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Structural and kinematic analysis of the Corredoiras detachment: evidence for early Variscan synconvergent extension in the Ordenes Complex, NW Spain

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Abstract An important detachment is described in the allochthonous Ordenes Complex, in the NW Iberian Massif, and its meaning is related to the kinematics of contemporaneous convergent structures. The Corredoiras Detachment (CD) separates a hangingwall unit, characterised by a medium-pressure metamorphic gradient, from a footwall high-pressure and high-temperature unit and an underlying ophiolitic unit. An associated ductile shear zone, nearly 2000 m thick, developed in the lower part of the hangingwall unit, where the Corredoiras Orthogneiss, a Lower Ordovician metagranite, was progressively transformed into augengneisses, mylonitic and ultramylonitic gneisses. The attitude of the stretching and mineral lineation in the mylonites varies due to late refolding at map scale, but the sense of movement can be estimated, being roughly top to the SE. According to crosscutting relationships, the CD developed subsequent to the thrusting of the high-pressure/high-temperature unit onto the ophiolitic unit, and prior to younger extensional detachments, upright folding and strike-slip tectonics. The geometric relationships of the CD with the previous structures in the footwall unit, the subtractive character of the metamorphic gap between its hangingwall and footwall, and the available isotopic data suggest that the CD is an early Variscan, ductile extensional detachment, the movement of which was roughly simultaneous with the onset of thrusting of the allochthonous complexes over their relative autochthon.

Key words Extensional detachment · Synconvergent extension · Allochthonous complexes · Ordenes Complex · Iberian Massif

Introduction

Recent studies have shown that extension plays a major role in the later stages of orogenic evolution, especially during the extensional collapse of orogens (Dewey 1988). Previously, synconvergent extension was described also in collisional mountain belts such as the Himalayas (Burchfield et al. 1992), the Alps (Seward and Mancktelow 1994) and the Betic-Rif cordillera (Platt and Vissers 1989), but it is more difficult to prove and its importance is more difficult to assess, because of the overprinting by new compressional structures.

However, as far as crustal underthrusting and thickening does occur from the onset of convergence, gravitational gradients may arise that tend to equilibrate the orogenic wedge, triggering a process of thinning and tapering of the wedge that may proceed by more or less distributed deformation, and by the development of extensional dislocations, as proposed by Platt (1986). When this process acts early in the history of mountain building, following limited subduction of the continental crust, the exhumation of units with high-pressure (HP) metamorphism seems very rapid, and it is suggested that it occurs in close association with normal faults (Platt 1986; Chemenda et al. 1995). While the models developed by these authors are based on actual cases, additional examples supporting them and, in particular, detailed descriptions of the normal faults involved, are scarce in the literature.

This paper describes one such fault. The Corredoiras Detachment (CD) is a structure that seems to have played a significant role in the exhumation of high-pressure units. It is extensively exposed in the SE

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part of the Ordenes Complex, in the NW Iberian Massif. The description starts with a summary of the regional tectonic framework and continues with a systematic treatment of the geometry and crosscutting relations of the CD, based on geological mapping, and with the description of its kinematics and of the changes undergone by the rocks during mylonitization. The metamorphic evolution and published isotopic ages are used to infer the extensional character of the detachment and to discuss its geological meaning.

Geological setting

The Variscan belt in NW Iberia is characterised by fold nappes and east-directed thrusts affecting relatively autochthonous metasedimentary sequences of Upper Proterozoic and Paleozoic ages (Matte 1968; Bastida et al. 1986; Pérez-Estaún et al. 1991). Above, five allochthonous complexes have been preserved as megaklippen, three of them in Galicia, NW Spain (Fig. 1).

The Ordenes Complex is the largest of the allochthonous massifs. It consists of a stacking of allochthonous units that were subsequently overprinted by upright folds, strike-slip ductile shear zones and faults. The tectonostratigraphic units forming the Ordenes Complex can be ascribed to three groups, according to their relative position in the nappe pile, their lithological associations and their tectonothermal evolution: basal, ophiolitic and upper units (Arenas et al. 1995; Martínez Catalán et al. 1996, 1997). Their main characteristics are summarised in Fig. 2.

A comprehensive evolutionary model of the internal part of the belt, including the suture zone, was proposed by Arenas et al. (1995) and Martínez Catalán et al. (1996). According to these authors, the structural and metamorphic evolution of the allochthonous units reflects the history of an accretionary wedge created by the incorporation of different terranes into the southern margin of Laurentia along the middle and upper Paleozoic. The accretion ended with the subduction of the leading edge of Gondwana toward the west, below the accretionary wedge, and this was followed by the collision between both continental masses. The outermost margin of Gondwana is represented by the basal units, and its subduction was followed by the exhumation of the basal units, which involved the development of several low-angle normal detachments in the upper parts of the orogenic wedge.

The suture is represented by the ophiolitic units, and the pre-collisional accretionary wedge is represented by the upper units. These can be subdivided according to their metamorphic characteristics, into the uppermost units, showing a medium-pressure (MP) Barrovian-type metamorphism, and the underlying high-pressure and high-temperature (HP–HT) units.

The target of our study, the CD, separates the two types of upper units in the SE part of the Ordenes Complex (Fig. 1). The MP units occupy the hangingwall and the HP–HT units, as well as the ophiolitic units, occur in the footwall. The CD developed after the stacking of the upper and ophiolitic units and crosscuts compressional recumbent folds and thrusts, and ductile extensional detachments previously developed in the HP–HT and the ophiolitic units (Figs. 3, 4, 5). It was in turn affected by late steep folds, a transcurrent ductile shear zone, late extensional detachments and high-angle reverse faults.

The Corredoiras Detachment

Due to the interference pattern created by late cross folding, the CD outcrops abundantly in the SE of the Ordenes Complex (Fig. 3). Its geometry, structures, kinematics, fault rocks and metamorphic evolution can be analysed along 13 km in the estimated transport direction. The detachment separates one of the main components of the uppermost MP unit, the Corredoiras Orthogneiss, above, from the Sobrado-Melide HP–HT unit and the Careón Ophiolitic unit, below. The internal deformation related to the detachment has been studied mainly in the hangingwall, taking advantage of the fact that large parts of the Corredoiras Orthogneiss were barely deformed prior to the activity of the detachment.

The deformation produced strong microstructural changes in the Corredoiras Orthogneiss. Three bands have been mapped which reflect the increase in shear strain toward the base of the massif (Figs. 4, 5): an upper band of weakly deformed metagranites, an intermediate band of augengneisses, with a thickness of 1000–2000 m and showing gradual transitions to the adjacent bands, and a lower band consisting of up to 500 m of mylonitic gneisses and ultramylonites. In the footwall, the CD contributed to the development of the retrogressive regional foliation. This is an amphibolite-facies foliation linked to a strong decompression (Martínez Catalán and Arenas 1992), and the later stages of its evolution were related to the movement of the detachment.

Geometry

A low-dipping initial attitude can be envisaged for the CD by removing offsets on faults and unfolding the upright, mostly symmetrical open folds (see cross sections in Figs. 1, 3, 5). Furthermore, the structures have been projected along plunge in the cross section of Fig. 3, where the rough parallelism between the CD and the Lalín-Forcarei Thrust (LFT; see Martínez Catalán et al. 1996 for a description of this structure) can be seen. A tectonic superposition of more than 25 km in the direction of tectonic transport, which is N60 E to N70 E, can be measured for the LFT in the SE Ordenes Complex (Fig. 3). However, its character of basal thrust of the Ordenes and Malpica–Tui

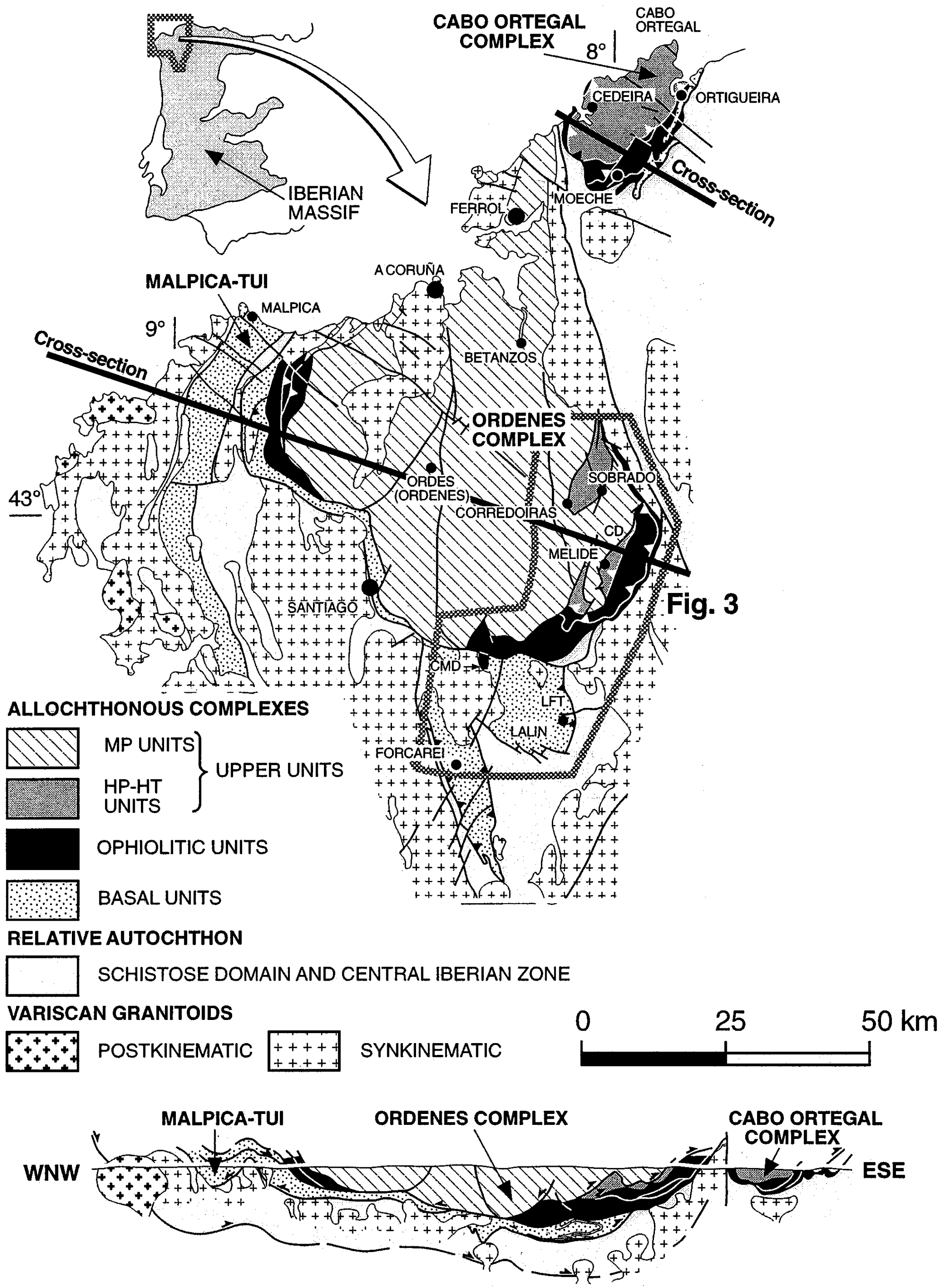

Fig. 1 Sketch map and composite cross section of the Galician allochthonous complexes showing their main units

complexes (Fig. 1) points to a much larger superposition, granting a low-dipping attitude for the LFT.

Because the orthogneisses are the only lithology outcropping above the CD, the geometrical relationships in the hangingwall are difficult to ascertain. In the footwall, observation of the Sobrado Antiform (Fig. 4) reveals obliquity between the CD and the underlying unit: The mylonitic orthogneisses of the hangingwall rest on progressively lower levels of the footwall toward the east. A comparable relationship is seen in the Melide area (Fig. 5), where the mylonites rest on the HP–HT unit to the north and progressively cut across lower levels toward the east and SE, eventually lying on the Careón Ophiolitic unit. Actually, the CD crosscuts the main structures developed in the HP–HT units, including the recumbent folds in the Melide unit, and thrusts in the Careón unit. In short, it is a post-nappe detachment cutting down to the east or SE through the tectonic pile.

Attitude of the mylonitic foliation and the stretching lineation

The most prominent feature of the CD is the development of a shear zone 2 km thick in its hangingwall,

Fig. 2 Summary of geological information available for the different allochthonous units and the underlying relative autochthon domain. Patterns in the *column to the left* correspond to those used in Fig. 1

		DOMINANT LITHOLOGIES	PRE-VARISCAN IGNEOUS ROCKS	METAMORPHIC EVOLUTION	PUBLISHED AGES	GEOTECTONIC REALM
ALLOCHTHONOUS COMPLEXES – Upper units	Uppermost units	Terrigenous, flyschoid metasediments; 3.000 m slates, schists and parag.	Lower Ordovician bimodal magmatism: gabbros and granitoids (1)	Low to high grade Barrovian-type met. (1, 2)	**495-500 Ma**: orthogneiss (protoliths) (1)	Sugested arc. Convergent plate boundary (1)
	CD	Gabbros and Orthog. to the base	Corredoiras Orthog.	Variscan MP retrograde met.	**375 Ma**: Mylonitic orthogneiss (retrograde met.) (7)	Synconvergent extension
	HP-HT units	High-grade parag. some younger than 507 Ma:age of detrital zircons (21) Mafic granulites, eclogites and ultramafics.	Early Paleozoic bimodal magmatism: MORB type basic rocks, continental rift-type gabbros and granitoids (4, 18).	HP-HT granulitic/eclogitic event:9-18kb, 700-850 °C (18, 27) Amphibolite facies (15) Greenschists facies (15)	**490-480 Ma**: Mafic protolits and (HP-HT ?) met. (21, 23) **405-390 Ma**:Eclogite facies met. (18,23) **390-385 Ma**: Amphibolite facies (6, 22) **355 Ma**: Late met. stages (15, 17)	Piece of continental fragment detached from Gondwana (10, 16)
ALLOCHTHONOUS COMPLEXES	Ophiolitic units	Metapelites, cherts, metabasites, meta gabbros, diabases, plagiogranites, amphibolites and ultramafics (2, 8).	Upper ophiolitic unit: gabbros and ultramafics Lower ophiolitic units : sediments, metabasalts and scarce serpentinites.(8, 16).	Prograde amphibolite facies MP met. in upper units. Low grade HP and greenschists facies in lower units (8, 16)	**395 Ma**: Gabbro (protolith) (8, 9) **390-385 Ma**: amphibolite facies met. (6, 18) **370 Ma**: Greenschists facies met. (6)	Paleozoic oceanic lithosphere (2, 8, 16)
ALLOCHTHONOUS COMPLEXES	Basal units	Schists and paragneisses. Middle-Upper Ordovician and older. Felsic orthog. (11, 20, 26)	Early Paleozoic bimodal magmatism: basic rocs and felsic, alkaline and peralkaline granitoids (20).	HP event: 15-17 kb, 500-700 °C. Amphibolite and low grade events (3, 13)	**480-460Ma**: Orthog. (20,22,26) **374 Ma**: End of HP met. (22, 26) **360 Ma**: Late met. event (22)	External edge of the continental margin of Gondwana (2, 3, 16)
RELATIVE AUTOCHTHON		Schists and subordinate quartzites Ordovician or older to Lower Devonian	Early Paleozoic mainly felsic magmatism: granitoids and volcanics.	Low to medium grade MP event (Barrovian) met. transitional to LP type (3).	**490- 450 Ma**: Lower Paleozoic ortog. (12, 14). **360-320 Ma**: Main deformative events and met. (7). **350-340 Ma**: Early Variscan granitoids (19, 24, 26). **330-310 Ma**: Syn-kinematic leucogranites (5). **315±10 Ma**: Late deformations (5). **295-270 Ma**: Post-kinematic granitoids (5, 20, 25).	Transitional zone of the continental margin of Gondwana (16).

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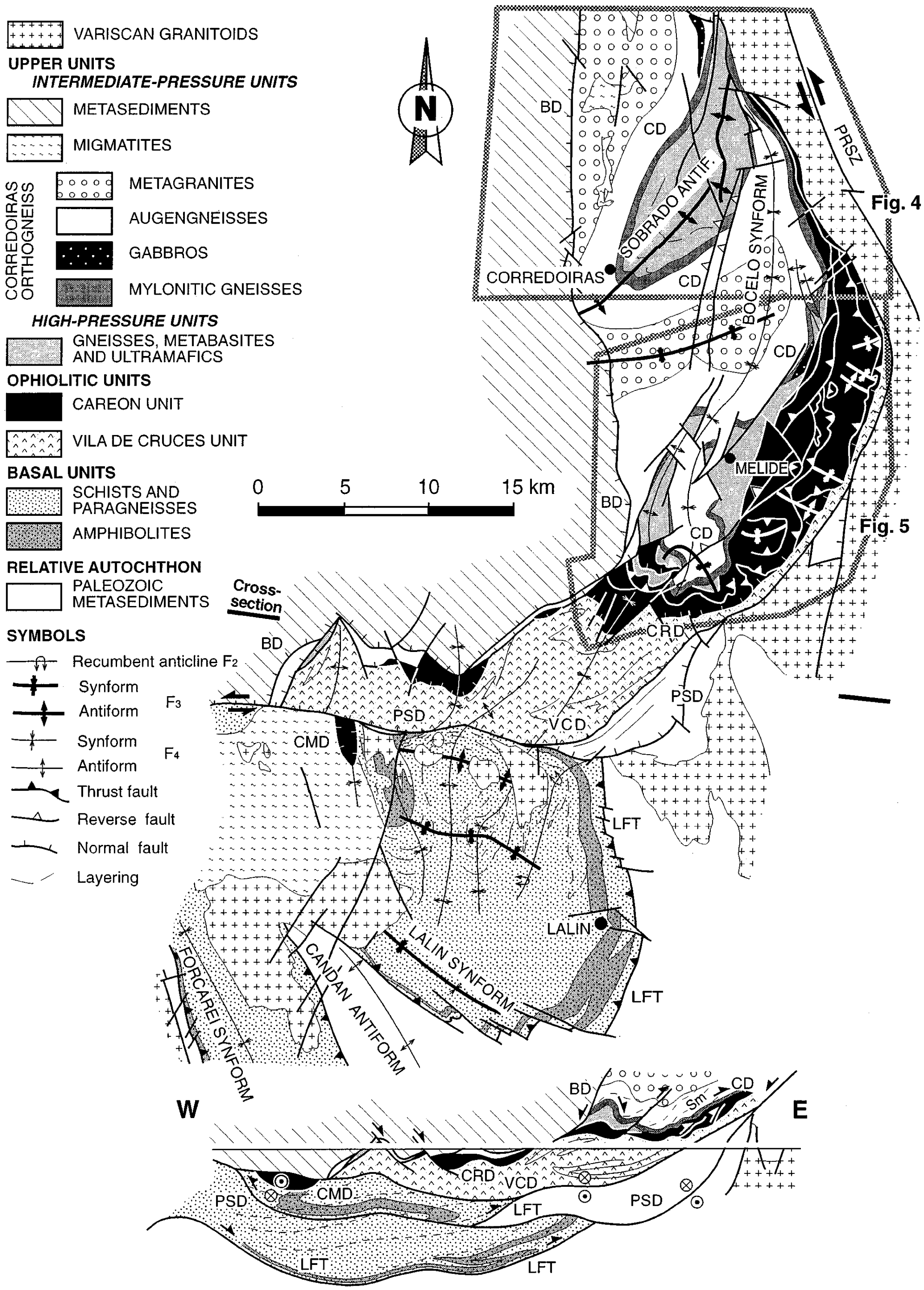


Fig. 3 Map and cross section of the SE part of the Ordenes Complex showing the position of the Corredoiras Detachment (CD; *dark grey*) and its relationships with other structures. *BD* Boimorto Detachment; *CD* Corredoiras Detachment; *CRD* Careón Detachment; *LFT* Lalín-Forcarei Thrust; *PSD* Pico Sacro Detachment; *PRSZ* Palas de Rei shear zone; *VCD* Vila de Cruces Detachment; *Sm* mylonitic foliation. For location see Fig. 1

where a mylonitic foliation (Sm), shear bands and a widespread stretching lineation developed. The orientation of the foliation is shown in Figs. 4 and 5, where it defines the map-scale folds of the area. In the lower parts of the hangingwall, the foliation maintains a pronounced parallelism to the CD, whereas at higher levels, it progressively loses intensity, is more widely spaced and acquires an orientation oblique to the CD. In some areas the obliquity progresses from 20 to 40°, corresponding to an asymptotic attitude typical of ductile shear zones formed by heterogeneous simple shear (Ramsay 1980). The mylonitic foliation is transected at a small angle by subparallel minor shear zones (C′ bands of Berthé et al. 1979) and their attitude in relation to the CD is shown in the cross sections of Figs. 4 and 5.

The stretching lineation is normal to the intersection between the foliation and the C′ planes, and is defined by elongation ribbons. As a whole, it shows a strong dispersal (Fig. 6A), but the changes in orientation are consistent with the map-scale late folds. Thus, in the western limb of the Belmil antiform (Fig. 5), and in the

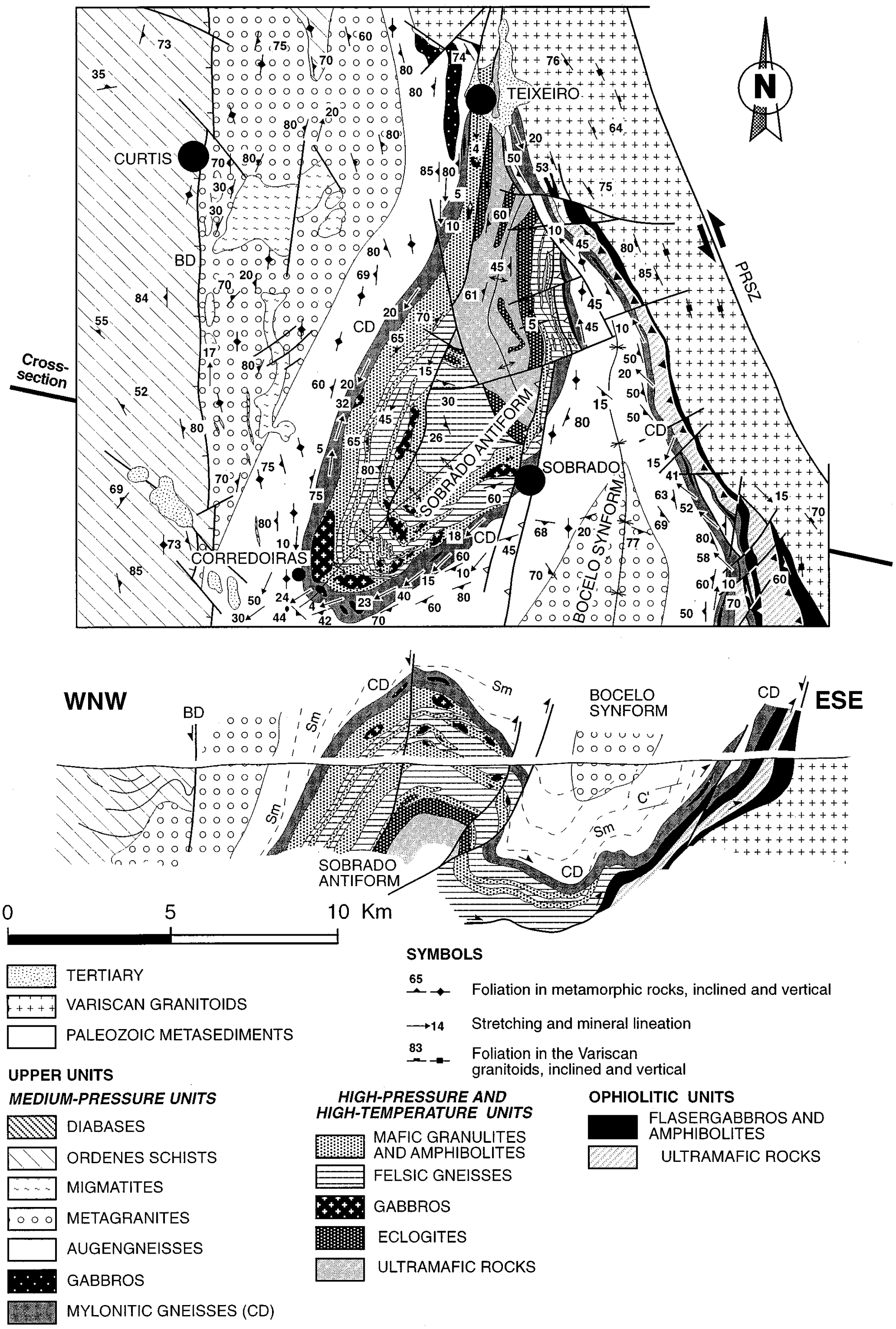


Fig. 4 Map and cross section of the Sobrado area, showing the attitude of the CD shear zone and related mylonitic foliation and stretching lineation. *C′*: shear bands. For location and other abbreviations see Fig. 3

eastern limb of the Bocelo-Santiso synform (Figs. 4 and 5), the lineation is subparallel to the dip of the mylonitic foliation, and varies from N150°E to east–west (Fig. 6B). In contrast, the lineation shows a NE–SW orientation in both limbs of the tight Sobrado Antiform and in the eastern limb of the Belmil antiform. Consequently, their variation is attributed to folding. Very open folds occur to the north and NW of Melide (Fig. 5) and there the lineation does not change significantly across the folds. Its attitude there, NW–SE, is considered close to the original orientation, which cannot be established with more precision.

Shear sense

The orthogneisses in the hangingwall to the CD show numerous kinematic indicators clearly visible to the

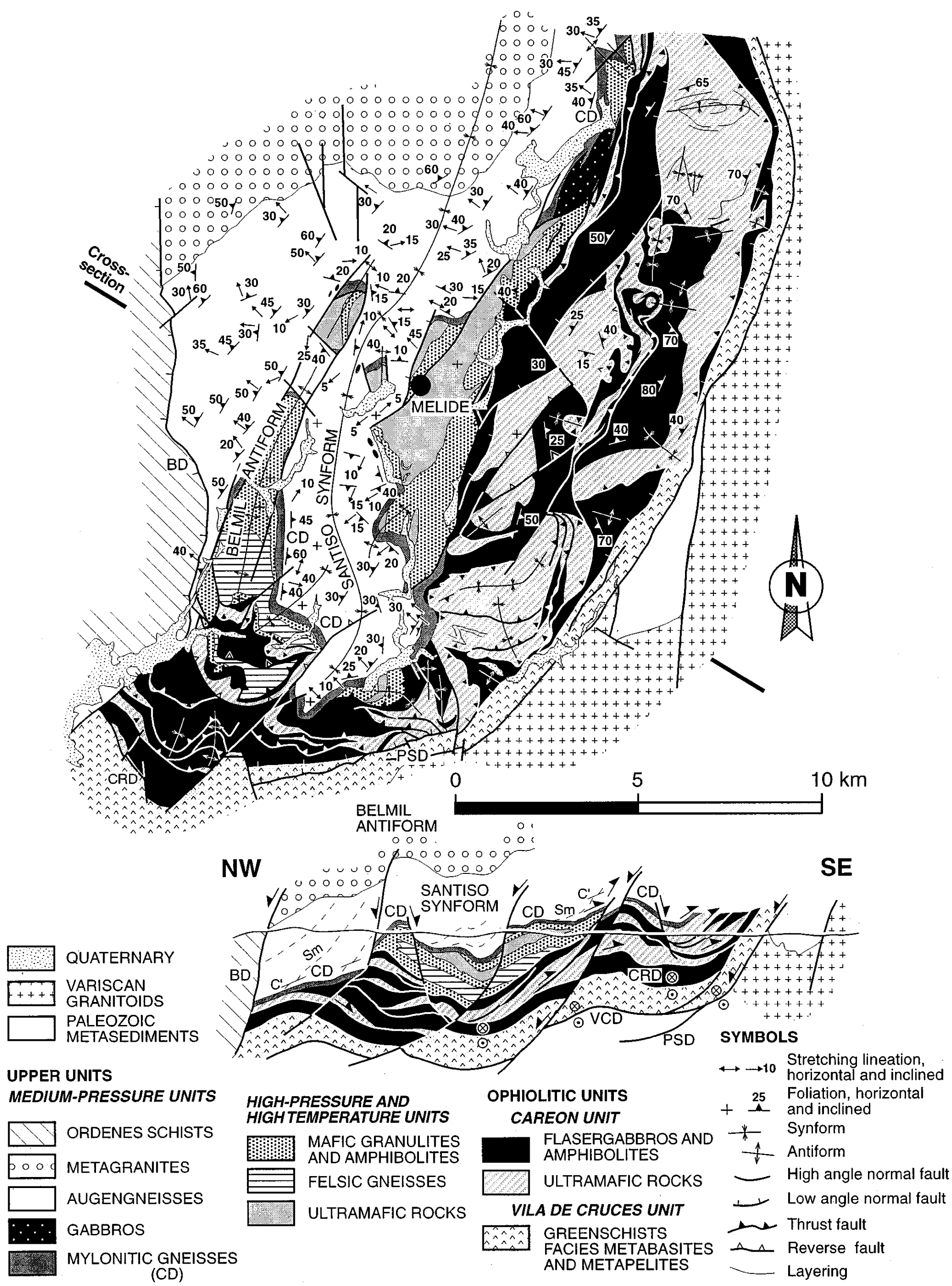
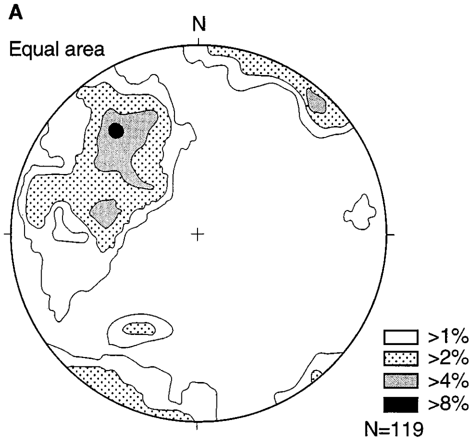


Fig. 5 Map and cross section of the Melide area, showing the attitude of the CD shear zone and related mylonitic foliation and stretching lineation. Abbreviations as in Figs. 2 and 3. For location see Fig. 3

naked eye, such as widespread shear bands or C′ planes (Berthé et al. 1979) and asymmetrical strain shadows and recrystallization tails of the σ type, developed around feldspar porphyroclasts (Simpson and Schmid 1983; Passchier and Simpson 1986). Less common δ types have been found in the basal ultramylonites. Widespread mica fish and weak steady-state foliation oblique to the quartz ribbons, formed by local dynamic recrystallization, were observed in thin section.

The changes in orientation undergone by folding of the lineation affect the apparent shear sense. The mylonites with east–west and NW–SE lineation, show top-to-east or top-to-SE criteria and, when the folded lineation has a NE–SW attitude, the observed shear sense is top to NE. An additional criterion is given by the asymptotic pattern of the foliation in the augengneiss in relation to the CD (cross sections in Figs. 4, 5), which indicates a movement of the hangingwall to the NE or SE, depending on the fold limbs.

From the measured shear senses and the attitude of the stretching lineation, the hangingwall seems to have moved toward the SE. However, the motion of younger and structurally lower thrusts, and also the late Palas de Rei sinistral shear zone (Fig. 3), might have rotated the original orientation to the presently deduced NW–SE.



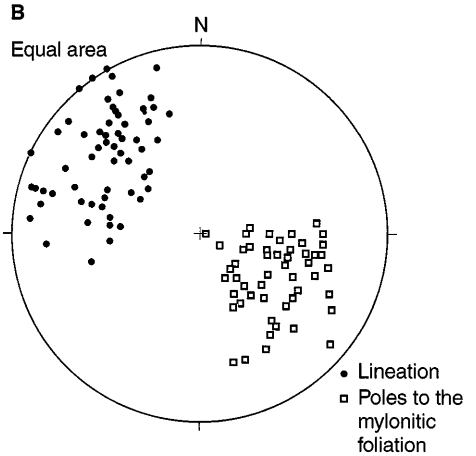


Fig. 6 **A** Stereoplot of the stretching lineation for the whole Corredoiras Detachment. **B** Stereoplots of the stretching lineation (*dots*) in the mylonitic gneisses in the western limb of the Belmil Antiform and eastern limb of the Santiso Synform. The attitude of the mylonitic foliation (*squares*) is also shown. Lower hemisphere projections

Fig. 7 **A** Early stages of augengneiss development with incipient formation of C′ shear bands. Coin diameter is 23 mm. **B** Field aspect of the ultramylonite developed at the base of the Corredoiras Detachment. **C** Common microstructures developed in an augengneiss. Cross-polarised light. K-feldspar porphyroclasts showing mechanical twining (*top left*) and myrmekites (*bottom right*). Both porphyroclasts have developed σ-type strain shadows composed of plagioclase and quartz. A completely recrystallised plagiocase porphyroclast can be observed in the *top right*. The attitude of S, C and C′ planes is also indicated. **D** Plane-polarised photomicrograph showing quartz ribbons and highly sheared phyllosilicate domains wrapping around feldspar porphyroclasts, which sometimes develop quarter folds (*q*). **E** Photomicrograph under cross-polarised light, showing compositional domains in a banded augengneiss

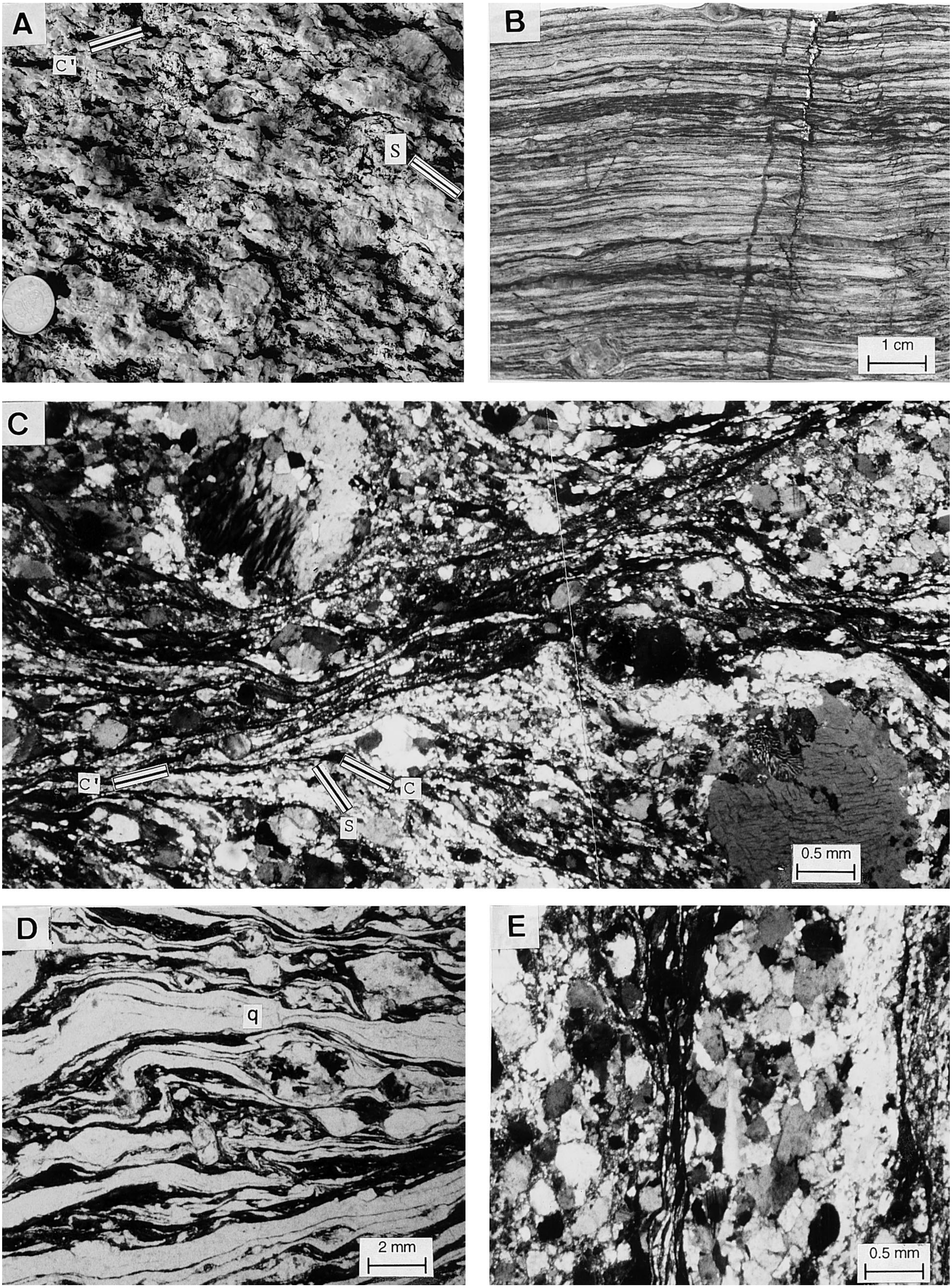
Microstructural evolution

The Corredoiras Orthogneiss depicts, from top to bottom, the appearance of a moderately deformed metagranite, an augengneiss, a mylonitic banded augengneiss and an ultramylonitic gneiss. The moderately deformed metagranites occur on top of the shear zone in the core of the Bocelo Synform (Fig. 4), where they show a porphyritic texture, with megacrysts of K-feldspar and plagioclase, and include bluish quartz, biotite, apatite, titanite, clinozoisite and garnet. The augengneisses (Fig. 7A,C) show a composite foliation due to the existence of C and C′ shear bands (Berthé et al. 1979; Hanmer and Passchier 1991). The quartz is organised in ribbons. The plagioclase shows almost complete recrystallization and the individual crystals show slight internal deformation (with either no twins or wide growth twins). Microperthitic K-feldspar shows deformation twins and a mantle microstructure which progresses into the porphyroclast, either due to the development of myrmekite colonies that gradually become incorporated to the matrix, or to recrystallization of new grains. The biotite has undergone a considerable grain-size reduction.

The lower 200–500 m of the shear zone have been mapped as a mylonitic band. It consists of mylonitic banded augengneisses, characterised by millimetre compositional domains, formed by quartz ribbons, more irregular phyllosilicate domains, and feldspar-rich domains (Fig. 7E). The augen textures are preserved, but the feldspars are commonly more rounded in shape and the matrix becomes more abundant, developing a continuous, planar foliation, locally distorted by asymmetrical microfolds (Fig. 7D) and shear bands. In these rocks the density of porphyroclasts is lower, and those remaining are almost exclusively of K-feldspar, with a mantle microstructure occupying up to 50% of the crystal. The plagioclase aggregates are stretched and organised in continuous ribbons several centimetres in length. The quartz forms polycrystalline ribbons with elongate mosaics or long quartz discs. The development of shear bands (C′) which distort the foliation is not so widespread, and these are at low angles to the foliation.

The ultramylonitic gneisses (Fig. 7B) are found in the basal 20–30 m. These rocks are characterised by a strong grain-size reduction and the presence of isolated K-feldspar porphyroclasts in lesser quantities than in the former types, in many cases detached from the matrix and with no recrystallization mantle. Asymmetrical porphyroclast systems of the σ, δ and complex σ–δ types (Passchier and Simpson 1986) developed around these porphyroclasts. The ultramylonites show well-marked millimetre banding and are characterised by a significant increase in the muscovite, chlorite, titanite and epidote contents.

The transformation from the igneous protolith to augengneisses occurred in high-grade metamorphic conditions, as evidenced by the first generation of microstructures, which are indicators of high-temperature flow of the main mineral phases. The recovery processes in K-feldspars, which include dynamic recrystallization and subgrain rotation, have been observed in rocks deformed in natural conditions at temperatures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higher than 550 °C (Vidal et al. 1980). The observed behavior of the plagioclase agrees with the experimental and field data provided by Marshall and MacLaren (1977), which indicate that above 560 °C there is abundant evidence of intracrystalline slip accompanied by recovery and recrystallization. The late stages of mylonite development induced garnet and biotite retrogression, with the generalised development of muscovite, chlorite, titanite and epidote in the foliation. This indicates temperatures below 450 °C. Moreover, the behavior of quartz was always ductile, implying temperatures higher than 350 °C (Sibson 1977).

Metre to kilometre bodies of gabbro are widespread close to the base of the Corredoiras Orthogneiss (Figs. 4, 5). Inside the augengneisses, they usually remain undeformed, but in the mylonitic band they appear transformed into well-foliated amphibolites with a common assemblage consisting of hornblende, epidote, albite, ilmenite, sphene and, occasionally, garnet.

We conclude from the observed microstructures that the mylonitic rocks show a retrograde evolution from temperatures greater than 550 °C to temperatures between 300 and 450 °C, whereas the deformation was being concentrated in the lower levels of the CD. Synkinematic cooling preserved the fabrics from postectonic annealing and enabled the different textural types to be preserved.

Metamorphic evolution

The CD separates two lithological ensembles with contrasted metamorphic evolution. The hangingwall is occupied by a medium-pressure (MP) unit (Fig. 3), where a thick metasedimentary sequence, the Ordenes Series, was intruded by Lower Ordovician granitic orthogneisses and metagabbros. Typical Barrovian metamorphic zones, ranging from low to high temperatures, can be distinguished across the Ordenes Series. The lower parts of this sequence consists of migmatitic paragneisses with high-temperature mineral assemblages transitional between the amphibolite and the granulite facies. The peak mineral assemblage developed in these paragneisses is constituted by Bt + Grt + Pl + Kfs + Sil + Qtz, without stable muscovite. General P–T conditions of equilibration of this mineral assemblage can be calculated using the petrogenetic grids for metapelites of Vielzeuf and Holloway (1988) and Powell and Holland (1990), and are represented in Fig. 8. Post-peak metamorphic evolution is characterised by destabilisation of the Grt + Kfs assemblage, and by the general development of mineral assemblages with cordierite and, finally, muscovite. This evolution suggests, as is the case in other gneissic complexes (Escuder Viruete et al. 1994, 1997), an initial, almost isothermal decompression followed by an important cooling (Fig. 8).

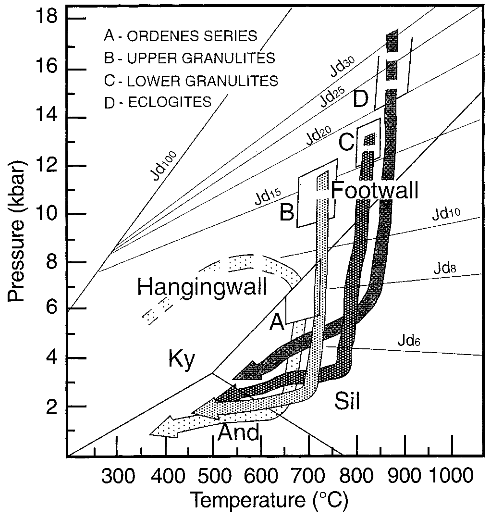

Fig. 8 Pressure–temperature paths representative of the metamorphic evolution followed by some characteristic lithologies located in the hangingwall (path A) and footwall (paths *B–D*) to the Corredoiras Detachment. *Boxes* in the diagram are indicative of peak conditions. Isopleths of jadeite content in clinopyroxenes coexisting with albite (Xalb = 1) and quartz (Holland 1980, 1983), and stability curves of the Al_2SiO_5 polymorphs (Holdaway 1971), are also shown

A high-pressure and high-temperature (HP–HT) unit underlies most of the CD, the Sobrado-Melide unit. Martínez Catalán and Arenas (1992) described in Sobrado three different slices limited by two minor extensional detachments. The upper slice consists of felsic gneisses and gabbros with igneous features variably preserved. The prograde metamorphic evolution of the gabbros began with the development of coronitic types and ended with the local equilibration of well-developed granoblastic high-pressure granulite facies assemblages (Na-Di + Grt + Pl + Qtz + Rt). The intermediate slice is also constituted by migmatitic felsic gneisses with high-pressure granulite facies mafic inclusions (Na-Di + Grt + Pl + Qtz + Rt ± Ky), but the intensity of the deformation and metamorphism precluded the preservation of igneous relicts. Finally, the lower slice consists, from top to bottom, of a layer of eclogites (Omp + Grt + Qtz + Rt ± Ky ± Zo) and related clinopyroxene–garnet rocks without primary plagioclase (Na-Di + Grt + Qtz + Rt ± Zo), and highly serpentinised ultramafic rocks with some alternations of retrogressed eclogites. The sequence of the unit is a strongly condensated one, due to the extensional tectonics developed after the HP–HT event, and an almost complete transition from the granulite facies to the eclogite facies occurs within a band approximately 3000 m thick.

Pressure–temperature determinations of peak metamorphic conditions in the mafic rocks of the HP–HT Sobrado unit were obtained by Arenas and Martínez Catalán (1993), using clinopyroxene–garnet thermobarometry (Fe^{2+} content in clinopyroxene and garnet estimated by charge-balance methods; Krogh 1988;

Holland 1980, 1983). The eclogitic rocks at the base of the sequence were equilibrated at 850 °C and minimum pressures of 15 kbar. P–T conditions of 830 °C and 12.75 kbar were obtained in the mafic granulites included in the lower gneisses, whereas their equivalents in the upper slice gave P–T values ranging from 675 to 750 °C and 9.5 to 12 kbar. These P–T peak conditions are represented in Fig. 8, where the decompressive paths of the HP–HT mafic rocks are also shown. The post-peak location and general geometry of the paths have been determined according to the nature of the retrogressive mineral assemblages, taking into account the chemical composition of the more characteristic minerals. Thus, in eclogites and clinopyroxene–garnet rocks, several post-peak generations of clinopyroxenes, progressively poorer in jadeite, developed. The compositions of these clinopyroxenes justify a post-eclogitic, almost isothermal, decompression (Fig. 8). A similar post-peak path can be inferred for the lower and upper granulites of the Sobrado unit.

The metamorphic evolution of the units separated by the CD is characteristic of regions affected by extensional tectonics. The hangingwall to the CD shows an intermediate pressure evolution, with a general P–T path characterised by moderate post-peak decompression, probably related to minor extension in the series overlying the CD. In the footwall unit, the metamorphic evolution is clearly different, and a general HP–HT event has been described in the Sobrado-Melide unit. In this context, a very significant metamorphic subtraction (minimum values of 10 km) appears clearly associated with the CD. The magnitude of the extension linked to this detachment is shown by the P–T paths of the HP–HT lithologies, which registered stages of pronounced decompression followed by cooling.

Discussion

The CD drove the MP unit into contact with the underlying HP–HT unit of the Ordenes Complex, but also with a structurally lower ophiolitic unit. The latter represents the suture of a former oceanic lithosphere, probably forming part of the Rheic oceanic realm (Martínez Catalán et al. 1997; F. Díaz García et al., in press). The ophiolitic units of the Iberian allochthonous complexes separated two different palaeogeographic realms: Gondwana, to the east (approximately and in present coordinates), and an active accretionary wedge, to the west. The upper units formed part of this wedge. The MP and HP–HT units, and the Careón Ophiolitic unit, at least, had been stacked prior to the development of the CD, according to crosscutting relationships (Fig. 9A).

The isotopic data available in Ordenes and the rest of the allochthonous complexes of NW Iberia also support this assertion: The HP–HT units experienced the first Variscan metamorphic episode during the Lower Devonian, as reported by U–Pb analyses on zircons (392 ± 4, Peucat et al. 1990; 406 ± 4 Ma, Santos Zalduegui et al. 1996), and on brown titanite (389 ± 2 Ma, Santos Zalduegui et al. 1996). The HP–HT units underwent a decompressive episode during their emplacement onto the ophiolitic units. Synchronous amphibolite-facies metamorphism has been dated at 385.8 ± 1.5 and 389.1 ± 2.0 Ma by $^{40}Ar/^{39}Ar$ method in hornblende concentrates from retrogranulite rocks (Dallmeyer et al. 1991). This metamorphism was retrogressive in the HP–HT units and prograde in the ophiolites (389.1 ± 3.1 and 383.7 ± 2.3 Ma, $^{40}Ar/^{39}Ar$ method, hornblende concentrates from metagabbros and amphibolites; Dallmeyer et al. 1991), indicating a Lower to Middle Devonian age for the stacking of the oceanic slices.

The amphibolite facies foliation in a deformed metagabbro included in the CD mylonite has been dated at the limit between the Middle and Upper Devonian (375 Ma, $^{40}Ar/^{39}Ar$, hornblende concentrate; Dallmeyer et al. 1997). In addition, an amphibolite sample collected at the Careón Ophiolitic unit close to the CD gave an $^{40}Ar/^{39}Ar$ plateau of 376.8 ± 0.4 Ma (Dallmeyer et al. 1997). These ages date the early stage of the detachment because hornblende has a closure temperature for argon retention of around 500 °C. An age of 373 Ma was obtained for the subsequent greenschists-facies stage in a muscovite concentrate from a mylonitic metagranite identical to the Corredoiras Orthogneiss in facies, age and structural position, in northern Portugal (Dallmeyer et al. 1991).

These ages confirm the field evidence showing that the CD is a relatively old structure, predating most of the extensional detachments, upright folds and transcurrent ductile shear zones in the Ordenes Complex. They also suggest contemporaneity with the ongoing convergence. The end of the HP metamorphic event of the basal units has been dated at 374 Ma (average Rb–Sr ages obtained in post-eclogitic phengites by Van Calsteren et al. 1979). This and other Rb–Sr ages ranging from 365 to 352 ± 3 Ma (Santos Zalduegui et al. 1995) reflect the progressive exhumation of the subducted outer margin of Gondwana (Fig. 9B). This exhumation was partially carried out by thrusts, such as the LFT, which placed the HP basal units over the relative autochthon (Figs. 1, 3). The LFT developed before the onset of low-temperature greenschist-facies metamorphism (dated at 366.8 ± 0.4 and 364.4 ± 0.7 Ma, $^{40}Ar/^{39}Ar$ muscovite concentrate and whole-rock analysis in metapelites of the ophiolitic units; Dallmeyer et al. 1997).

Bracketed by these younger ages, and recognised as the only important thrust carrying the basal units, the LFT probably provoked the end of the eclogitic metamorphism in these units, initiating their exhumation. The unroofing was accompanied by synchronous tectonic denudation, as suggested by the P–T paths of the basal units (Arenas et al. 1995, 1997; Martínez Catalán et al. 1996). Because the ages of the beginning

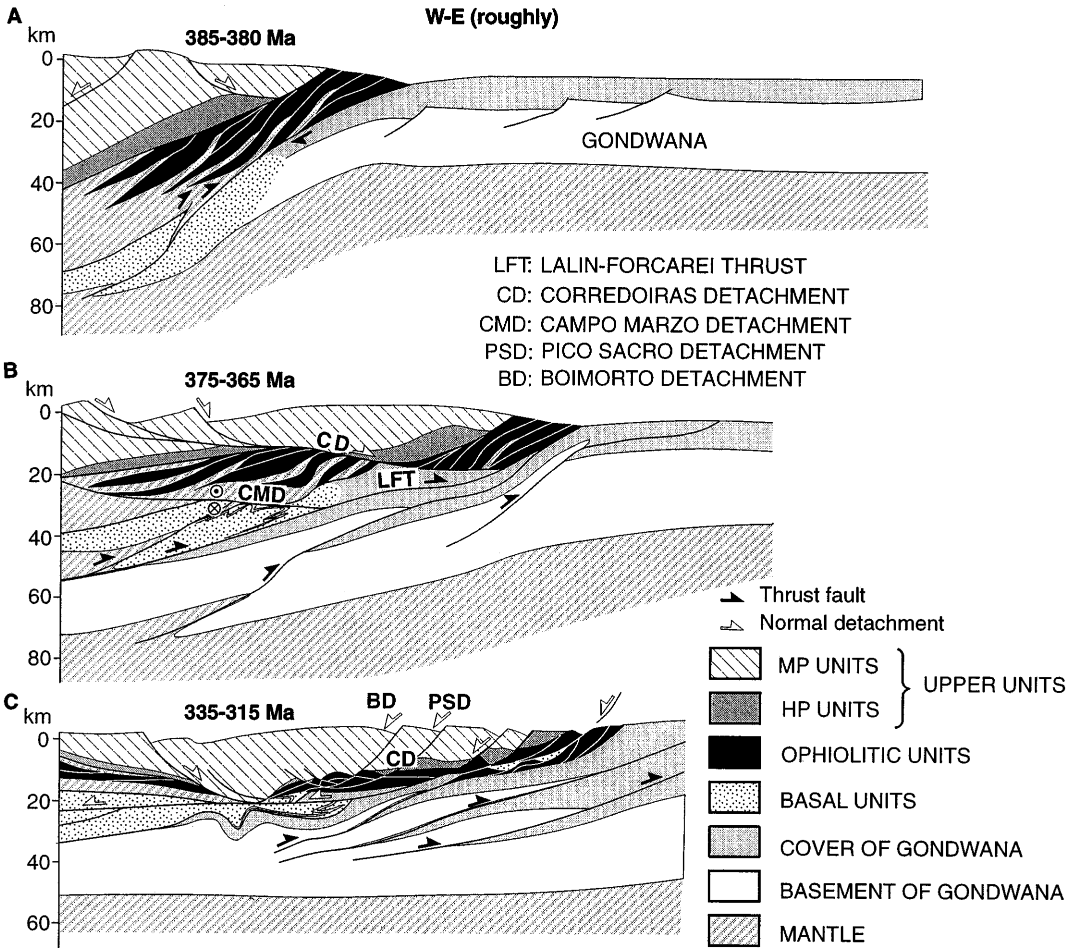

Fig. 9 Evolution of the accretionary wedge showing **A** the stacking of the upper and ophiolitic units and the subduction of the basal units, **B** the exhumation of the latter and the development of the main extensional detachments and **C** a later stage of development of normal detachments

of exhumation and the CD coincide, a synchronism is postulated between CD and LFT. In any case, the CD developed during a convergent process initiated 400 m.y. ago and that was still active at 360 and 340 Ma, ages of the first and second foliations, associated to recumbent folds and thrusts, respectively, in the relative autochthon ($^{40}Ar/^{39}Ar$ whole-rock analyses; Dallmeyer et al. 1997).

We have shown that the CD had a low-dipping attitude, and a top-to-the-SE sense of emplacement. The characterisation of the CD as an extensional detachment relies primarily on three considerations:

1. It overprints the earlier major compressional structures involved in the building of the accretionary wedge, crosscutting the nappe pile from the structurally higher to the structurally lower units toward the SE, in the direction of tectonic transport.
2. At the map scale, the geometry of the HP–HT unit in relation to the CD is that of a footwall ramp (Figs. 4, 5), indicating a relative local descent of the hangingwall in the direction of movement.
3. The metamorphic jump between the hangingwall (amphibolite facies) and the footwall (granulite facies), recognised across the CD, implies the subtraction of part of the original metamorphic zoning, a typical feature for a normal fault.

These arguments are not definitive, however, as the described relationships can also be fitted by an out-of-sequence, low-dipping thrust crosscutting a stack of metamorphic slices dipping to the west. It is the tectonometamorphic evolution of the whole ensemble that provides a better understanding of the meaning of the detachment. The footwall units (HP–HT, ophiolitic and also basal units) are characterised by differing levels of burial (including subduction), followed by drastic decompression (Arenas and Martínez Catalán 1993; Arenas et al. 1995; Martínez Catalán et al. 1996; F. Díaz García et al., in press). With the set of isotopic ages available, an understacking mode for the emplacement of the units can be assumed (Davy and Gillet 1986). Thus, the upper units were accreted first, followed by the ophiolitic and the basal units. This stacking mode (Fig. 9A) agrees with the vergence of the orogen and with the temporal migration of the deformation toward the external zones. None of the elements accreted to the base of the orogenic wedge recorded any subsequent significant pressurisation, and their P–T trajectories show pronounced decompressions compatible with the thinning, maintained over time, of the overlying parts of the wedge.

The basal units were exhumed from a depth of more than 40–50 km (12–15 kbar of minimum pressure) to approximately 15–20 km (4–6 kbar) according to Arenas et al. (1995) and Martínez Catalán et al. (1996). The removal of 20–30 km of overburden is difficult to explain only by erosion, given the fact that low-grade rocks are still preserved in the uppermost MP unit, very close to the basal units exhumed by the LFT. This is one of the criteria most widely used as indicator of extensional structures (Platt 1986; Dewey 1988). The need for extensional structures to equate the load removed, and the isotopic ages suggesting a synchronism between the CD and the LFT, strongly support the interpretation of the CD as a synconvergent normal structure (Fig. 9B). The detachment fits the metamorphic criterion of Wheeler and Butler (1994) that for a shear zone to be related to crustal extension, the pressure recorded by rocks in the footwall should, during shear zone movement, decrease faster than that recorded in the hangingwall. Of the 20–30 km of overburden removed, the CD may well be responsible for at least the 10 km of tectonic denudation suggested by the metamorphic jump between its hangingwall and footwall (Fig. 8).

The kinematics of the exhumation of the high-pressure rocks differs from the model of Platt (1986), in which the gravitational collapse is not directed towards the foreland. The CD shows top-to-SE sense of movement, whereas the emplacement of the LFT was toward the ENE. This seems a case of lateral spreading, where extension occurs at a high angle to the synchronous shortening direction. According to Dewey (1988) this happens also in the Himalayas, Tibet and the Alpine Belt of southern Europe, and may occur when extension is synchronous with plate convergence.

Conclusion

The CD is a first-order structure in the allochthonous Ordenes Complex, in the NW Iberian Massif. The detachment drove into contact the uppermost unit, characterised by a medium-pressure metamorphism, on top of a high-pressure unit and of an underlying ophiolite. The CD developed as a ductile shear zone, nearly 2000 m thick, where the Corredoiras Orthogneiss, a Lower Ordovician metagranite, was transformed into augengneisses and strongly mylonitised. This process was accompanied by cooling from the amphibolite to the greenschist facies, and by progressive localisation of deformation at the base.

Taking into account the structural and geometrical characteristics, the tectonometamorphic evolution of the units and the isotopic data available, the CD is interpreted as a ductile extensional detachment, dated around the Middle–Upper Devonian boundary, which implies it is a structure developed during the Variscan plate convergence. According to the isotopic ages, it seems synchronous with the first stages of exhumation of the previously subducted basal units. These units were transported over the non-subducted metasediments of the relative autochthon along the Lalín-Forcarei Thrust (LFT). This interpretation supports the view that extensional structures may occur early in the orogenic process, may develop in the upper part of orogenic wedges, whereas convergence continues, and may be involved in the exhumation of HP metamorphic rocks (Platt 1986).

The sense of movement estimated for the hangingwall unit from the stretching lineation, shear-sense indicators and the asymptotic pattern of the mylonitic foliation is to the SE. The LFT moved to the ENE, so that we are dealing with a case of extensional collapse at high angle to the slip vector of contemporaneous convergent structures.

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