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Metamorphic and deformational imprint of Cambrian–Lower Ordovician rifting in the Ossa-Morena Zone (Iberian Massif, Spain)

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Abstract

The high-temperature metamorphism recorded in the Valuengo and Monesterio areas constitutes a rare occurrence in the Ossa-Morena Zone of Southwest Iberia, where low-grade metamorphism dominates. The metamorphism of the Valuengo area has been previously considered either Cadomian or Variscan in age, whereas that of Monesterio has been interpreted as a Cadomian imprint. However, these areas share important metamorphic and structural features that point towards a common tectonometamorphic evolution. The metamorphism of the Valuengo and Monesterio areas affects Late Proterozoic and Early Cambrian rocks, and is syn-kinematic with a top-to-the-north mylonitic foliation, which was subsequently deformed by early Variscan folds and thrusts. The U–Pb zircon age (480 ± 7 Ma) we have obtained for an undeformed granite of the Valuengo area is consistent with our geological observations constraining the age of the metamorphism. We propose that this high-temperature metamorphic imprint along a NW–SE ductile extensional shear zone is related to the crustal extension that occurred in the Ossa-Morena Zone during the Cambro-Ordovician rifting. In the same way, the tectonothermal effect of the preorogenic rifting stage may have been wrongly attributed to orogenic processes in other regions as well as in this one.

Keywords: Rifting; Variscan; Preorogenic metamorphism; Preorogenic deformation; Southwest Iberia

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1. Introduction

The Ossa-Morena Zone, in the Iberian Massif (Fig. 1a), is a key crustal element in the Variscan puzzle (Burg et al., 1981; Matte, 1986; Simancas et al., 2002), being limited to the North and South by orogenic sutures (Bard, 1977; Fonseca and Ribeiro, 1993; Azor et al., 1994; Simancas et al., 2001). The rocks of the Ossa-Morena Zone are generally affected by low-grade Variscan metamorphism, but there are some areas of higher metamorphic grade. Just along the southern border of the Ossa-Morena Zone, there is a very conspicuous band of high-temperature/low-pressure Variscan metamorphism (Bard, 1977; Crespo Blanc, 1989; Castro et al., 1999) and, to the western border, poorly preserved allochthonous klippen with high-pressure metamorphism have been recently described (Fonseca et al., 1999). Apart from these demonstrable Variscan metamorphic domains, a few small medium/high-grade metamorphic areas are found in the central Ossa-Morena Zone, whose origin is less clear. This paper focuses on two of these latter areas: the Valuengo metamorphic area and the Monesterio metamorphic area (Fig. 1b).

Previous interpretations have considered the metamorphism of Valuengo either as Precambrian (Fernández Carrasco et al., 1981) or as the result of crustal thickening followed by collapse during the Variscan orogeny (Apraiz, 1998; Apraiz and Eguíluz, 1996), whereas the Monesterio area metamorphism has been assumed to be evidence of the role played by the Cadomian orogeny in the evolution of the Ossa-Morena Zone (Eguíluz, 1987). However, our structural studies, combined with geochronological data, suggest a connection between these two areas and allow us to present a new interpretation for both. This interpretation calls for the critical identification of the total imprint of preorogenic rifting, which is not only expressed in stratigraphy and magmatism (as usually recognized) but also in significant metamorphic and deformational

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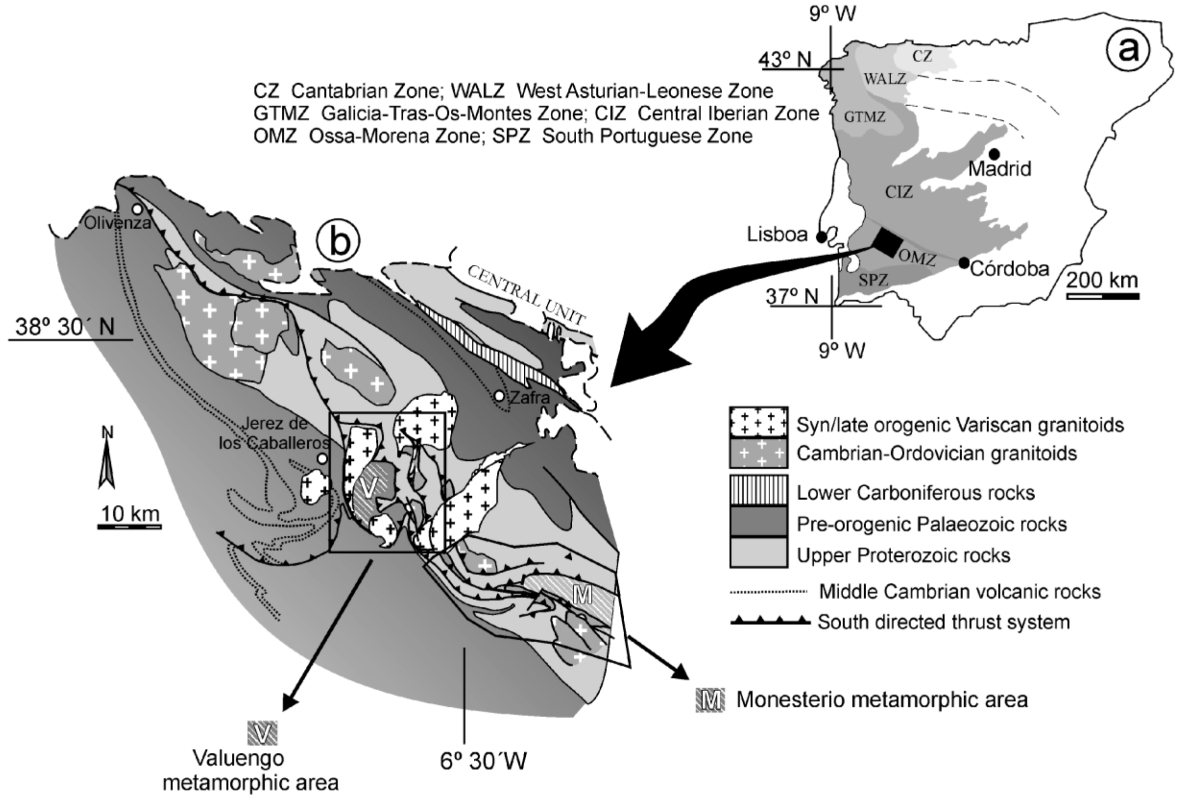

Fig. 1. Location of the Valuengo and Monesterio metamorphic areas in (a) the Iberian Variscan Massif, and (b) the Monesterio Precambrian Anticlinorium (Ossa-Morena Zone).

manifestations. The subject is not new (e.g. Weber, 1984; Wickham and Oxburgh, 1985; Sandiford and Powell, 1986), but our study illustrates the difficulties arising when there is strong subsequent orogenic deformation.

2. General stratigraphy of the Ossa-Morena Zone

The stratigraphic sequence of the Ossa-Morena Zone can be divided into four main parts: (a) Upper Proterozoic formations, (b) Lower Cambrian platform deposits, (c) pre-Variscan rifting deposits, and (d) syn-Variscan orogenic deposits.

Two main lithostratigraphic units represent the end of the Proterozoic in the Ossa-Morena Zone. The older of the two, Late Riphean or Vendian in age, is the 'Serie Negra', which is made up by schists, metagreywackes, black quartzites and amphibolites (Eguíluz, 1987). Above it, a volcanosedimentary complex of Vendian to earliest Cambrian age, the Malcocinado formation, seems to record subduction-related magmatism (Sánchez Carretero et al., 1990). Both lithostratigraphic units belong to the Cadomian orogenic cycle but have been strongly affected by Variscan-age deformation.

The Early Cambrian is represented by the terrigenous 'Torreárboles formation', followed by carbonates, which represent the settling of a wide carbonate platform in the region. The transition from Early to Middle Cambrian saw the breaking of the platform by the pre-Variscan rifting (Liñán and Quesada, 1990), so that volcanics (mainly in Middle Cambrian) and terrigenous sediments characterized the stratigraphic sequence till the Ordovician (Ribeiro et al., 1992). The Silurian is represented mainly by pelagic sediments, and fine-grained terrigenous sediments of Late Silurian and Early Devonian are the youngest deposits of the pre-Variscan sequence (Oliveira et al., 1992).

Syn-Variscan deposits could be as young as Early Devonian in age (Piçarra, 1998), but are mainly Early Carboniferous (Boogaard and Van den Vázquez, 1981) and lie unconformably over the pre-Variscan sequence (Expósito et al., 2002).

3. Valuengo metamorphic area

3.1. General description

Most of the medium/high-grade metamorphic rocks outcrop in a horse, the Valuengo horse, which belongs to a Variscan thrust system (Fig. 2; Expósito, 2000; Expósito et al., 2002). The rocks affected by the highest metamorphic grade (the gneissic-migmatitic formation of Fernández Carrasco et al.. (1981)) appear in an oval outcrop located in the middle of the Valuengo horse (Fig. 2); these rocks are migmatites, mica-schists and quartz-schists, and include small bodies of anatectic granite. They are overlain by a meta-volcanoclastic unit known as the Mayorgas formation (Fernández Carrasco et al., 1981), which consists of a clastic

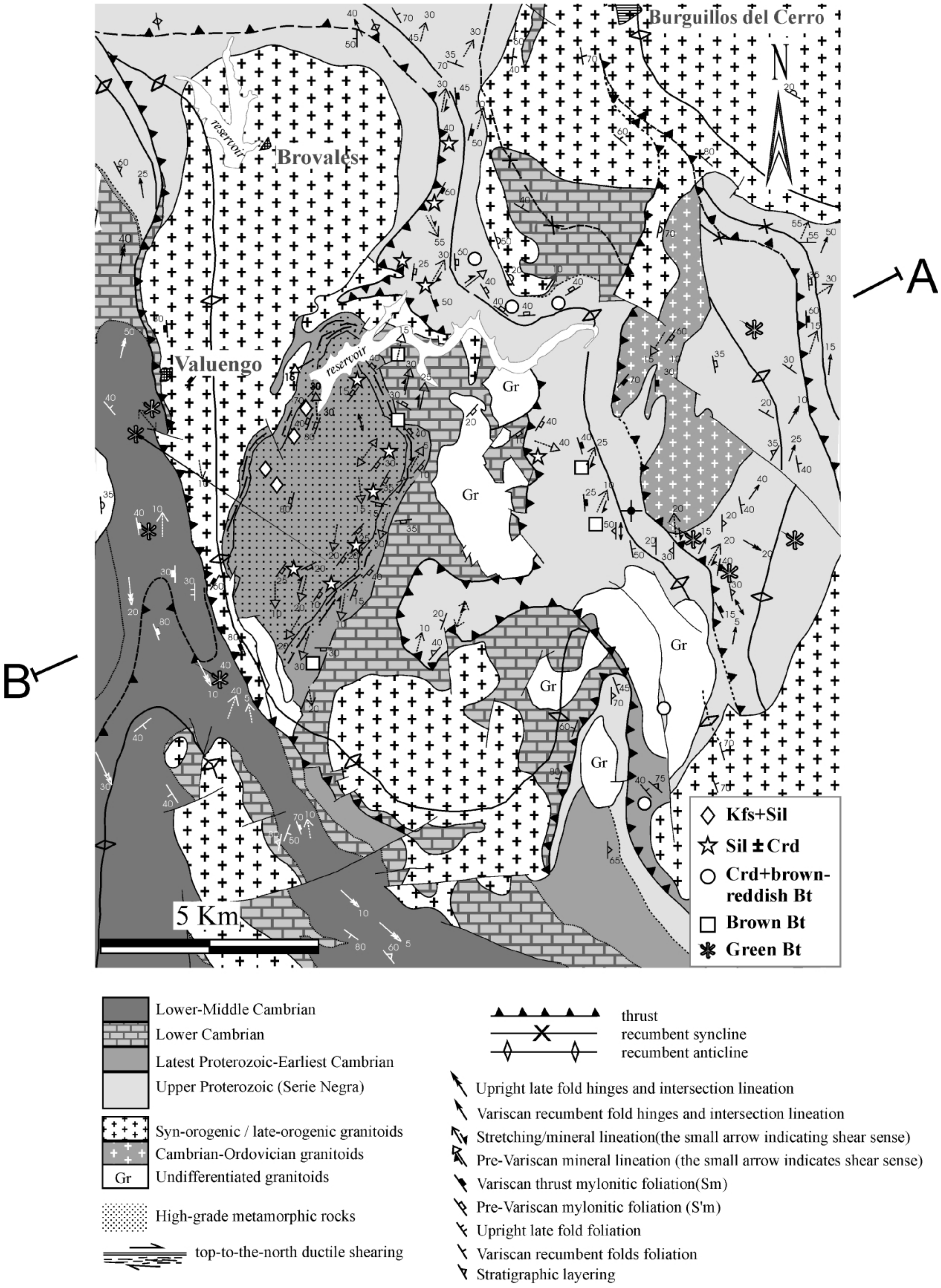

Fig. 2. Geological map of the Valuengo area. Cross-section AB is shown in Fig. 5a. The location of samples with different metamorphic index minerals is indicated with symbols explained in the lower-right inset.

member at the bottom that includes a thin carbonate level, and a gneissic member at the top, which was probably derived from volcanosedimentary rocks (Apraiz, 1998). Finally, calcitic and dolomitic marble outcrop on top of the succession.

The correlation between the formations described in the Valuengo horse and others constituting the general stratigraphic series of the Ossa-Morena Zone is not obvious, due to the medium/high-grade metamorphism affecting the Valuengo rocks. Nevertheless we propose a correlation that is mainly based on two facts: (1) the obvious lithological affinity between the carbonate formation in Valuengo and the Lower Cambrian carbonates of the Ossa-Morena Zone, and (2) the structure, as described below, which indicates normal polarity for the stratigraphic succession in most of the Valuengo area. In this way, the volcanoclastic Mayorgas formation has been correlated here to the volcanosedimentary unit regionally known as Malcocinado formation, which is Latest Proterozoic–earliest Cambrian in age. The lowermost gneissic–migmatitic formation could therefore be correlated to the dark shales and greywackes of the Upper Proterozoic Serie Negra, but the lack of its distinctive black quartzites points rather to the Malcocinado formation again as the most likely correspondent. Just to the east, outside the Valuengo horse, rocks obviously corresponding to the Upper Proterozoic Serie Negra outcrop (Fig. 2).

3.2. Metamorphic features of the Valuengo area

Inside the Valuengo horse, the rocks of the gneissic–migmatitic formation and those located at the bottom of the Mayorgas formation are affected by high-temperature metamorphism. The metamorphic grade abruptly decreases eastward (i.e. structurally upwards), from high grade in the gneissic–migmatitic formation to low grade in the upper marbles. This strong gradient of metamorphism is shown by means of symbols in Fig. 2. The highest grade has given way to the following association of characteristic minerals in pelitic quartz–feldspar rocks:

$$\text{sillimanite} + \text{K} - \text{feldspar} + \text{reddish brown biotite}$$

(very small quantities of garnet occur in a few samples); then, intermediate assemblages with sillimanite but without K-feldspar (stars), followed by rocks with brown biotite as the only index mineral (squares), are found within a short distance.

The Valuengo horse is surrounded along its northern and eastern sides by mica schists and migmatitic gneisses of the Upper Proterozoic Serie Negra, containing the index minerals:

$$\text{sillimanite} + \text{K} - \text{feldspar} + \text{reddish brown biotite} + \text{cordierite}$$

Garnet is absent from the Serie Negra medium/high-grade rocks, whereas cordierite, not found in the gneissic–migmatitic formation, is abundant. This fact suggests that the chemical composition has been a decisive factor in the occurrence of either garnet or cordierite. The high Fe content in rocks of the gneissic–migmatitic and the Mayorgas formations, suggested by the high Fe/(Fe + Mg) ratio value in garnets (Apraiz and Eguíluz, 1996) and by the abundant presence of ilmenite and tourmaline, seems to have extended the garnet stability field in both formations of the Valuengo horse (Hsu and Burnham, 1969). These petrographic observations clearly point towards a low-pressure facies series metamorphism. Accordingly, we do not share the suggestion by Apraiz and Eguíluz (1996) of medium or even high pressures for this metamorphism. As discussed by Expósito (2000), we think that there must be some disequilibrium between the minerals they used for barometric calculations.

The metamorphic grade of the rocks surrounding the horse along the North and the East also decreases abruptly towards the East, as shown by the rapid appearance of low-grade mineral assemblages with green biotite (Fig. 2). The same mineral assemblages are found in rocks outcropping to the west of the Valuengo horse.

3.3. Deformation related to the metamorphism of the Valuengo area

The strong metamorphic gradient observed in the area of Valuengo is the essential result of two factors: the high thermal gradient of the metamorphism and the thinning caused by a syn-metamorphic shearing, responsible for the main deformation recorded in these rocks. In fact, the main foliation (S'_m) is syn-metamorphic and mylonitic (Fig. 3), being mainly marked by biotite and sillimanite growing in pelites (Fig. 3a and b) and by deformed grains in quartz–feldspar rocks. Its attitude varies as a consequence of late folding, defining a gentle dome (Fig. 4a). The lineation, marked often by biotite and stretched quartz grains, is NNE–SSW (Fig. 4b). Several microstructures (mantled porphyroclasts, S–C structures, subgrain boundaries, etc.) consistently give a top-to-the-NNE sense of shear (Fig. 3c and d), as already pointed out by Apraiz and Eguíluz (1996).

Quartz crystallographic preferred orientations in quartz-feldspar rocks of the gneissic–migmatitic formation confirm that the shearing took place under medium/high-temperature conditions. The *c*-axis pattern of sample (a) in Fig. 5 has a maximum near the *X*-axis, indicating the activation of prism ⟨c⟩ slip; the pattern asymmetry suggests a top-to-the-north shear sense, the same one as the one defined by microstructures. Sample (b) in Fig. 5 has a *c*-axis maximum around the *Y*-axis, indicating the dominant influence of prism ⟨a⟩ slip. Both slip systems are characteristic of medium/high-temperature mylonites (Mainprice et al., 1986; Tubía and Cuevas, 1986; Okudaira et al., 1995).

The mylonitic foliation (S'_m) is folded, not only by the gentle dome referred to above (Fig. 4a), but also by Variscan

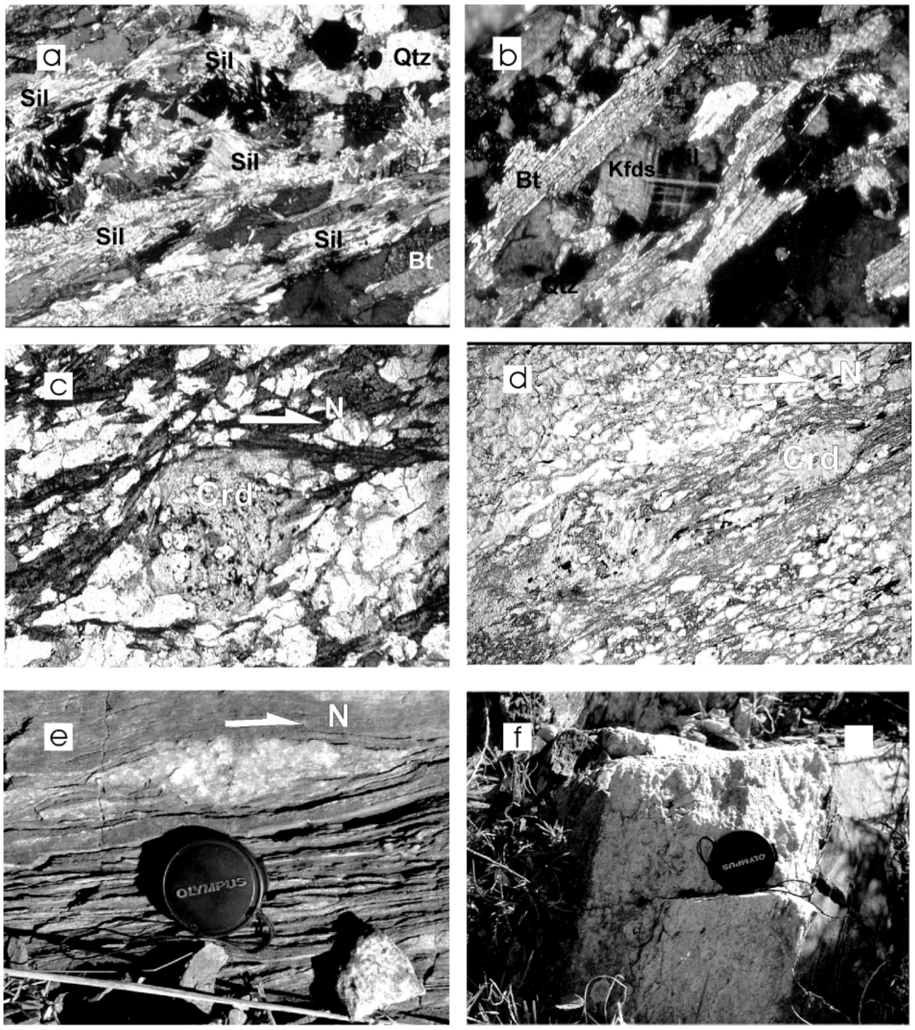

Fig. 3. Medium/high-grade rocks of the Valuengo area. (a) Sillimanite and brown-reddish biotite syn-kinematic with a top-to-the-north mylonitic foliation (S'_m), in the gneissic–migmatitic formation (× 6.3). (b) K-feldspar and biotite in the same formation (× 6.3). (c) and (d) Cordierite syn-kinematic with top-to-the-north mylonitic foliation (S'_m), in Serie Negra schists outcropping east of the Valuengo horse (× 2.5). Medium/high-grade rocks of the Monesterio area. (e) Serie Negra schist with tiny plate of quartz defining the mylonitic foliation S'_m, and asymmetric lenses of quartz indicating sense of shear. (f) Leucogranitic syn-kinematic vein showing the same mylonitic deformation that affects the Serie Negra schists.

recumbent folds whose axial-plane foliation is the oldest one recorded in rocks outside the metamorphic area. Actually, the Valuengo horse is a portion of the hinge of a large recumbent anticline, which folded the ductile shear zone. The folded shear zone was subsequently dissected by a south-directed thrust system (the origin of the Valuengo horse), and finally folded by late folds (Fig. 6a and b; Expósito, 2000).

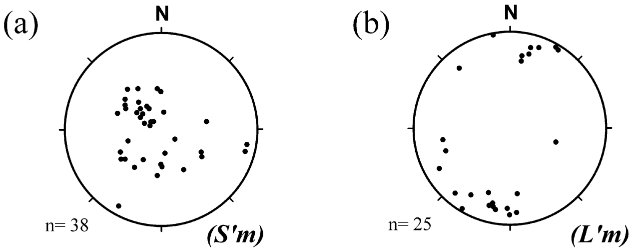

Fig. 4. Lower-hemisphere equal-area plot by Wintek of: (a) the top-to-the-NNE mylonitic foliation (S'_m), and (b) the stretching/mineral lineation (L'_m), in the Valuengo metamorphic area.

The different mineral assemblages depicted in Fig. 2 have been approximately projected onto the cross-section in Fig. 6a. If the effect of late folds and thrusts is removed, we can envisage the structure of the Valuengo area just after the recumbent fold development (Fig. 6b). Unfolding of the recumbent folds let us determine a rough zonation of the metamorphism syn-kinematic with the first mylonitic deformation (Fig. 6c). Despite the fact that this is not a precise restoration, since finite strain has not been taken into account, it serves the purpose of showing that metamorphism was limited in extent along the SW–NE direction.

3.4. Age of the Valuengo area metamorphism

The metamorphism in the Valuengo area took place

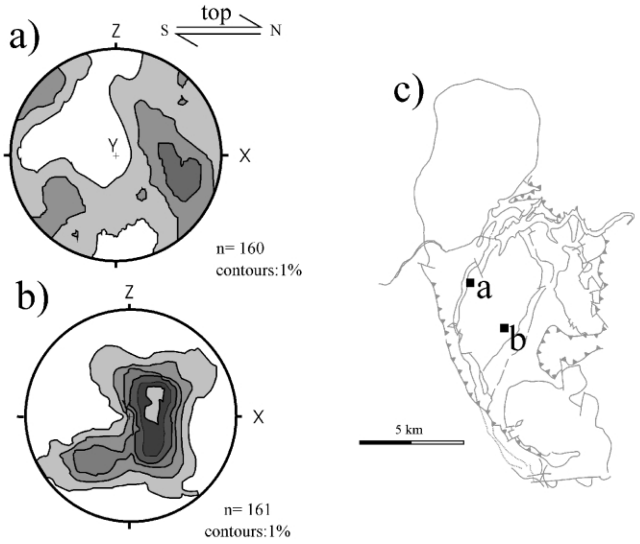

Fig. 5. Quartz *c*-axis fabric in rocks belonging to the gneissic–migmatitic formation. Lower-hemisphere equal-area plot by Wintek. (a) Paragneiss, and (b) meta-arkose. Notice medium to high-temperature slip systems. (c) Location of (a) and (b).

before the Variscan crustal thickening. In addition, it affects rocks that are reasonably correlated to others of latest Precambrian/earliest Cambrian age. Therefore, it can be said that metamorphism is post-Vendian though younger than the main Variscan deformation. For a better constraint of the age of the metamorphism, we have carried out preliminary geochronological dating on two rock samples collected in the Valuengo area: a medium-grade orthogneiss and an apparently undeformed microgranite (Fig. 7). For that purpose, we have applied the single-zircon stepwise-evaporation ^{207}Pb/^{206}Pb method (Kober technique; Kober, 1986, 1987) using a thermal ionisation mass spectrometer.

The most representative zircon grains, regarding their size (100–400 μ) and their external and internal shape, were mounted on canoe-shaped Re filaments and heated until the Pb beam intensity was sufficient. Then, the evaporated Pb was collected on the ionization filament for 20–30 min and afterwards analysed in five blocks with seven scans per block. Data were obtained by peak hopping with the 206–204–206–207–208 mass sequence, using a secondary electron multiplier (SEM) as detector. The

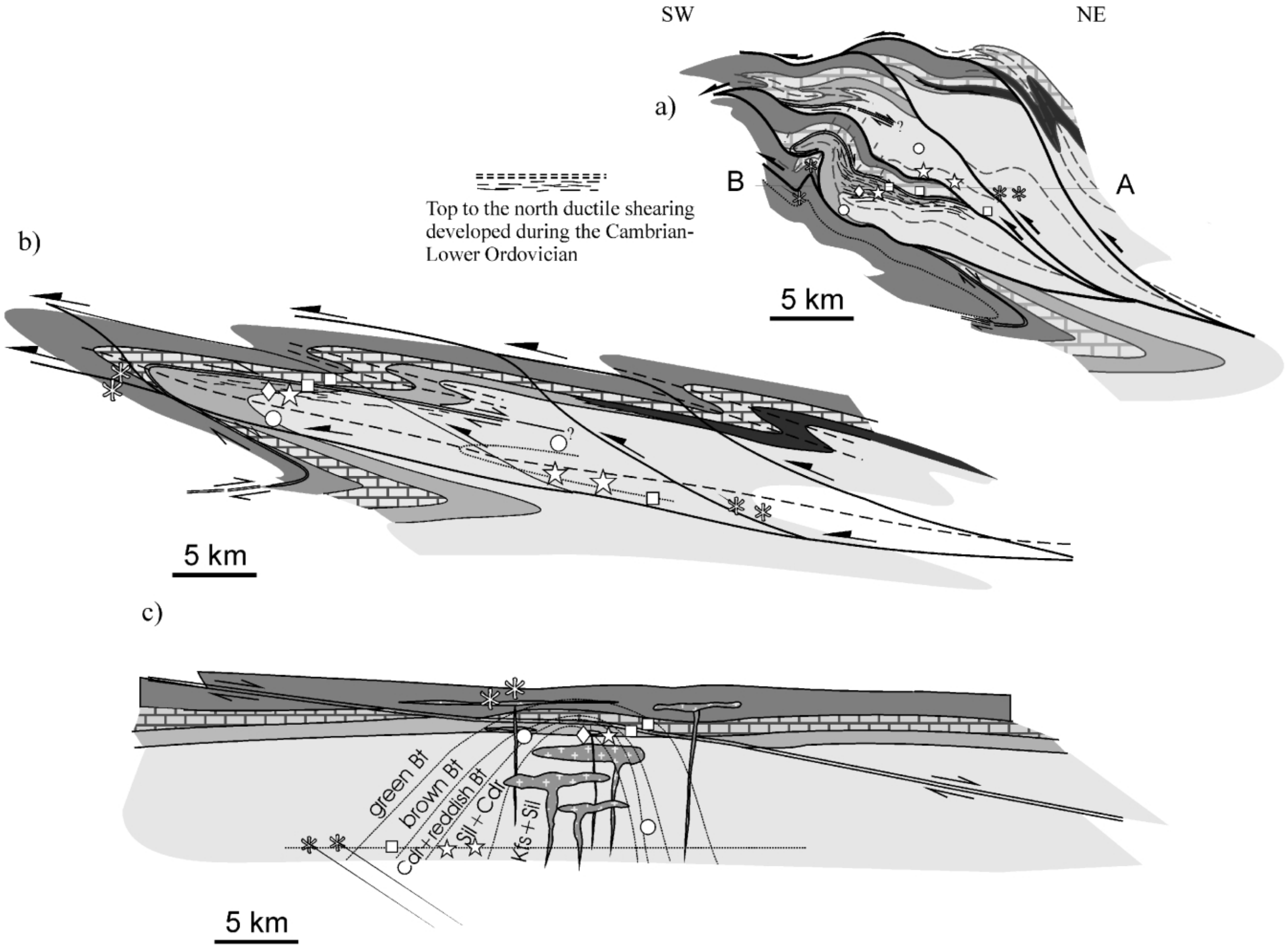

Fig. 6. (a) Cross-section of the Valuengo area (see map and legend in Fig. 2). Plutons have been removed in order to simplify the picture. The index minerals depicted in Fig. 2 have been projected on the structure (symbols). (b) Partial restoration of the cross-section, showing the structure before thrusting and late folding. (c) Complete restoration of the Variscan structures, showing the Valuengo area in Cambro-Ordovician times. The position of the different mineral associations in this approximate restoration indicates the limited extension of the metamorphic area.

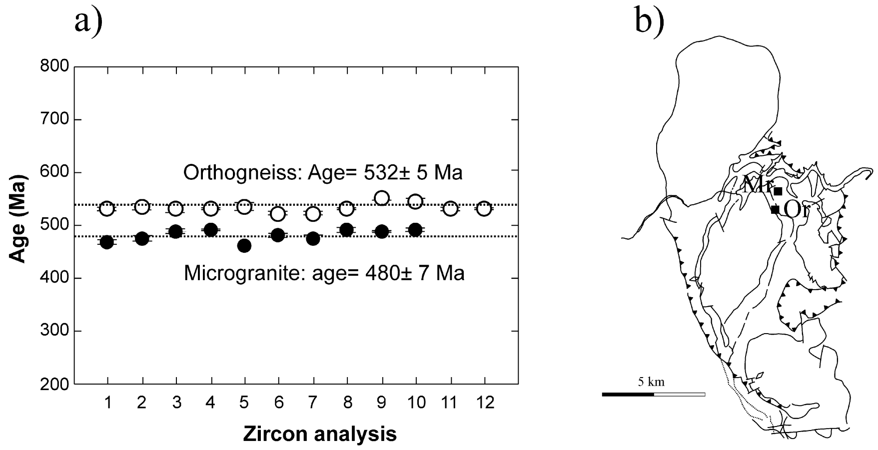

Fig. 7. (a) Single-zircon stepwise ^{207}Pb/^{206}Pb ages of a orthogneiss and a microgranite of the Valuengo area. (b) Location of the orthogneiss (Or) and the microgranite (Mr).

204/206 mass-ratio was monitored to detect and, if necessary, correct the common lead. Once this first analysis was finished, a new analytical cycle (hereafter called step) started by heating the zircon on the evaporation filament to higher temperatures than in the previous step and analysing on the ionization filament as before. The procedure continued until all the Pb was exhausted from the zircon. The number of steps depends on the size and Pb content of each zircon. Measurements with ^{204}Pb/^{206}Pb higher than 0.001 or standard errors (SE) on ^{207}Pb/^{206}Pb higher than 0.8% at the 2σ level were rejected.

The ages obtained by means of that analytical technique were 532 ± 5 Ma for the orthogneiss, and 480 ± 7 Ma for the microgranite (Fig. 7). The orthogneiss outcrops in medium-grade rocks near the migmatitic area, and its age (earliest Cambrian) is interpreted as the crystallization age of a late-Cadomian igneous protholith, deformed afterwards by the tectonothermal event. The small body of undeformed post-kinematic microgranite intrudes medium-grade rocks, and the age obtained indicates that its crystallization ocurred during Early Ordovician times, marking perhaps an upper limit for the tectonometamorphic event recorded in the Valuengo area. Actually, the microgranite must be seen as a late product of the tectonometamorphic event.

4. Correlation to the Monesterio metamorphic area

The structural restoration of the Valuengo area (Fig. 6) shows that metamorphism is restricted to a relatively narrow band of rocks. However, along the NW–SE direction metamorphism reaches at least the Monesterio area (Fig. 1b), which shows significant tectonometamorphic similarities to the Valuengo area. A high-grade metamorphic NW–SE band outcrops just north of Monesterio (Fig. 8), which is made up of migmatites, gneisses, schists, small anatectic granitic bodies, and intercalations of amphibolites and black quartzites (Eguíluz, 1987). These high-grade rocks correlate with the schists, metagreywackes, amphibolites and black quartzites of the Upper Proterozoic Serie Negra formation, usually presented as low-grade rocks.

4.1. Main deformation in the Monesterio area rocks

A top-to-the-north syn-metamorphic mylonitic foliation is developed in the Monesterio area (Fig. 3e), which we correlate with the foliation described in Valuengo since it shows identical features (S'_m). This foliation is clearly simultaneous with the migmatization, given that it is common to find differentiated veins cutting S'_m and others affected by that foliation (Fig. 3f). S'_m is NW–SE striking and dips mainly to the NE (Fig. 9a); it is commonly marked by very thin quartz lenses whose stretching is the expression of a strong deformation (Fig. 3e). On the S'_m planes, a NE plunging lineation is found (Fig. 9b), which is typically defined by biotite grains and deformed quartz grains.

Recent structural work (Expósito, 2000) has demonstrated that the structure in this area is very similar to the Valuengo structure, since high-grade metamorphic rocks outcrop enclosed by branch lines of the same Variscan thrust-system described in Valuengo (Figs. 1b and 8). Furthermore, both S'_m and isograds are folded by a large recumbent anticline that structural mapping demonstrates is the same fold found in Valuengo, though displaced by thrusting (Expósito, 2000; Expósito et al., 2002; Figs. 6a and 10).

4.2. Metamorphism

Metamorphism in Monesterio has been described by Eguíluz (1987) as high-temperature/low-pressure metamorphism. The rocks affected by the highest metamorphic grade contain mineral assemblages characterized by andalusite, cordierite, sillimanite and K-feldspar, with estimated pressure conditions of around 250 MPa (Eguíluz, 1987).

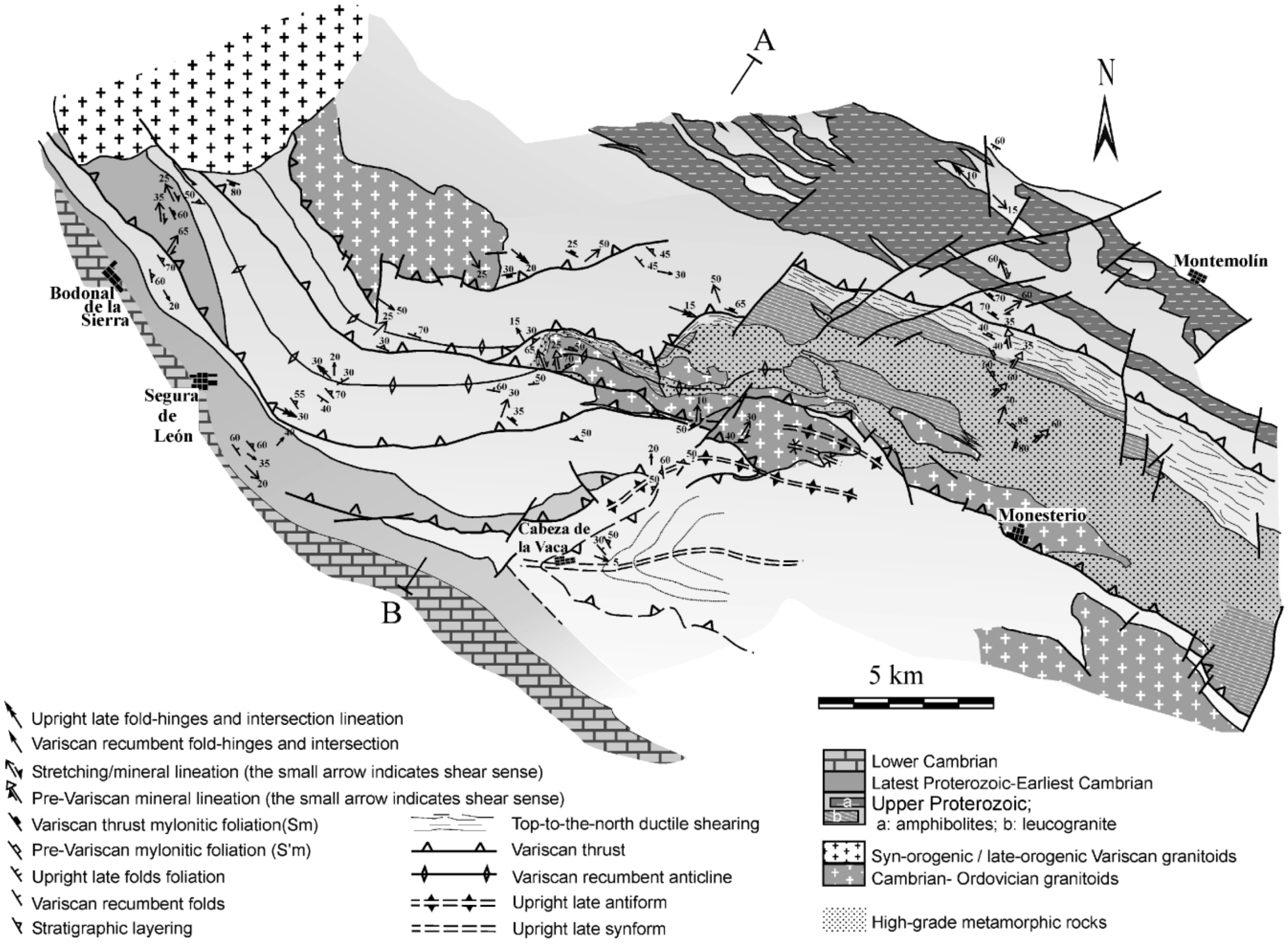

Fig. 8. Geological map of the Monesterio area (modified from Eguíluz et al.., 1980). Cross-section AB is shown in Fig. 10.

Cordierite rather than garnet is common in these Serie Negra rocks, as it happens in the Serie Negra schists that outcrop in the Valuengo area (Fig. 2).

Available geochronological dating in the Monesterio area is not very precise. For migmatites and presumably syn-metamorphic intrusive bodies, radiometric ages obtained by a number of analytical methods (Schäfer, 1990; Ochsner, 1993; Ordoñez Casado, 1998; Montero et al., 1999) show a significant variation, ranging between 500 and 530 Ma, i.e. Early to Upper Cambrian. On the other hand, two hornblende concentrates from amphibolites have given ambiguous $^{40}Ar/^{39}Ar$ age spectra; one of them (sample 9, in Dallmeyer and Quesada, 1992) suggests cooling at c. 500 Ma. Muscovites from migmatitic schists display also discordant apparent age spectra, indicating Variscan rejuvenation that affected argon systems which had initially cooled through appropriate closure temperatures sometime prior to c. 450 Ma (Dallmeyer and Quesada, 1992).

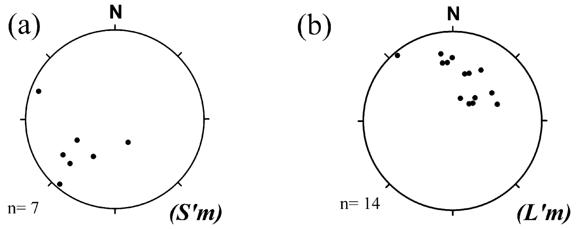

Fig. 9. Lower-hemisphere equal-area plot of: (a) the top-to-the-north mylonitic foliation (S'_m), and (b) the mineral lineation (L'_m), in the Monesterio metamorphic area.

5. Discussion and conclusion

Our study has found strong similarities between the Valuengo and Monesterio areas, which leads us to raise the following points:

1. There is a structural connection between the areas of Valuengo and Monesterio, suggesting that both belong to a narrow, NW–SE-trending band of metamorphic rocks.
2. The metamorphism is coeval with a mylonitic foliation (S'_m), never found outside of this band, which is related to ductile, top-to-the-north shearing.
3. The S'_m is folded by Variscan recumbent folds, therefore both metamorphism and top-to-the-north shearing precede Variscan thickening.

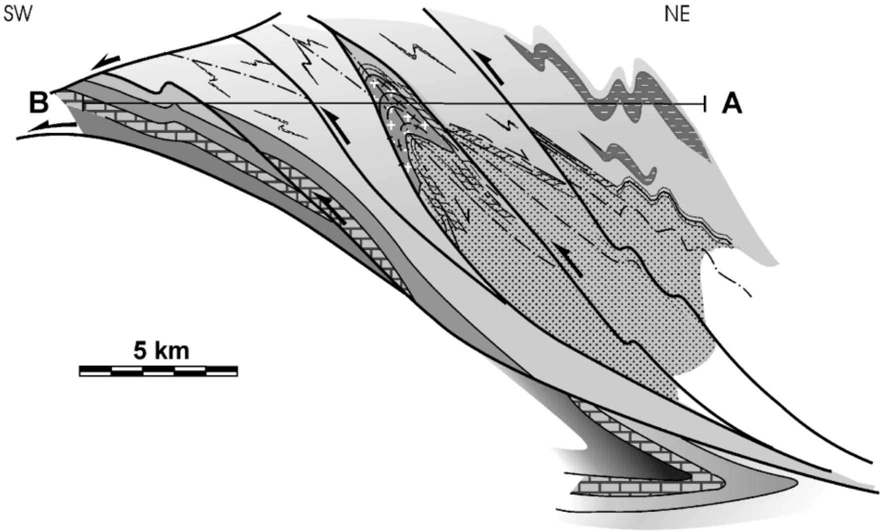

Fig. 10. Cross-section of the Monesterio area (located in Fig. 8). Note folding of metamorphic isograds and mylonitic foliation.

4. All avalaible geochronological data point to Cambrian–Early Ordovician ages for the tectonothermal event.

The Early Palaeozoic stratigraphy of the Ossa-Morena Zone gives essential data to understand the tectonic framework of this tectonometamorphic event. The Lower Cambrian terrigenous and carbonate deposits overlying the orogenic Cadomian (Vendian) magmatism, bear witness of the settling of a wide sedimentary platform in the region (Liñán and Quesada, 1990). The period of tectonic calm was, however, very short: a continental rifting, starting at the late Early Cambrian, developed during the Cambrian and Ordovician (Liñán and Quesada, 1990; Oliveira et al., 1992). The rifting had a high magmatic productivity, mainly during the Middle Cambrian, as indicated by the abundant occurrence of volcanics and plutons (Mata and Munhá, 1990; Ribeiro et al., 1992; Sagredo and Peinado, 1992; Giese and Buhn, 1993). All these data lead us to connect the deformation and metamorphism of the Valuengo and Monesterio areas with the crustal (and lithospheric) extension that occurred in the Ossa-Morena Zone during the Cambro-Ordovician rifting. In this context, the mylonitic foliation S'_m would have developed in a low-angle top-to-the-north shear zone that belonged to the extensional system responsible for the Lower Palaeozoic crustal thinning (Fig. 6c).

Metamorphism is concentrated within a narrow band, something that can be explained by an anomalously high and localized heat flow, likely to be of magmatic derivation (e.g. Wickham and Oxburgh, 1985; De Yoreo et al., 1991). The role of magma in providing heat input is not mere supposition, but based on the abundant evidence of Lower Palaeozoic magmatic activity in the Ossa-Morena Zone, as previously indicated. Therefore, magmatic accumulation likely took place at that time under the Monesterio–Valuengo areas, inducing concentrated fluid and melt flow and locally raising the heat flow. Thermal softening is another effect of melt input (Hollister and Crawford, 1986; Zulauf and Helferich, 1997), and we believe this is the reason why ductile shearing deformation and metamorphic band are closely related in space and time.

We conclude that metamorphism and deformation in the Valuengo and Monesterio areas define an extensional shear zone formed in the context of a pre-Variscan, Early Palaeozoic, continental rifting. In the Iberian Massif, this rifting was especially conspicuous in the Ossa-Morena Zone, given that this zone may have become an isolated (but not far from Gondwana) piece of crust during the Silurian times, as a final consequence of this tectonothermal event (Matte, 2001; Nysaether et al., 2002; Simancas et al., 2002). Early Palaeozoic rift-related magmatism is widespread throughout the Variscides of Europe (e.g. Dörr et al., 1992, 1998; Crowley et al., 2000; Kemnitz et al., 2002), and the high magmatic productivity of that rifting has been related to the effects of an underlying mantle plume (Crowley et al., 2000; Floyd et al., 2000). In spite of this, there are very few reports on the tectonometamorphic effects of this event (Weber, 1984; Kröner et al., 2000), probably due to the intense Variscan overprinting.

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