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From the Cadomian orogenesis to the Early Palaeozoic Variscan rifting in Southwest Iberia

La Orogenia Cadomiense y el rifting del Paleozoico Inferior en el Sudoeste de Iberia

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Abstract

The imprint of the Cadomian orogeny in SW Iberia has been a controversial issue over the last two decades. At present, the amount of geological, geochronological and geochemical data available enable one to envisage the most relevant features of the Cadomian orogenesis in SW Iberia. The Cadomian imprint mostly consists of a widespread, though not very voluminous, calc-alkaline, Upper Vendian magmatism, which has been related to a subduction zone. Locally, in the Peraleda del Zaucejo outcrop, low-grade metamorphism and a foliation of Late Precambrian age are preserved in Upper Proterozoic rocks. This is not the case in most of the Ossa-Morena Zone, where km-scale recumbent folds and thrusts have been described affecting both the Upper Proterozoic rocks and the overlying Palaeozoic succession and giving rise to the main penetrative foliation in both Precambrian and Palaeozoic rocks. Drawing on stratigraphic and geochronological data, we claim that the Cadomian orogenic events must have occurred in Late Proterozoic times, not entering the Cambrian period as proposed by other researchers. As for the magmatism, which shows an apparent continuity from Late Proterozoic to Early Cambrian, we postulate that lowermost Palaeozoic granitoids were generated in the context of a rifting process related to the beginning of the Variscan cycle. This Early Palaeozoic rifting is very well attested by the stratigraphic record, which shows a transition from a quiet carbonate platform in Early Cambrian times to terrigenous sediments with tholeiitic-alkaline volcanics in Middle Cambrian times. Thus, the Early Cambrian can be argued to be a transient stage of tectonic quiescence between the end of the Cadomian orogeny and the beginning of the pre-Variscan rifting in Early-Middle Cambrian times. Within this same context of rifting, we also place the medium- to high-grade – low-pressure metamorphism in the Valuengo and Monesterio areas. In these areas, there is a top-to-the-north mylonitic and synmetamorphic foliation which is folded by the Variscan structures and seems to be Cambrian in age, thus being interpreted as another record of the pre-Variscan rifting. The Ossa-Morena Zone may well have become an isolated continental block in Silurian times as a final result of the Early Palaeozoic rifting.

Keywords: Cadomian orogeny, Variscan orogeny, pre-Variscan rifting, southwest Iberia, Ossa-Morena Zone

Resumen

La intensidad y la duración de la Orogenia Cadomiense en el sudoeste de Iberia han sido temas controvertidos. El magmatismo calcoalcalino del Vendiense superior, que se encuentra ampliamente representado en la Zona de Ossa Morena, es el efecto orogénico cadomiense más significativo. Además, en las rocas del Proterozoico superior que afloran en Peraleda del Zaucejo (sur de la Zona Centroibérica) se ha establecido firmemente la existencia de foliación y metamorfismos tardiprecámbricos. En la Zona de Ossa Morena, sin embargo, la deformación penetrativa de las rocas precámbricas parece corresponder casi exclusivamente a pliegues y cabalgamientos de edad varisca. En conjunto, la intensidad de la orogenia cadomiense en el sudoeste de Iberia es, como en el resto del Macizo Ibérico, moderada. Los datos geocronológicos existentes aparentan la existencia de un magmatismo initerrumpido desde el Proterozoico superior hasta el Ordovícico; sin embargo, se sugiere que tal continuidad no es real. Del análisis de los datos estratigráficos se deduce que la orogenia cadomiense se habría desarrollado exclusivamente en el Proterozoico terminal, siendo el Cámbrico inferior un período de transición entre el ciclo orogénico cadomiense y el ciclo varisco. Desde el Cámbrico Inferior alto, se desarrolló en la Zona de Ossa Morena el rifting pre-varisco, cuyo reflejo estratigráfico es la sustitución de carbonatos de plataforma (Cámbrico Inferior) por sedimentos terrígenos y rocas volcánicas. Localmente, el rifting pre-varisco originó una fábrica milonítica y un metamorfismo de grado medio-alto, como el que se observa en Valuengo y en Monesterio. Como consecuencia del rifting cambro-ordovícico, la Zona de Ossa-Moreno debió de ser en el Silúrico un fragmento aislado de corteza continental.

Palabras Clave: orogénesis cadomiense, orogénesis varíscica, rifting pre-varíscico, Iberia sudoccidental, zona Ossa Morena

1. Introducción

The transition between the Cadomian and the Variscan orogenic cycles occurred between the very late Precambrian and the earliest Palaeozoic. Drawing on the basis of the research findings presented in several papers in this monograph, we will be basically concerned in this paper with the following issues:

a) The review of the Cadomian-Variscan transition from a tectonic perspective.

b) A detailed discussion of the earliest magmatic and tectono-metamorphic events of the Variscan cycle, which are related to an Early Palaeozoic rifting (preorogenic evolution).

However, in order to properly deal with these questions, we consider it necessary to take into account a number of subjects which inevitably impinge on the interpretation of the Cadomian orogeny in SW Iberia, such as: a) the controversy (e.g., Abalos *et al.*, 1991; Azor *et al.*, 1993) on the assignment of tectono-metamorphic events recorded in rocks of southwest Iberia to the Cadomian or to the Variscan orogenies; b) the intense Variscan deformation resulting in obliteration, thus making it difficult to interpret earlier events. On the other hand, even though the main focus of our discussion will be on the Ossa-Morena Zone, we will refer frequently to southwest Iberia because this broader context, including the southern Central Iberian Zone, is more appropriate to tackle some topics.

Some of our interpretations will probably conflict with others presented in this monographic volume, thus reflecting the still controversial state of the art on the issues at hand here.

2. The Cadomian orogeny in southwest Iberia. A brief discussion

There have been different appreciations of the Cadomian imprint in southwest Iberia. For some authors, the penetrative deformation and metamorphism affecting the Upper Proterozoic rocks (the Serie Negra) and the rocks of the Badajoz-Córdoba Shear Zone (the boundary between the Ossa-Morena Zone and the Central Iberian Zone) are due to the Cadomian orogeny (Garrote, 1976; Pérez Lorente, 1977; Chacón, 1979; Eguiluz, 1987; Quesada, 1991; Abalos *et al.*, 1991; Eguiluz *et al.*, 2000). For other researchers, the Variscan evolution caused the main tectono-metamorphic imprint in these rocks (Bard, 1967; Vegas, 1971; Azor *et al.*, 1993, 1994; Martínez Poyatos *et al.*, 1995; Simancas *et al.*, 2001; Expósito *et al.*, 2002). Fortunately, there are at least some data that can be unanimously taken as evidence for the existence of the Cadomian orogeny in southwest Iberia; these data are summarized below:

a) The Serie Negra outcropping in the Peraleda del Zaucejo anticline, in the southernmost part of the Central Iberian Zone, (Fig. 1) shows a main foliation and a low-grade metamorphism which must have developed before the Variscan orogeny, at Vendian time (Capdevila *et al.*, 1971; Blatrix and Burg, 1981; Dallmeyer and Quesada, 1992). The Variscan imprint is here restricted to a crenulation cleavage affecting the main pre-Variscan foliation. The crenulation cleavage in the Precambrian rocks passes, as a rough slaty cleavage, to the overlying Ordovician rocks.

b) North of the Pedroches batholith, also in the southern part of the Central Iberian Zone (Fig. 1), the Serie Negra does not outcrop. Instead, lying unconformable under the Lower Ordovician, the Alcudian is generally found (Bouyx, 1970). An intra-Alcudian unconformity has been described in some localities, separating an Upper from a Lower Alcudian (Ortega and González Lodeiro, 1986; Palero, 1993; Martínez Poyatos, 1997; Pieren and García Hidalgo, 1999). There is neither a penetrative deformation nor a metamorphic gap associated with this unconformity, which has been considered to reflect Cadomian moderate folding.

c) The calc-alkaline magmatism in the uppermost part of the Serie Negra and in the Malcocinado Formation, as well as a number of granitoids of Vendian/earliest Cambrian age, are usually interpreted as arc-related magmatic products of a Cadomian subduction (Sánchez Carretero *et al.*, 1989, 1990; Almarza, 1996; Martínez Poyatos, 1997; Pin *et al.*, 2002).

In addition to these compelling pieces of evidence, a number of further supporting data can be taken to show that tectono-metamorphic events alleged to be Cadomian in many areas of southwest Iberia are in fact Variscan in age:

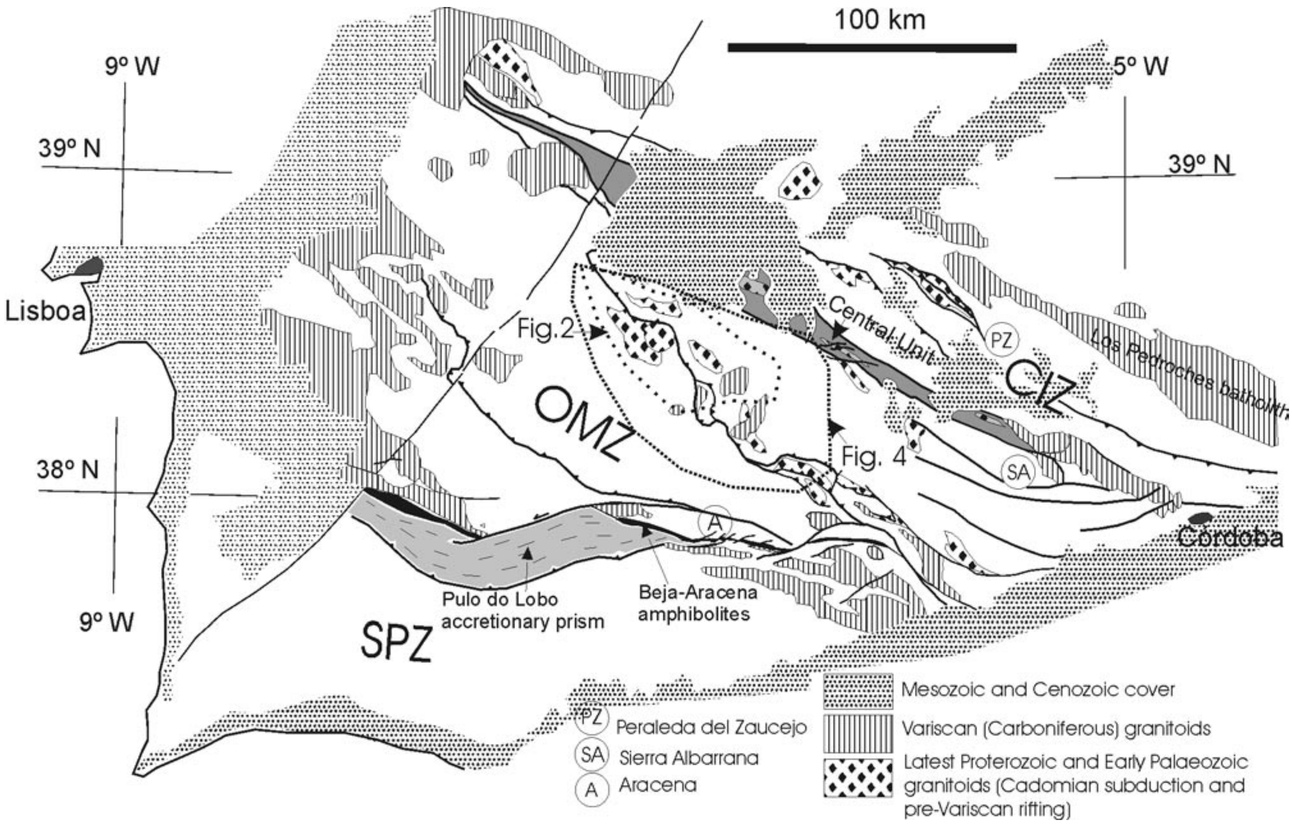

Fig. 1.- Sketch of SW Iberia, showing the location of the Central Iberian Zone (CIZ), the Ossa-Morena Zone (OMZ) and the South Portuguese Zone (SPZ), as well as their boundaries. Main plutonic bodies are depicted with two patterns in order to differentiate the Carboniferous (Variscan) plutons from the Vendian-Early Ordovician ones (Cadomian and pre-Variscan rifting).

Fig. 1.- Esquema del SO de Iberia, mostrando la localización de la Zona Centro Ibérica (CIZ), la Zona Ossa Morena (OMZ) y la Zona Surportuguesa (SPZ), asi como sus límites. Los plutones más importantes se representan con dos tramas distintas, para diferenciar las intrusiones carboniferas (Varíscico), de las de edad Vendiense-Ordovícico Inferior (Cadomiense y rifting pre-Varíscico).

a) In the Sierra Albarrana region (Fig. 1), rocks previously attributed to the Precambrian (Delgado Quesada, 1971; Garrote, 1976; Quesada, 1991) contain Phanerozoic trace fossils (Marcos *et al.*, 1991). As a consequence, the putative Precambrian deformation and metamorphism affecting these rocks cannot be but Variscan in age (Azor *et al.*, 1992). Moreover, the Variscan age has been independently confirmed by radiometric $^{40}Ar/^{39}Ar$ dating (Dallmeyer and Quesada, 1992).

b) In the Badajoz-Córdoba Shear Zone, redefined as the Central Unit (Fig. 1) by Azor *et al.* (1994) (this name will be invoked henceforth in the remainder of this paper), the main deformation and metamorphism have been attributed to the Cadomian orogeny by Quesada (1991) and Abalos *et al.* (1991). However, the Palaeozoic radiometric ages of many orthogneissic bodies, as well as some of the amphibolitic rocks, have demonstrated that the high- to medium-grade tectono-metamorphic evolution affecting these rocks is Variscan in age (see Central Unit; Table 1). This seems to apply also to the early high-pressure metamorphism because the radiometric ages available on this event, although poorly consistent among them, are Variscan too (Schäfer *et al.*, 1991; Ordóñez Casado, 1998). Drawing on these radiometric data as well as on the structural evidence available, we conclude the Central Unit to be a major tectonic boundary during the Variscan evolution, separating the Ossa-Morena Zone and the Central Iberian Zone continental blocks (Azor *et al.*, 1994; Simancas *et al.*, 2001). Recently, amphibolites with oceanic signature have been attested in this boundary (Gómez-Pugnaire *et al.*, 2003).

c) Most of the foliations in the Serie Negra rocks of the Ossa-Morena Zone have also been attributed to the Cadomian orogeny by some authors (Eguiluz, 1987; Quesada, 1991). However, in all the Ossa-Morena Zone and in a strip along the southern border of the Central Iberian Zone, great recumbent folds and thrusts have been mapped (Vauchez, 1975; Martínez Poyatos *et al.*, 1995; Expósito *et al.*, 2002) affecting both the Serie Negra and the overlying Palaeozoic succession. These Variscan folds give rise to the main penetrative foliation (which in some cases may be the only one) in both Precambrian and Palaeozoic rocks. Certainly, the tectonic fabric is often more compli-

GEOCHRONOLOGICAL DATING OF IGNEOUS PROTOLITHS IN SW IBERIA

Central Unit

La Cardenchosilla amphibolite	611 +17 -11	U-Pb zircons	Schäfer (1990)
La Cardenchosilla amphibolite	566±9	SHRIMP monozircons (core)	Ordóñez (1998)
Las Mesas amphibolite	596±14	SHRIMP monozircons (core)	Ordóñez (1998)
Los Pocillosamphibolite	483±13	SHRIMP monozircons (core)	Ordóñez (1998)
Arronches amphibolite	490±17	U-Pb zircons	Ordóñez (1998)
Higuera de Llerena gneiss	489 ±10	Rb-Sr whole rock	Azor et al. (1995)
Riscal gneiss	496 ±14	Rb-Sr whole rock	Azor et al. (1995)
Higuera de Llerena gneiss	460 ±4	SHRIMP monozircons (core)	Ordóñez (1998)
Arroyo Argallón gneiss	525 ±13	SHRIMP monozircons (core)	Ordóñez (1998)
Arroyo Argallón gneiss	509±8	SHRIMP monozircons (core)	Ordóñez (1998)
Arroyo Argallón leucosome	514±8	SHRIMP monozircons (core)	Ordóñez (1998)
Arronches migmatitic gneiss	465 ±14	SHRIMP monozircons (core)	Ordóñez (1998)
Almendralejo orthogneiss	475 ±9	Rb-Sr whole rock	Garcia Casquero et al. (1985)
Almendralejo orthogneiss	474 +9 -6	U-Pb zircons	Ochsner (1993)
Almendralejo orthogneiss	471 +16 -10	U-Pb zircons	Ochsner (1993)
Aceuchal orthogneiss	477 ±4	U-Pb zircons	Ochsner (1993)
Aceuchal orthogneiss	474 +7 -6	U-Pb zircons	Ochsner (1993)
Ribera del Fresno orthogneiss	423 ±8	Rb-Sr whole rock	Garcia Casquero et al. (1985)
Ribera del Fresno orthogneiss	556 +159 - 65	U-Pb zircons	Ochsner (1993)
Ribera del Fresno orthogneiss	542 +80 -47	U-Pb zircons	Ochsner (1993)
Ribera del Fresno orthogneiss	475±7	SHRIMP monozircons (core)	Ordóñez (1998)
Ribera del Fresno orthogneiss	470 ; 475	SHRIMP monozircons	Schäfer (1990)
Las Minillas orthogneiss	474	SHRIMP monozircons	Schäfer (com. pers., 1993)

Southern border of the Central Iberian Zone

Plutonic cumulate in Mérida	554±4	Sm/Nd (grt, anf, rocatotal)	Bandrés et al. (2000)
Mina Afortunada amphibolite	554±16	SHRIMP monozircons(core)	Ordóñez (1998)
Valle de la Serena granite	573±14	SHRIMP monozircons	Ordóñez (1998)
Mina Afortunada orthogneiss	507 +9 -7	U-Pb zircons	Ochsner (1993)
Mina Afortunada orthogneiss	528 ±6	SHRIMP monozircons	Ordóñez (19989
Portalegre orthogneiss	466 ±12	Rb-Sr	Priem et al. (1970)
Figueiró dos Vinhos granite	499±9	K-Ar muscovite	Pereira & Macedo (1983)
Figueiró dos Vinhos granite	514±9	K-Ar biotite	Pereira & Macedo (1983)
Pedrogao Grande granite	523 ±10	K-Ar moscovite	Pereira & Macedo (1983)
El Escribano granitoid	452±22	K-Ar whole rock	Bellon et al. (1979)
Varas-Guadalbarbo basalts	334±17;348±17	K-Ar	Bellon et al. (1979)
Pedroches granite	295±15	K-Ar whole rock	Bellon et al. (1979)
Pedroches granite	300±6	Rb-Sr	Fernández et al. (1990)
Pedroches granite	307±2	Rb-Sr	Cueto et al. (1991)
Pedroches granite	310±12	Rb-Sr	Larrea et al. (1999)
Santa Elena granite	331±34	Rb-Sr	Larrea et al. (1999)
Los Arenales granite	316±16	K-Ar whole rock	Bellon et al. (1979)
Los Arenales granite	332±17	K-Ar biotita	Bellon et al. (1979)
Alburquerque granite	284±5	K-Ar	Penha & Arribas (1974)
Nisa granite	290 ; 309	Rb-Sr	Mendes (1968)

Ossa-Morena Zone

Ahillones granite	552±10	SHRIMP monozircons (core)	Ordóñez (19989
Ahillones granite	585±5	U-Pb	Schäfer (1990)
Mosquil tonalite	544 +5.7-4.7	U-Pb	Oschner (1993)
Bodonal tufs	525 ±		Gebauer (com.pers., 1993)
Bodonal tufs	514±9	SHRIMP monozircons (core)	Ordóñez (1998)
Barcarrota granite	505 ±5	Rb-Sr	Galindo et al. (1990)
Barcarrota granite	501+4-3	U-Pb zircons	Ochsner (1993)
Barcarrota diorite	503+5-2	U-Pb zircons	Ochsner (1993)
Táliga granite	525 ±2.5	Rb-Sr	Galindo et al. (1990)
Táliga granite	525±1	U-Pb monazite	Ochsner (1993)
Salvatierra de los Barros granite	516+9-3	U-Pb monazite	Ochsner (1993)
Tablada granite	511±8	U-Pb monazite	Ochsner (1993)
Tablada granite	512±8	U-Pb xenotime	Ochsner (1993)
Tablada granite	494±18	Rb-Sr whole rock	Quesada (umpubl., recalculated by Ochsner, 1993)
Castillo granite	498+10-7	U-Pb zircón	Ochsner (1993)
Castillo granite	502 ±8	Kober method	Salman (2002)
Valverde- Almendral granite	450±12; 481±10	K-Ar	Galindo y Portugal Ferreira. (1988)

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Calera de León granite	524 ±4	Kober method	Salman & Montero (1999)
El Culebrín tonalite	532 ±4	Kober method	Salman (2002)
Monesterio granodiorite	495 ±8	U-Pb en zircons	Schäfer (1990)
Monesterio granodiorite	507 ±21	apatite	Schäfer (1990)
Monesterio granodiorite	533 ±8	SHRIMP monozircons	Ordóñez (1998)
Monesterio granodiorite	527 +10-7	U-Pb xenotime	Ochsner (1993)
Monesterio granodiorite	510 ± 4	Kober method	Montero et al. (1999)
Pallares granodiorite	518±15	SHRIMP monozircons	Ordóñez (1998)
Pallares granodiorite	495+7-8	U-Pb en zircón	Schäfer (1990)
Pallares granodiorite	507 ±21	Sm-Nd	Schäfer (1990)
Monteagudo gabbro	536±11	SHRIMP monozircons	Ordóñez (1998)
Arronches amphibolite	490±17	SHRIMP monozircons	Ordóñez (1998)
Alter Pedroso alkaline pluton	482 ±16	U-Pb zircón	Lancelot & Allégret (1982)
Barreiros orthogneis (Alter do Chao)	466±10	Rb-Sr	Gonçalves & Fernandes (1973) *in* Oliveira et al. (2002)
Barreiros orthogneis (Alter do Chao)	518-45	U-Pb zircons	Oliveira et al. (2002)
Alter do Chao - Cabeço de Vide gabbros	480 ±25	K-Ar	Carrilho Lopes et al. (1993)
Alter do Chao - Cabeço de Vide gabbros	501 ±25	K-Ar	Carrilho Lopes et al. (1993)
Burguillos del Cerro diorite	335 ; 340	Ar-Ar amphibole	Dallmeyer et al. (1995)
Burguillos del Cerro diorite	338 ±1.5	U-Pb allanite	*ref. in* Casquet et al. (2001)
Burguillos del Cerro leucogranite	330 ±9	Rb-Sr	Bachiller et al. (1997)
Valencia del Ventoso pluton	339	?	*ref. in* Salman (2002)
Brovales pluton	340 ±7	Kober method	Montero et al. (2000)
North of Valuengo gabbro	342±4	Kober method	Montero et al. (2000)
Santa Olalla granodiorite	354±17	Rb/Sr	Casquet et al. (1998)
Santa Olalla granodiorite	332 ±3	Kober method	Montero et al. (2000)
Teuler granite	348 ± 4	Kober method	Montero et al. (2000)
Beja gabbro	340 ±1	Ar-Ar amphibole	Dallmeyer et al. (1993)
Beja gabbro	338±1	Ar-Ar amphibole	Dallmeyer et al. (1993)
Beja gabbro	350±4 ; 352±4	U-Pb zircons	Pin et al. (1999)
Aroche tonalite	347 +51-12	U-Pb zircons	Hoymann & Kramm (1999)
South Portuguese Zone			
El Berrocal granite	300 ±6	Rb-Sr	Quesada et al. (1989)
Gil Márquez granodiorite	330	Rb-Sr	Giese et al. (1993)
Gil Márquez granodiorite	330±3	Ar-Ar	*ref. in* Onézime et al. (2002)
Gil Márquez granodiorite	328±2	U-Pb zircons	Kramm et al. (1991)
Gil Márquez granodiorite	353±14	U-Pb zircons	De la Rosa et al. (1999)
Gabbros north of Sevilla	336±98	Rb-Sr	De la Rosa et al. (1993)
Aznalcóllar sulphide mineralization	351±8	Re-Os	Nieto et al. (2000)
Aznalcóllar sulphide mineralization	346±5	U-Pb hydrothermal zircons	Nesbitt et al. (1999)
Ignimbrites	347±1.5	U-Pb zircons	Quesada (1999)
Ignimbrites	355±5	U-Pb zircons	Quesada (1999)

Table 1. Geochronological dating of igneous protoliths in SW Iberia
Tabla 1. Dataciones geocronológicas de protolitos ígneos del SO de Iberia

cated and composite fabrics are observed that have been interpreted by some authors as being entirely Cadomian or Cadomian plus Variscan (Eguiluz, 1987; Eguiluz *et al.*, 2000). Our observations, however, can be taken to point to a Variscan origin for most of these composite fabrics, according to the following features (Expósito, 2000; Expósito *et al.*, 2002):

- The Variscan thrusts locally develop a mylonitic foliation imposed over the axial-plane foliation of recumbent folds.

- In many areas there is a (locally intense) crenulation cleavage which is axial-plane of late-Variscan upright folds.

- A more complex case involves the recognition in some restricted areas of a pre-Variscan foliation and metamorphism. This situation will be largely documented later; let us say now that we interpret it as a tectono-metamorphic event related to the preorogenic Variscan rifting, instead of a Cadomian event.

In summary, we have been unable to detect in the Upper Proterozoic rocks of the Ossa-Morena Zone a penetrative foliation related to the Cadomian deformation. We do acknowledge, nonetheless, that a Cadomian foliation can exist locally, as demonstrated in the Peraleda del Zaucejo anticline, in the southernmost part of the Central Iberian Zone.

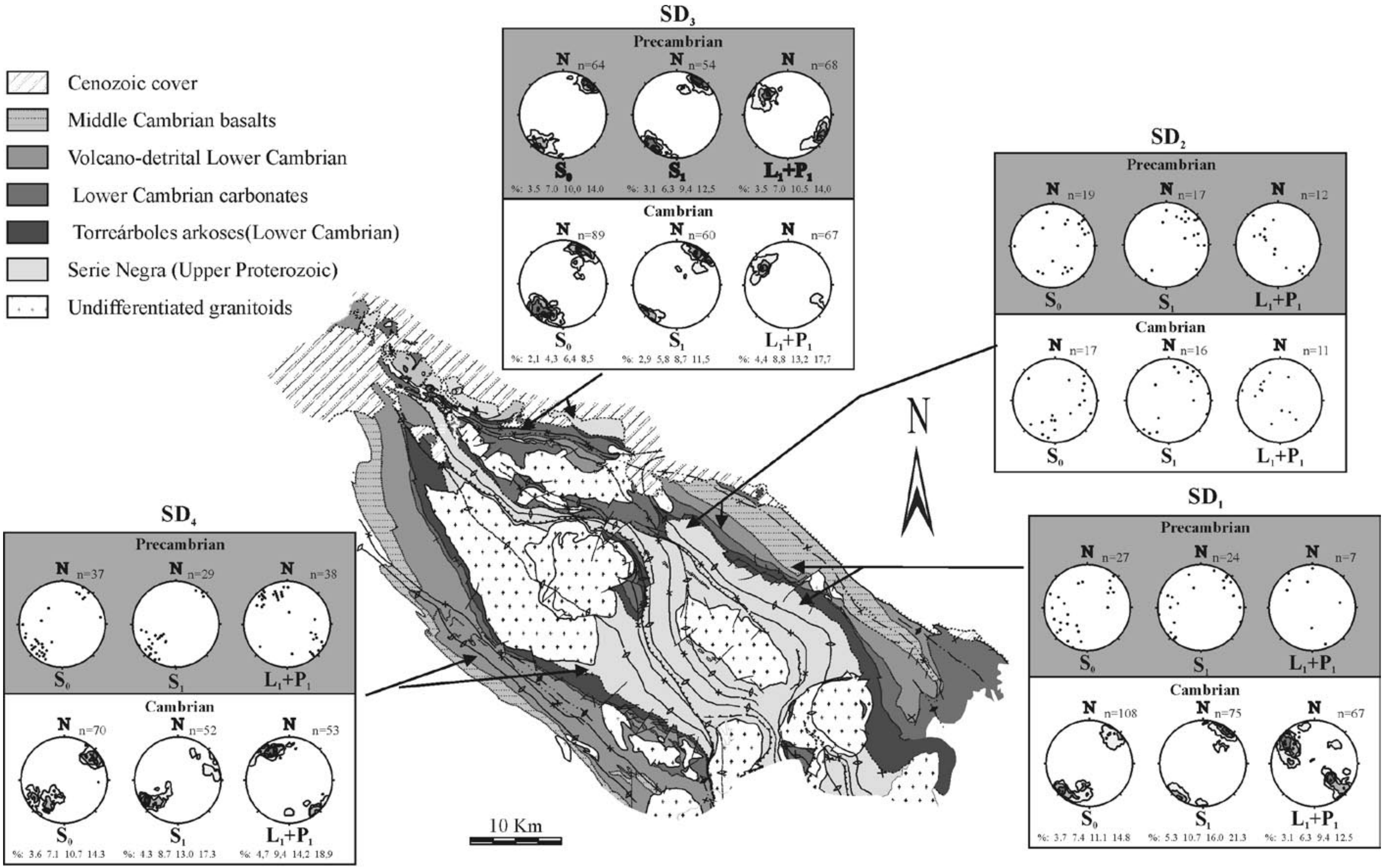


Fig. 2.- Comparative analysis of the orientation of lithologic banding (S_0), axial-plane foliation of recumbent folds (S_1), minor recumbent fold-axes (P_1) and S_0/S_1 intersection lineation (L_1), in Precambrian and Cambrian rocks of the areas indicated. Diagrams are equal-area plots.

Fig. 2.- Análisis comparativo de la orientación del bandeado litológico (S_0), la foliación de plano axial de los pliegues recumbentes (S_1), ejes de pliegues recumbentes menores (P_1), y lineaciones de intersección S_0/S_1 (L_1), en rocas cámbricas y precámbricas de las areas indicadas. Los diagramas son proyecciones equiareales.

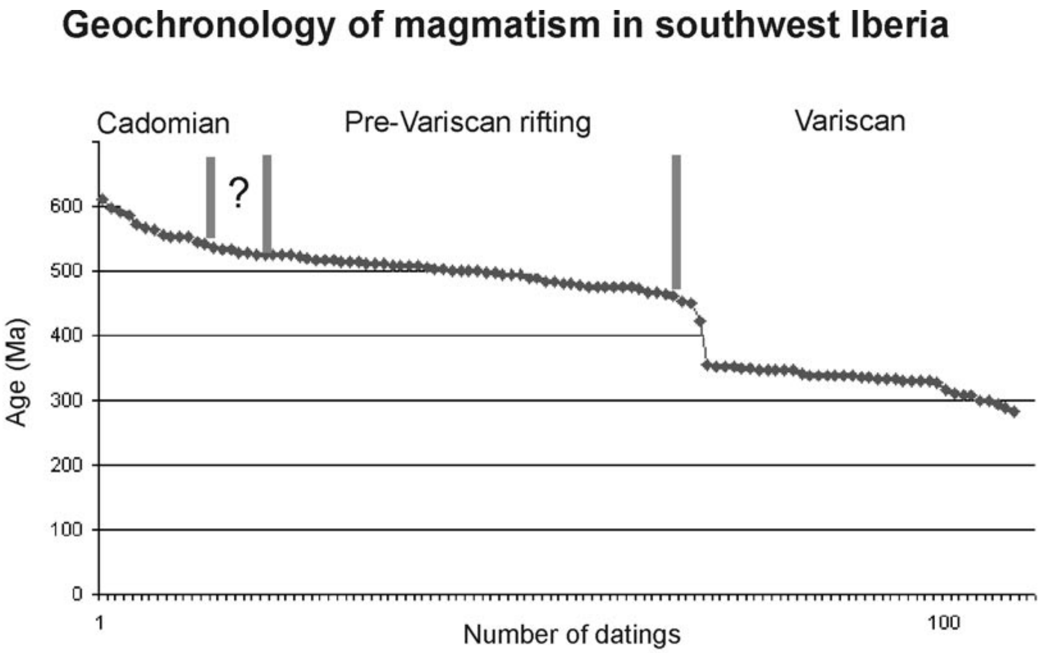


Fig. 3.- Geochronological ages of magmatism in southwest Iberia. An apparent continuity exists between the subduction-related Cadomian magmatism and the rifting-related Early Palaeozoic magmatism. See discussion in the text.

Fig. 3.- Edades geocronológicas del magmatismo en el SO de Iberia. Existe una aparente continuidad entre el magmatismo relacionado con la subducción cadomiense y el relacionado con el rifting del Paleozoico Inferior. Ver discusión en el texto.

d) In some areas of the Ossa-Morena Zone where only one foliation is visible and metamorphism is low, a detailed microstructural analysis has been carried out (Fig. 2), yielding the following results (Expósito, 2000):

- The foliation passes in continuity from the Serie Negra to the overlying rocks.

- There is no metamorphic gap between the Serie Negra and the Cambrian rocks.

- The b-lineation (intersection lineation and axes of microfolds) has the same orientations in both the Serie Negra and the Cambrian rocks (Fig. 2).

Therefore, in the areas analyzed even the existence of a marked angular unconformity between the Serie Negra and the overlying Cambrian rocks is doubtful.

e) Finally, foliation in pebbles of Lower Cambrian conglomerates of the Ossa-Morena Zone has been cited as evidence of intense Cadomian orogenic activity (Apalategui *et al.*, 1990; Abalos *et al.*, 1991). Certainly, we do not discard completely such argument, but we would like to highlight the lack of any adequate description which includes both outcrop location and the illustration of the relationship between pebbles and matrix. Our observations in Lower Cambrian conglomerates have thus far indicated that foliation affecting the pebbles cannot be considered different from the foliation in the matrix (Expósito, 2000).

From all of these data, we envisage a moderate imprint of the Cadomian orogeny in southwest Iberia. The only conspicuous manifestation of this orogeny is the widespread, though not very thick, calc-alkaline, Upper Vendian magmatism. In northern Iberia, the Cadomian imprint is perhaps even less intense: the Precambrian/Cambrian boundary is an unconformity that does not involve any pre-Palaeozoic foliation (Julivert and Martínez García, 1967; Pérez Estaún, 1978), although recent observations point to the existence of foliated pebbles in Lower Cambrian conglomerates (Abalos, 2001), there also being a meager volume of calc-alkaline magmatism (Fernández-Suárez *et al.*, 1998). The Andean-type interpretation of the Cadomian orogen (Murphy and Nance, 1991; Fernández Suarez *et al.*, 1998; Linneman, 1999) is coherent with the restricted deformational imprint and the comparatively important magmatic activity observed in southwest Iberia.

3. Timing of the transition from the Cadomian to the Variscan orogenic cycle

Some authors have suggested that the Cadomian orogeny in Iberia lasted until the end of the Cambrian period (Ochsner, 1993; Eguiluz *et al.*, 2000; Bandrés *et al.*, 2002), while other authors favor the existence of a fuzzy stage of unclear tectonic meaning, transitional between the Cadomian and the Variscan rifting (Ordóñez Casado, 1998).

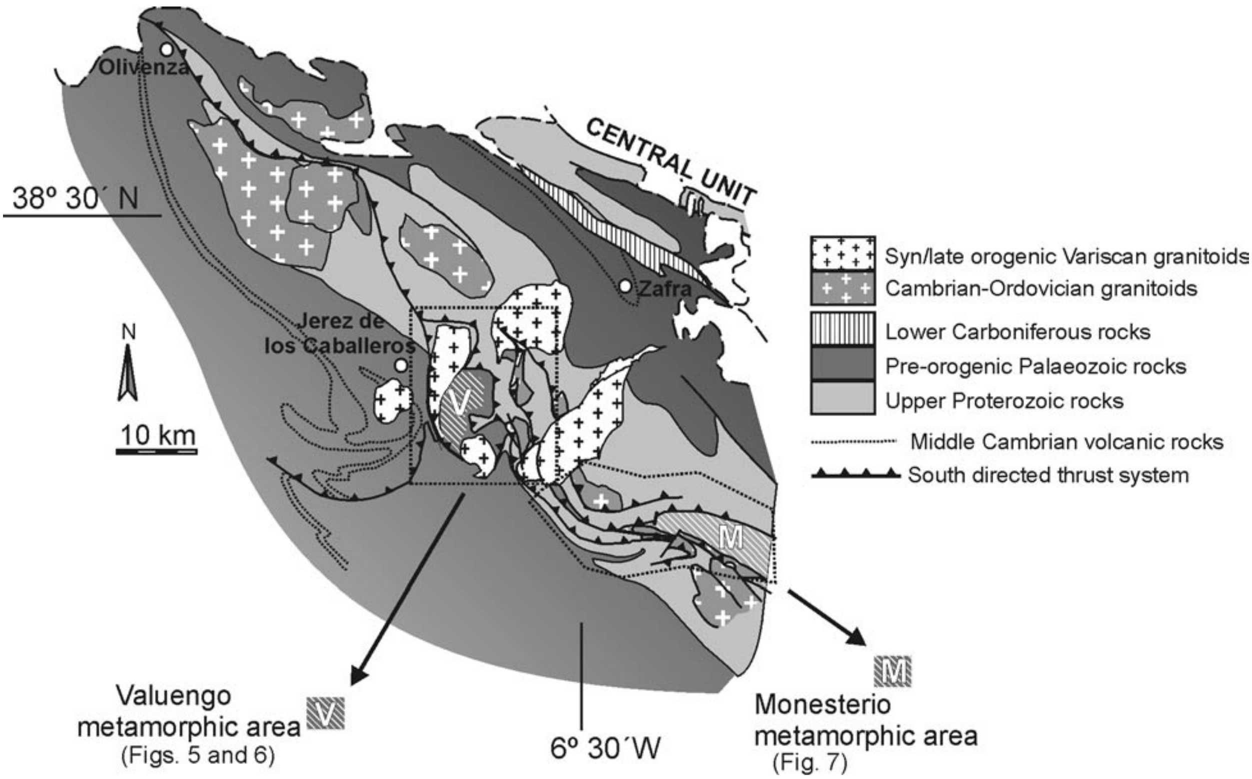


Fig. 4.- Geological and geographical location of the Valuengo and Monesterio metamorphic areas.
Fig. 4.- Localización geológica y geográfica de las áreas metamórficas de Valuengo y Monesterio

We contend that the transition between these two orogenic cycles can be defined with some precision and does not correspond with the above suggestions. We ground our interpretation on the following data:

a) Unconformities give a first figure but are not adequate to precisely determine the end of the Cadomian cycle:

- In the Peraleda del Zaucejo anticline, where Cadomian unconformity is clear, there is, however, a large gap between the Vendian age of the Serie Negra (Schäffer *et al.*, 1993; Ordóñez, 1998) and the Lower Ordovician age of the overlying quartzites. Actually, this long time-span results from the superposition of a Cadomian unconformity and a younger one at the base of the Ordovician, the latter being characteristic of all the Central Iberian Zone.

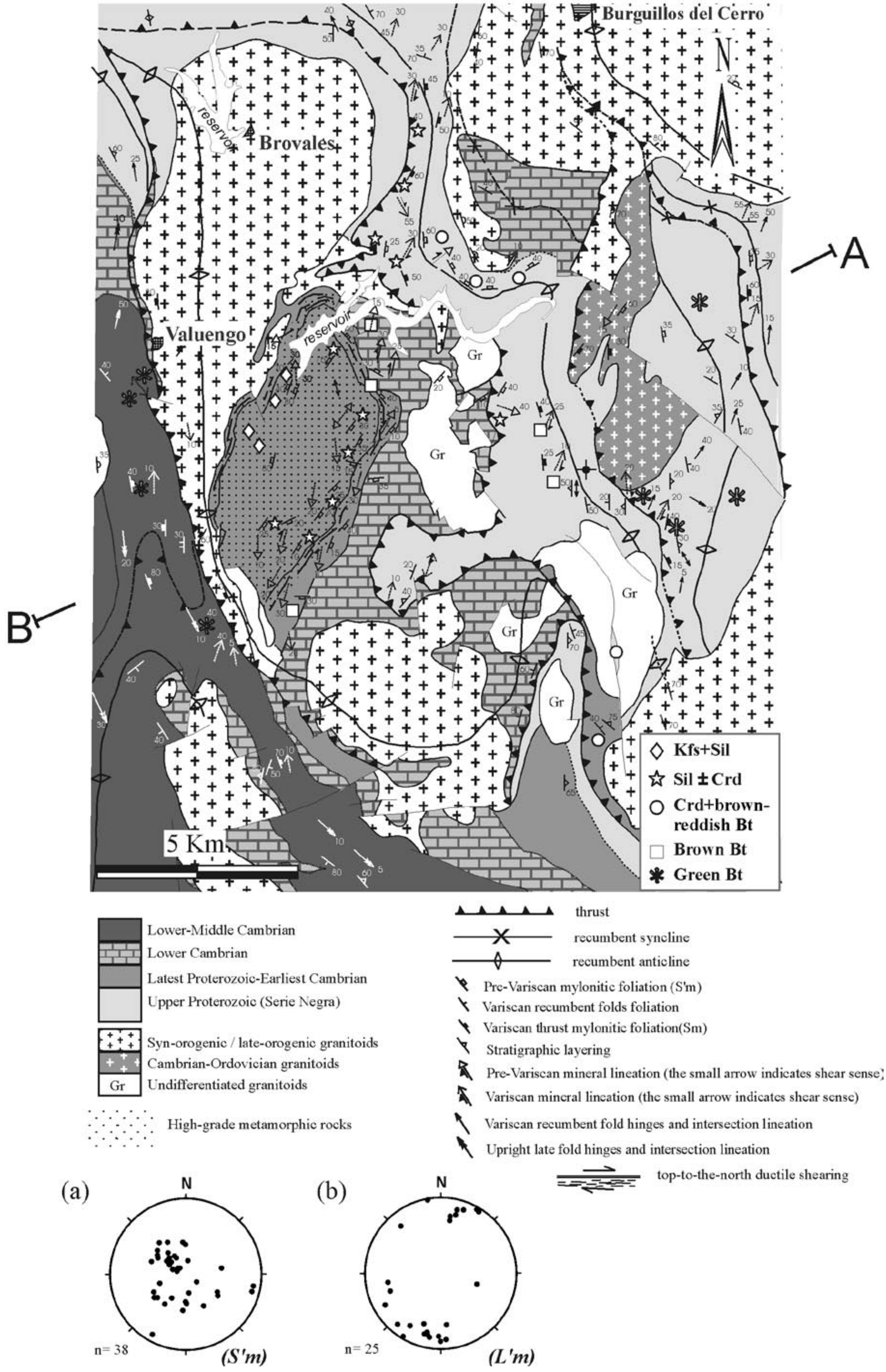
- The intra-Alcudian unconformity does not involve an important time gap and, should it be taken as the final manifestation of the Cadomian orogeny, it would be potentially more precise. Nevertheless, the age of the Upper and Lower Alcudian sequences is not well established. For the Upper Alcudian, an earliest Cambrian age seems quite probable, while the Lower Alcudian can be Vendian in age (Vidal *et al.*, 1994; García Hidalgo, 1993; Pieren and García Hidalgo, 1999). On this ground, the end of Cadomian orogeny could be latest Vendian in age.

b) There are very few radiometric data on the Cadomian metamorphism, because it has been clearly detected only in the Peraleda del Zaucejo locality (Fig. 1). The metamorphic ages there, in the range 560 - 550 Ma, i.e., the top of Vendian (Blatrix and Burg, 1981; Dallmeyer and Quesada, 1992), are consistent with the age proposed for the intra-Alcudian unconformity.

Younger than the 560-550 Ma metamorphic event indicated above are the 507 and 528 Ma radiometric ages of the Mina Afortunada orthogneiss (Oschner, 1993; Ordóñez Casado, 1998). However, we do not endorse the interpretation presented in Abalos *et al.* (1991) and Eguiluz *et al.* (2000), who consider this outcrop as a Cadomian anatectic dome. Instead, drawing on the basis of evidence from field

Fig. 5.- (Opposite page) Geological map of the Valuengo metamorphic area (modified from Fernández Carrasco et al., 1981 and Expósito, 2000). In the lower part, two equal-area plots show the orientation of the mylonitic foliation (S'_m) and the associated mineral lineation (L'_m), formed during the top-to-the-north tectono-metamorphic extensional event.

Fig. 5.- (Página siguiente) Mapa geológico del área metamórfica de Valuengo (modificado de Fernández Carrasco et al., 1981 y Expósito, 2000). En la parte inferior, dos proyecciones equiareales muestran la orientación de la foliación milonítica (S'_m) y de la lineación mineral asociada (L'_m), generadas durante el evento tectónico extensional con desplazamiento con sentido techo-al-norte.


Burguillos del Cerro
N
Brovales
reservoir
Valuengo
Gr
A
B
Kfs+Sil
Sil ± Crd
Crd+brown-reddish Bt
Brown Bt
Green Bt
5 Km
Lower-Middle Cambrian
Lower Cambrian
Latest Proterozoic-Earliest Cambrian
Upper Proterozoic (Serie Negra)
Syn-orogenic / late-orogenic granitoids
Cambrian-Ordovician granitoids
Undifferentiated granitoids
High-grade metamorphic rocks
thrust
recumbent syncline
recumbent anticline
Pre-Variscan mylonitic foliation (S'm)
Variscan recumbent folds foliation
Variscan thrust mylonitic foliation(Sm)
Stratigraphic layering
Pre-Variscan mineral lineation (the small arrow indicates shear sense)
Variscan mineral lineation (the small arrow indicates shear sense)
Variscan recumbent fold hinges and intersection lineation
Upright late fold hinges and intersection lineation
top-to-the-north ductile shearing
(a)
(b)
n= 38
(S'm)
n= 25
(L'm)

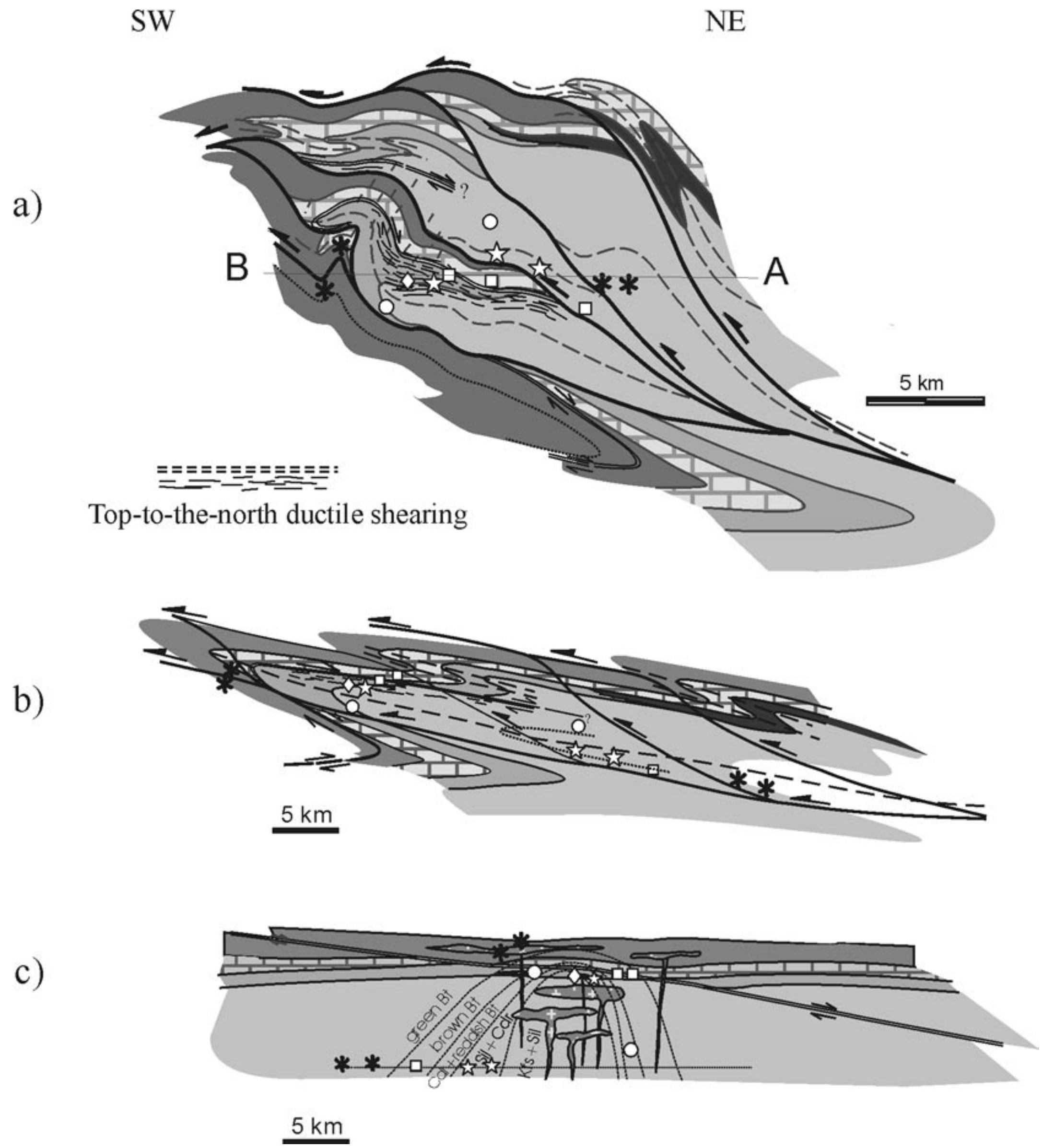


Fig. 6.- a) Geological cross-section of the Valuengo area. b) Partially restored cross-section, after removal of late folds and thrust displacements. c) Approximate complete restoration, showing the shape and distribution of metamorphic zoning. Subsurface plutons drawn in the metamorphic core are inferred to exist, but there is no direct evidence of them.

Fig. 6.- a) Corte geológico del área de Valuengo. b) Corte parcialmente balanceado corregido para el efecto de los pliegues tardíos y el desplazamiento provocado por el cabalgamiento. C) Balanceado aproximadmente completo, mostrando la forma y distribución de las zonas metamórficas. Se infiere la existencia de plutones ocultos en el núcleo metamórfico, aunque no hay evidencia de ellos.

work, it seems that the Mina Afortunada body is a granite intruding the Serie Negra rocks and producing a thermal aureole; some leucogranitic dykes around the orthogneiss can be misinterpreted in some places as migmatitic structures. The foliation responsible for the gneissic appearance of the Mina Afortunada granite is axial plane of Variscan recumbent folds mapped in the region (Azor *et al.*, 1992b; Martínez Poyatos *et al.*, 1995). The Mina Afortunada orthogneiss is, thus, an early magmatic intrusion related to the preorogenic Variscan rifting, subsequently deformed in the Variscan orogeny; it must not be taken as evidence of a Cadomian, Middle Cambrian, tectono-metamorphic event.

c) Because magmatism is the most important manifestation of the Cadomian orogeny in southwest Iberia, the Cadomian cycle could be considered to last until this magmatism ends. Unfortunately, as far as magmatism is concerned, there is an almost continuous transition from the one to the other orogenic cycle, with abundant magmatic production during both the end of the Cadomian cycle and the beginning of the Variscan cycle. The apparent continuity in magmatic production from the Vendian to the Ordovician can be appreciated in figure 3, in which the radiometric data available (Table 1) have been plotted. Despite the almost perfect continuity shown in the graph, a small gap could exist, though hidden by the overlapping of uncertainties in the radiometric ages. Since the gap concerned cannot be detected, the possibility of establishing the end of the Cadomian cycle in this way is avoided.

d) The expected geochemical differences between the orogenic Cadomian magmatism (calc-alkaline) and the rift-related Variscan magmatism (alkaline or tholeiitic) suggests a way of separating them. In practice discrimination is difficult, as rocks of calc-alkaline affinity are found in a wide range of ages from Vendian to Early Ordovician. The converse is not true, however, as alkaline rocks are not older than Cambrian. A more detailed picture emerges in the case of the alkaline and tholeiitic volcanics (Mata and Munhá, 1985, 1990; Ribeiro *et al.*, 1992; Sagredo and Peinado, 1992; Giese and Bühn, 1993) found in Lower-Middle Cambrian stratigraphic levels (Gil Cid, 1973; Liñán and Perejón, 1981; Liñán and Quesada, 1990). Both, radiometric and palaeontological datings indicate that a continental rifting regime must have existed at least from Early- to Middle Cambrian.

The calc-alkaline signature of some magmatic rocks formed well inside a rifting stage is an interesting petrogenetic problem described elsewhere (e.g., Hanson and Al-Shaieb, 1980). This problem has also been described in the Variscides of central Europe, where it has been argued that the calc-alkaline features of some Cambrian granitoids may be a consequence of remagmatization of older arc-type crust in a non-subduction regime with high heat flow (Dorr *et al.*, 1992; Finger *et al.*, 1997; Zulauf *et al.*, 1999).

4. Stratigraphic evidences for the preorogenic Variscan rifting

The most precise criteria for defining the transition from the Cadomian to the Variscan cycle come from the stratigraphic analysis.

In many areas of the Ossa-Morena Zone, just onto the volcano-sedimentary formation of latest Vendian age (Malcocinado formation) or directly onto the Serie Negra, there is a terrigenous, shallow marine to fluvial unit, made up of polygenic conglomerates, greywackes, arkoses and slates (Torreárboles formation), whose age is earliest Cambrian (Liñán, 1978; Liñan and Quesada, 1990; Perejón and Moreno Eiris, 1992). These deposits are transgressive over a paleorelief, and are further characterized by the fact that they do not appear confined to fault-controlled basins and they do not contain intercalated volcanics. These features can be taken to favour their interpretation as a tectonically quiet detritic platform, rather than as a Cadomian molasse. To the top, the Torreárboles formation is fine-grained (Giese *et al.*, 1994), passing upwards to a Lower Cambrian carbonate formation found throughout the Ossa-Morena Zone. As a matter of fact, this broad terrigenous and carbonate platform is a feature of a very large region, from the Meseta of Morocco (Piqué, 1981) to the Saxothuringian Zone in central Europe (Falk *et al.*, 1995), including indeed the Iberian Massif (Zamarreño, 1983). Therefore, a general stage of tectonic quiescence can be concluded to have prevailed at Early Cambrian in extended domains.

Before the end of the Early Cambrian, signs of instability started to appear: the carbonate platform broke, becoming first restricted and then, at the beginning of the Middle Cambrian, disappearing in favor of terrigenous sediments and tholeiitic –alkaline volcanics (Liñán and Quesada, 1990). This time span can be said to correspond with the beginning of the preorogenic Variscan rifting, which extended throughout the remaining Cambrian period and the Ordovician one (Ribeiro *et al.*, 1992). Once again, this tectonic episode can be recognized in most of the Variscides. In the Iberian Massif, both boundaries of the Ossa-Morena Zone became oceanic domains as a result of the evolution of this rifting (Quesada *et al.*, 1994; Gómez Pugnaire *et al.*, in press). However, it seems that a large oceanic domain (Tait *et al.*, 1997; Crowley *et al.*, 2000) may well have existed only to the south of the Ossa Morena crust, while the northern boundary of this thinned piece of continental crust would have always been near the border of the Gondwana continent (Matte, 2001).

In summary, there are compelling stratigraphic pieces of evidence to propose that a large part of the Early Cambrian was a transient stage of tectonic quiescence between the end of the Cadomian orogeny, in the transition Vendian/Cambrian, and the beginning of the pre-Variscan rifting, in the Early-Middle Cambrian. This stage would have been no longer than 15-20 Ma, thus being too short to be detected as a gap in radiometric ages between the latest Cadomian and the earliest preorogenic Variscan magmatic activity.

5. Tectono-metamorphic evidence for the preorogenic Variscan rifting

The stratigraphic record of orogenic regions provides the most reliable pieces of evidence for their preorogenic rifting stage, as described above for the Ossa-Morena Zone. In addition, structural studies in the orogens have described the tectonic inversion of pre-existing normal fault systems (e.g. Coward, 1994). Nevertheless, the thermal input of rifting is usually postulated (e.g. Sandiford and Powell, 1986) but the expected tectono-metamorphic effects of preorogenic rifting have been rarely described. We argue here that in the Ossa-Morena Zone a tectono-metamorphic imprint of the preorogenic Variscan rifting can be recognized in some localities, despite the superimposed intense Variscan synorogenic deformation (recent detailed descriptions of the Variscan deformation in the Ossa-Morena Zone can be found in Expósito *et al.*, 2002 and Simancas *et al.*, 2003).

The rocks of the Ossa-Morena Zone are generally affected by a low-grade metamorphism, but there are some areas where medium- and high-grade metamorphism occurs. This is the case of a belt of high temperature – low pressure rocks along the southern border of the Ossa-Morena Zone (Aracena region; Fig. 1), whose origin is clearly Variscan in age (Bard, 1977; Crespo-Blanc, 1989; Castro *et al.*, 1999; Simancas *et al.*, 2003). Two other small medium/high grade metamorphic areas are found in central Ossa-Morena Zone, around the localities of Valuengo and Monesterio (Fig. 4). The metamorphism of Valuengo has been considered Precambrian (Fernández Carrasco *et al.*, 1981) or due to a crustal thickening followed by collapse during the Variscan orogeny (Apraiz, 1998; Apraiz and Eguíluz, 1996). The metamorphism in the Monesterio area has been assumed to be Cadomian in age and representative of the importance of Cadomian tectono-metamorphic events in the Ossa-Morena Zone (Eguíluz, 1987). Pace these views, we present here structural and geochronological data suggesting that the metamorphism in these two areas was originated in the context of the preorogenic Variscan rifting.

5.1 The Valuengo metamorphic area (Figs. 5, 6)

The medium- high-grade metamorphic rocks of the Valuengo area outcrop inside and around a horse of the Olivenza-Monesterio Variscan thrust system (Figs. 5a, 6a; Expósito, 2000). The rocks with the highest metamorphic grade (the gneissic-migmatitic formation of Fernández Carrasco *et al.* (1981) are migmatites, mica-schists and quartz-schists, which include small granitic bodies. This formation is overlain by a meta-volcanodetrital unit known as Las Mayorgas formation (Fernández Carrasco *et al.*, 1981), which consists of a detrital member overlain by a gneissic one, the latter deriving from a volcano-sedimentary unit (Apraiz, 1998). Moreover, calcitic and dolomitic marbles outcrop at the top.

The position that the formations outcropping in the Valuengo horse occupy in the stratigraphic series of the Ossa-Morena Zone is not immediately obvious. We propose a correlation which is mainly based on the lithological affinity between the Valuengo carbonate formation and the Lower Cambrian carbonates found everywhere in the Ossa-Morena Zone. Thus, the volcano-detrital Las Mayorgas formation can be said to be correlated with the volcano-sedimentary Malcocinado formation of Late Vendian age. The lowermost gneissic-migmatitic formation could therefore be correlated to the dark shales and greywackes of the Upper Proterozoic Serie Negra, although the lack of the distinctive black quartzites can rather be taken to suggest the Malcocinado formation again as the most likely correspondent.

Metamorphism.- Inside the Valuengo horse, the metamorphic grade abruptly decreases eastward, from high-grade in the gneissic-migmatitic formation to low-grade in the upper marbles. This variation is shown with symbols in figures 5a, 6a, where diamonds represent pelites and quartz-feldspatic rocks containing: sillimanite + K-feldspar + reddish brown biotite ± garnet, while squares indicate rocks in which brown biotite is the only index mineral. Surrounding the Valuengo horse by its northern and eastern sides, there are mica schists and migmatitic gneisses clearly belonging to the Upper Proterozoic Serie Negra; here, the index minerals are: sillimanite ± K-feldspar + reddish brown biotite + cordierite. The metamorphic grade of the rocks surrounding the horse along the north and the east also decreases abruptly eastward, where mineral assemblages with green biotite as the only index mineral are rapidly found. This latter index mineral is also found along the western side of the Valuengo horse, i.e., in the footwall of the thrust system.

A high Fe content in the rocks of the gneissic-migmatitic and the Mayorgas formations is suggested by the Fe/(Fe+Mg) ratio value in garnets (Apraiz and Eguíluz, 1996) and by the presence of abundant ilmenite and tourmaline. This particular rock composition seems to have extended the garnet stability field (Hsu and Burnham, 1969), thus explaining the occurrence of either garnet or cordierite. Accordingly, petrographic data point to a low-pressure facies series metamorphism, contrasting with the higher pressures suggested by Apraiz and Eguiluz (1996) from barometric calculations. Expósito (2000) discussed this conflict, suggesting disequilibrium between the minerals used by the authors in their barometric calculations.

Deformation related to the metamorphism. - The abrupt metamorphic gradient observed in the Valuengo area is the result of: a) the likely high thermal gradient of the metamorphism, and b) the thinning caused by a synmetamorphic shearing responsible for the main penetrative fabric recorded in these rocks. The main foliation in this area is synmetamorphic and mylonitic (S'_m), being mainly marked by biotite and sillimanite in metapelites and by deformed grains of quartz and feldspar in quartz-feldspathic rocks. The stretching lineation, often marked by biotite and stretched quartz grains, is NNE-SSW (Fig.

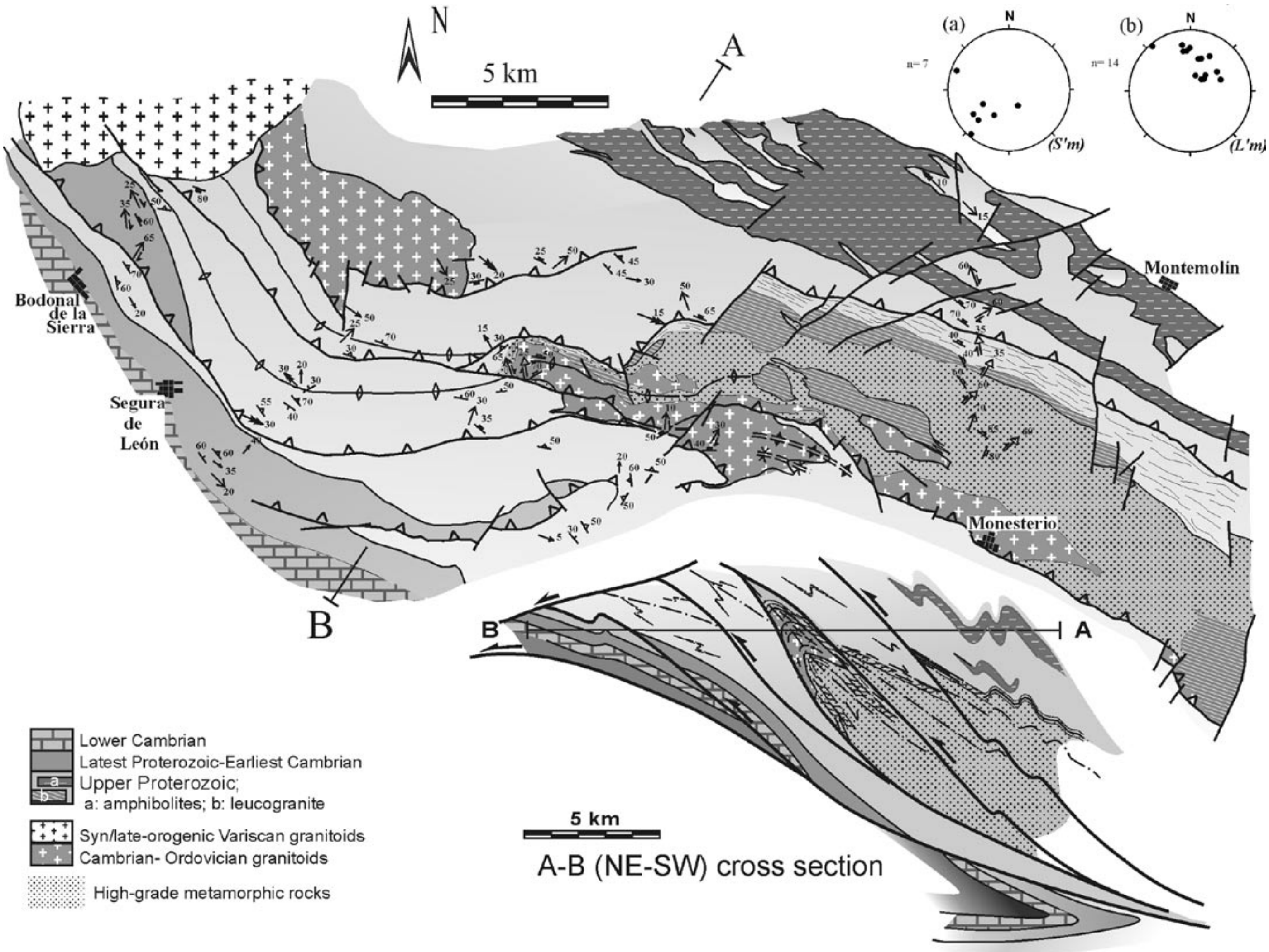


Fig. 7.- Geological map (modified from Eguiluz, 1987 and Expósito, 2000) and cross-section of the Monesterio metamorphic area. Two equal-area plots (upper-right corner) show the orientation of the mylonitic foliation (S'_m) and the associated mineral lineation (L'_m), formed during the top-to-the-north tectono-metamorphic extensional event.

Fig. 7.- Mapa geológico (modificado de Eguiluz, 1987 y Expósito, 2000) y corte geológico del área metamórfica de Monesterio. Dos proyecciones equiareales (esquina superior derecha), muestran la orientación de la foliación milonítica (S'_m) y de la lineación mineral asociada (L'_m), generadas durante el evento tectónico extensional con desplazamiento con sentido techo-al-norte.

5b). Several microstructures (mantled porphyroclasts, S-C structures, subgrain boundaries, etc.) consistently indicate a top-to-the-NNE sense of shear, as already pointed out by Apraiz and Eguiluz (1996). The mylonitic foliation (S'_m) is folded by regional Variscan recumbent folds. The axial plane foliation of these recumbent folds is the oldest foliation recorded by rocks outside the metamorphic area. A south-directed thrust system cuts the folds and is itself gently folded (Fig. 6a; Expósito, 2000; Expósito *et al.*, 2002).

The different mineral assemblages depicted in Fig. 5a have been approximately projected in the cross-section of Fig. 6a. After removing late folds, thrusts and recumbent folds (Figs. 6b, 6c), a rough zonation of the metamorphism can be envisaged (Fig. 6c).

Age of the metamorphism. - The metamorphism in the Valuengo area occurred before the Variscan crustal thickening due to recumbent folds and thrusts. In addition, it affects rocks that are reasonably attributed to the latest Precambrian / earliest Cambrian. Therefore, it can be said that this metamorphism is post-Vendian and younger than the Variscan orogeny. Geochronological dating by the Kober method (Kober, 1986) on zircon crystals of two magmatic bodies outcropping in the Valuengo area has been recently carried out, yielding the following results (Montero *et al.*, 2000): 532 ± 5 Ma for a medium-grade orthogneiss, and 480 ± 7 Ma for an apparently undeformed microgranite. The age of the orthogneiss is interpreted as the time of crystallization of an igneous protholith of the Malcocinado formation; it provides a lower boundary for the metamorphic and deformational event. The age of the undeformed microgranite indicates that its crystallization occurred in Early Ordovician, marking perhaps an upper limit for the tectono-metamorphic event recorded in the Valuengo area.

5.2 The Monesterio metamorphic area (Fig. 7)

North of the Monesterio village, a high-grade metamorphic NW-SE band outcrops, which is made up of of migmatites, gneisses, schists, amphibolites and black quartzites, being intruded by small anatectic granitic bodies (Eguiluz, 1987). These rocks clearly correspond to the Upper Proterozoic Serie Negra formation. Metamorphism and deformation found in Valuengo are strongly similar to those observed in the Monesterio area.

Deformation and structure in the Monesterio area.- As in Valuengo, a top-to-the-north synmetamorphic mylonitic foliation ($_{S'm}$) is present in the Monesterio area as the first tectonic fabric. $_{S'm}$ is clearly simultaneous with the migmatization, as shown by differentiated veins cutting $_{S'm}$ or affected by it. $_{S'm}$ dips mainly to the NE, (stereoplot *a* in Fig. 7). A NE plunging mineral/stretching lineation (stereoplot *b* in Fig. 7), defined by biotite and deformed quartz grains, developed on this foliation.

The structure is also very similar to the Valuengo one, since high-grade metamorphic rocks outcrop enclosed by two branches of the same Variscan thrust system described in Valuengo (Figs. 4, 7). Furthermore, both $_{S'm}$ and the isograds are folded by a large recumbent anticline that can be demonstrated through structural mapping to be the same fold found in Valuengo, albeit displaced by thrusting (Expósito, 2000).

Metamorphism.- In Monesterio, the rocks affected by the highest metamorphic grade contain mineral assemblages characterized by andalusite, cordierite, sillimanite and K-feldspar (Eguíluz, 1987). Unfortunately, the ages available for presumably synmetamorphic magmatic rocks show an important variation, ranging between 500 Ma and 530 Ma (Schäfer, 1990; Ochsner, 1993; Ordoñez Casado, 1998; Montero *et al.*, 1999), i.e., Early to Late Cambrian.

5.3. Interpretation of the early metamorphism in Valuengo and Monesterio

The interpretation of the early tectono-metamorphic event observed in both Valuengo and Monesterio areas is based on the following points:

a) Structural mapping has demonstrated the connection between both areas, suggesting that they belong to a narrow, NW-SE trending band of metamorphic rocks.

b) The metamorphism is coeval with a mylonitic foliation (S'_m), never found outside this band, which is related to ductile, top-to-the-north extensional shearing.

c) The S'_m is folded by Variscan recumbent folds, thus indicating that both metamorphism and shearing must precede Variscan thickening.

d) The geochronological data available point to Cambrian – Early Ordovician ages for this tectono-thermal event.

As discussed in the previous paragraphs, the stratigraphic succession in the Ossa-Morena Zone suggests that continental rifting must have taken place during Cambro-Ordovician times, thus producing abundant bimodal volcanics and plutons. It is in this context that we place the deformation and metamorphism of the Valuengo and Monesterio areas, as another manifestation of the crustal (and lithospheric) extension that took place in the Ossa-Morena Zone during Cambro-Ordovician rifting. The mylonitic foliation $_{S'm}$ would have developed in a low-angle extensional top-to-the-north shear zone during this Lower Palaeozoic rifting.

Metamorphism is concentrated within a narrow band, which can be explained by an abnormally high and localized heat flow of likely magmatic derivation. Magmatic accumulation may well have taken place took place at that time under the Monesterio-Valuengo band, inducing concentrated fluid and melt flow and locally raising the heat flow. Thermal softening (Hollister and Crawford, 1986; Zulauf and Helferich, 1997) may have been the reason why extensional ductile shearing is concentrated along this metamorphic band.

In the context of the Iberian Massif, the rifting of Early Palaeozoic age was especially conspicuous in the Ossa-Morena Zone, which may have become an isolated continental block in Silurian times as a final consequence of this tectono-thermal event (Matte, 2001; Simancas *et al.*, 2002). Early Palaeozoic rift-related magmatism is widespread, with variable intensity, throughout the Variscides of Europe (Crowley *et al.*, 2000).

6. Conclusions

Misinterpretation of the Variscan structures can, in our opinion, be said to underlie at the heart of most discussions on the imprints of the Cadomian and the Variscan orogenies on the crust of the Ossa-Morena Zone. In this zone, Cadomian magmatism is widespread, but we have invariably found that tectono-metamorphic fabrics are associated with the Variscan deformation or, in a few areas (Valuengo, Monesterio), to the preorogenic Early Palaeozoic rifting event. The case of these two specific areas is illustrative of how a complex Variscan overprint (mainly in the form of a complex Variscan structure) makes it difficult to unravel the significance of the tectonic and metamorphic record in Upper Proterozoic rocks.

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