dextral folds (for general location see box in Fig. 5).

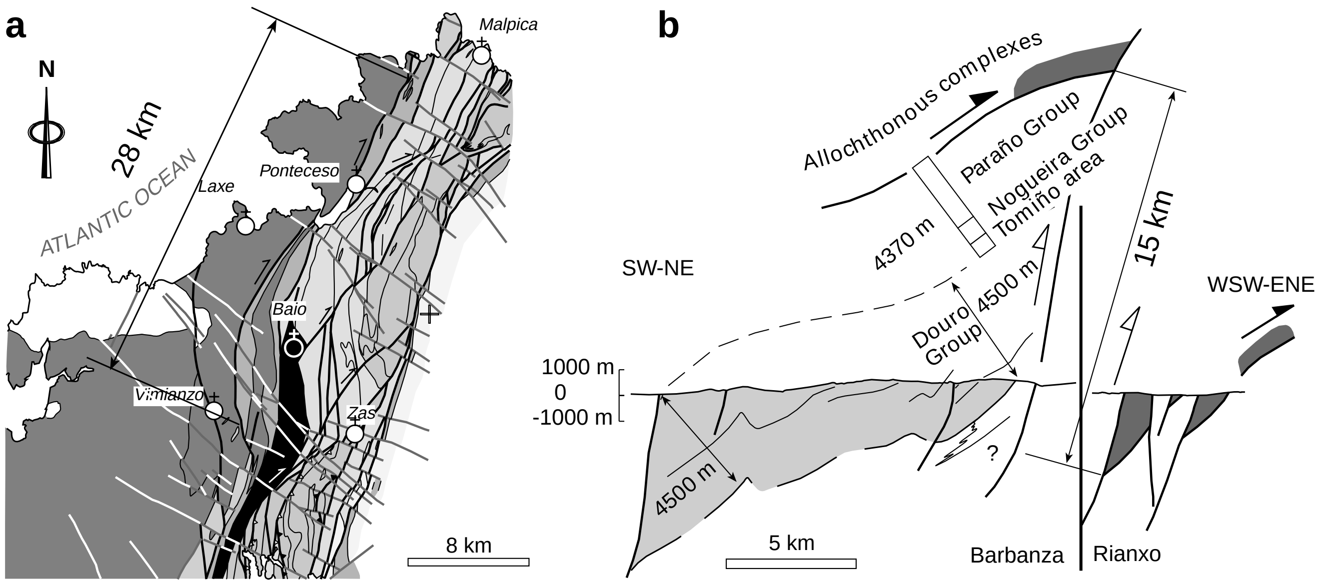

Fig. 9. Horizontal (a) and vertical (b) offsets in relation to the tectonic activity at the MLL. Thicknesses of missing units in (b), taken from related areas (see text), have been restored on the Barbanza–Rianxo cross-section, simplified Fig. 4b, to estimate the accumulated vertical offset during the tectonic activity of the MLL. The legend in (a) is the same as in Fig. 2.

stretched during the strike-slip deformation. We infer the minimum displacement during the strike-slip event to be 28 km, from the 'boudinage' of the folded body of glandular orthogneisses (Fig. 9a). The apparent vertical offset at the Barbanza peninsula implied by this event would be 6 km (obtained from calculations using a transport direction plunging 8° to the south that affects a sequence in MTU rocks plunging 4° to the north). Thus, the previous reverse faulting event would have a maximum accumulated dip-slip of 9 km, elevating the hanging wall over the footwall towards the east. It cuts across previous thrusts that emplace the allochthonous complexes in NW Iberia (Fig. 10).

This magnitude for the reverse faulting has not been previously reported for any other subvertical high-strain zone in NW Iberia in relation with the Variscan orogeny. As for the strike-slip event, the same order of displacements has been calculated in the Variscan belt of SW Europe (Ibero–Armorican Arc) for the Valdoviño Fault (25 km, Courrioux, 1983, 1984; located in Fig. 1), the left-lateral Estivaux wrench fault (30 km, Roig et al., 1996) and the northern branch of the Armorican Shear Zone (40 km, Jegouzo and Rossello, 1988).

5.3. Time constraints on tectonic activity

There are no published data concerning the age of deformation in the study area. Data from neighbouring areas are used here to broadly constrain the deformation period. The maximum age of the reverse faulting is constrained by the age of thrusting in NW Iberia, related to the emplacement of the allochthonous complexes and a minimum age is provided by the age of the granodioritic instrusions, which do not show structures prior to the strike-slip overprint. The ^{40}Ar/^{39}Ar ages in muscovites from greenschist facies rocks from the ophiolitic unit, above the basal units in the Órdenes Complex, cluster around 365 Ma (Dallmeyer et al., 1997) and represent the lower time boundary for the MLL. The Baio–Vigo granodiorite, the main granodiorite pluton in the MLL, gave a U–Pb zircon age of 350 Ma (Gallastegui, 1993), which is consistent with the published Rb/Sr, K/Ar ages for similar rocks in related areas (350 ± 11 Ma, Bellido Mulas et al., 1992; 358 ± 20 Ma, Serrano Pinto et al., 1987; 346 ± 3 Ma, Roig et al., 1996). As for the second episode of tectonic activity, the strong strike-slip reworking, the ages of intrusion of two-mica granites in related areas, ranging from 330 to 310 Ma (according with Dallmeyer et al., 1997 and references therein), can be regarded as contemporaneous with deformation (Iglesias and Choukroune, 1980). The time of deformation at the Valdoviño Fault, east of MLL (location in Fig. 1), has been calculated to range in the period 317–292 Ma (Ortega et al., 1997).

6. Tectonic interpretation and conclusions

We propose a two-stage tectonic evolution for the MLL. This shear zone separates wall rocks with different tectonometamorphic histories during the early part of the Variscan collision. The MLL plays a significant role in the deformation that postdates the nappe stage and has implications for related areas of NW Iberia, as well as the rest of the Variscan chain in Europe.

The occurrence of reverse faulting in this part of the belt has several consequences for the subsequent tectonic evolution in the hinterland. This type of structure has the main effect of thickening the orogenic wedge (Morley, 1988). On

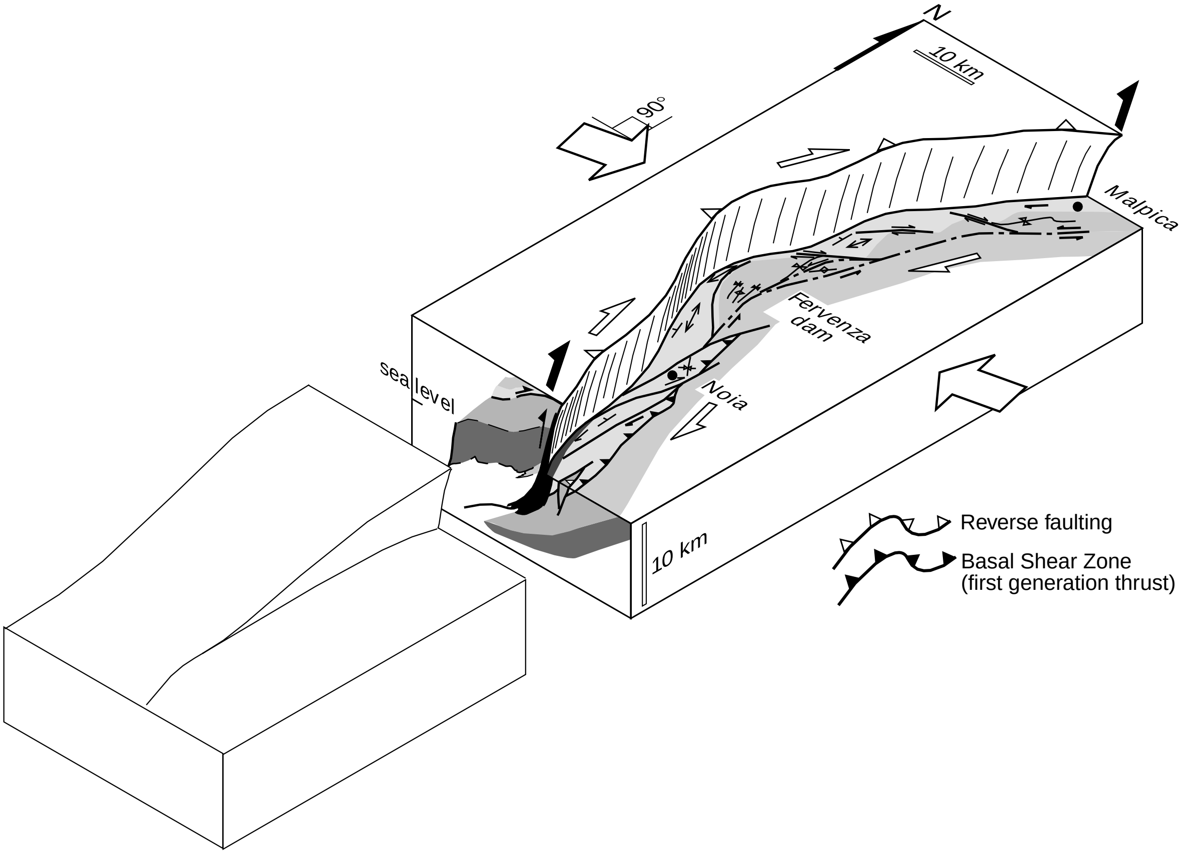

Fig. 10. Reconstruction of the vertical and horizontal offsets of geological elements observed in relation to the MLL.

the other hand, on-going shortening steepens the fault plane and causes thickening to become progressively more difficult. Both accelerate the unstable dynamic conditions of the reverse faulting (mainly given by the progressive steepening of fault plane) and restrict the period of reverse faulting activity in the MLL. For the shear zone to remain active during such unstable conditions, rapid ascent of rocks facilitated by high rates of erosional denudation at surface level and tectonic delamination underneath (the later in the sense of Sacks and Secor, 1990) is probably necessary. The intrusion of granodiorite bodies post-dates the activity of the reverse faulting and is probably related to relaxation after deformation. Processes of magmatic differentiation from magma mixing and mingling of granodioritic rocks from the lower crust and scarce basic rocks from upper mantle gave rise to these elongated I-type granodioritic plutons (Capdevila et al., 1973; Gallastegui, 1993). Intrusion of similar rocks continued after tectonic activity, as rounded non-foliated post-kinematic bodies also appear to be aligned with the MLL (Ferreira et al., 1987; Cabral et al., 1992). The role of ascending melts channelled by shear zones is not an isolated feature and, in fact, it constitutes one of the best indicators of crustal-scale shear zones (Pitcher, 1982). The presence of a steep weak zone in a still compressive regime triggers the transition to intracontinental deformation, characterised by strike-slip tectonics (Coward, 1994; Woodcock and Schubert, 1994; Moores and Twiss, 1995). In this tectonic regime, shortening is often accommodated by orogen parallel movement of continental masses, i.e. *tectonic escape* (Molnar and Tapponnier, 1976). Deformation is commonly partitioned in high strain zones (as described by Bell, 1981; Lister and Williams, 1983), where strike-slip shear zones take up most of the deformation and all the displacement of continental blocks. A similar interpretation can be argued to occur for the MLL.

Examples of polyphase crustal-scale structures are common in both ancient (e.g. Variscan) and recent collisional belts; for instance, the reported cases of: the Badajoz–Córdoba Shear Zone (Burg et al., 1981; Azor et al., 1994) in the Variscan belt of Iberia; the Indus–Tsangpo Suture Zone (ITSZ) (Coward, 1994; Searle et al., 1987; Moores and Twiss, 1995) in the Himalayas; or the Insubric Line (Schmid et al., 1987) and the Basal Brianconnais Thrust (Freeman et al., 1998), among many others, in the Alps. Most of the latter have an early dip-slip episode, which is reworked by a strike-slip event. As a comparison, the MLL presents some similarities in the general geological and geometrical features with the ITSZ, where an initial thrusting event along the suture zone is followed by later strike-slip reworking. The intrusion of the Lhasa granodioritic batholith, aligned with the ITSZ, emphasizes the similarity between both structures.

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