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# Low-Grade Metamorphism in the Central Sector of the Ossa-Morena Zone

## Metamorfismo de grado bajo en el Sector Central de la Zona de Ossa Morena

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**Abstract**

The diagenetic and metamorphic grade of low temperature processes which affected the pelitic materials of the Central Sector of the Ossa-Morena Zone is determined by electron microscopy and X-ray diffraction criteria. Cadomian metamorphic processes produced at least greenschist facies conditions even in the lowest grade rocks of the Serie Negra. Post-Cadomian rifting affected the early Paleozoic sedimentary basin giving way to an extensional metamorphism characterised by a burial pattern, which represents the earliest response to depth-controlled diagenetic and very low-grade metamorphic reaction progress caused by basin subsidence. No significant metamorphic overprint was produced by Variscan deformation, as shown by the preservation of typically sedimentary minerals and early-to-late diagenetic values of KI in Devonian and Carboniferous sediments.

*Keywords:* crystal-chemical parameters, low-grade metamorphism, Precambrian, Cambrian, Devonian-Carboniferous sediments, SW Spain.

**Resumen**

Se han determinado los procesos diagenéticos y metamórficos de baja temperatura que afectan a los materiales pelíticos del sector central de la Zona de Ossa Morena, mediante microscopía electrónica y difracción de rayos-X. En este sector, los procesos metamórficos cadomienses llegaron a alcanzar las condiciones de facies de esquistos verdes como mínimo, aún en las rocas de menor grado de metamorfismo de la Serie Negra. La fase de rifting post-cadomiense afectó a la cuenca sedimentaria durante el Paleozoico inferior, produciendo un metamorfismo extensional de enterramiento que representa la respuesta inicial al progreso de las reacciones diagenéticas y metamórficas de grado muy bajo, controladas por la profundidad debida a la subsidencia de la cuenca. Sin embargo, la deformación varisca no ha producido un metamorfismo significativo, como lo demuestra la conservación de minerales típicamente sedimentarios y los valores diagenéticos del índice de Kübler que presentan los materiales devónicos y carboníferos.

*Palabras Clave*: parámetros cristalquímicos, metamorfismo de grado bajo, Precámbrico, Cámbrico, sedimentos devónico-carboníferos, SW España.

## 1. Introduction

The structural, paleogeographic, and petrological characteristics of the Ossa-Morena Zone (ZOM) have been studied thoroughly in the last decades by numerous authors (e.g. Julivert *et al*., 1974; Apalategui *et al.,* 1990; Liñán *et al*., 1995; Bandrés *et al*., 2002; Expósito *et al*., 2002; and references therein). It consist of a wide range of volcanic, plutonic, and metamorphic rocks. All were formed over a long period of time, from the Late Precambrian to the Carboniferous. Tectonothermal events related to the Cadomian orogeny are well preserved and in large areas the Paleozoic cover shows only minor Variscan deformation and metamorphism (Bandrés *et al*., 2002).

The low-grade metamorphic rocks of the ZOM which are subject of the present work fundamentally consist of greywackes, shales, and slates. Anfibolites and marbles may occasionally also be present. The metamorphic grade

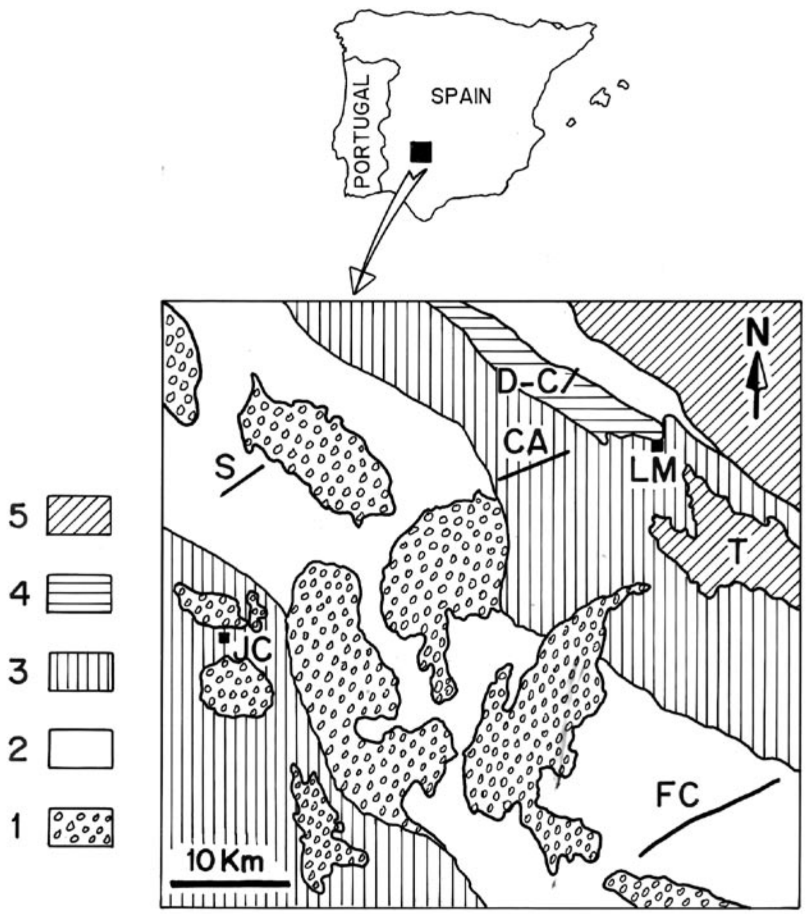


Fig. 1.- Geological setting of the Ossa Morena Central Sector (modified from Expósito *et al*., 2002) and sequence location. 1: Undifferentiated igneous rocks. 2: Precambrian rocks "Serie Negra". 3: Cambrian rocks. 4: Devonian-Carboniferous materials. 5: Tertiary (T). FC: Fuente de Cantos sequence ("Serie Negra"); S: Salvatierra sequence ("Serie Negra"); CA: Cambrian sequence; D-C: Devonian-Carboniferous sequence; LM: Los Santos de Maimona; JC: Jerez de los Caballeros.

Fig. 1.- Esquema geológico y localización de las secuencias estudiadas del sector central de la Zona de Ossa Morena (modificado de Expósito *et al*., 2002). 1: rocas ígneas indiferenciadas. 2: rocas precámbricas "Serie Negra". 3: rocas cámbricas. 4: materiales devónico-carboníferos. 5: Terciario (T). FC y S: secuencias de Fuente de Cantos y Salvatierra respectivamente, en la Serie Negra; CA: secuencia cámbrica. D-C; materiales devónico-carboníferos; LM: Los Santos de Maimona; JC: Jerez de los Caballeros.

is variable, from diagenetic to greenschist facies.

In these rocks, the mineral associations are usually not limiting assemblages and consequently the pressure/temperature (P/T) conditions are difficult to determine. For this reason, the measurement of the crystalchemical parameters of phyllosilicates is essential to approach an estimate of these conditions.

In order to obtain a continuous record of the metamorphic evolution in the ZOM, different areas of the Monesterio Domain, in the central sector of the ZOM, were studied. The most characteristic sequences were those from the oldest area, which show the highest metamorphic grade, and are represented by the so-called "Serie Negra" (Alía Medina, 1963). The age of these rocks is Upper Proterozoic and they consist of a high-grade anatectic complex at the base, a sequence of biotite-schists, black quartzite and carbonates with anfibolites and serpentine intercalations, and an alternation of slates and greywackes with abundant volcanic input (Eguíluz and Ábalos, 1992). The Precambrian-Lower Cambrian limit corresponds to the Malcocinado Formation, which presents abundant clastic components and interbedded tuffs and rhyolitic lavas. This formation is considered to be Lower Cambrian (Bandrés *et al*., 2002) or Vendian (Expósito *et al*., 2002). The low-grade metamorphism of the "Serie Negra" was studied by López Munguira *et al*. (1991).

Lower Palaeozoic rocks outcrop extensively in the Zafra anticline. A complete sequence of Cambrian age, formed by an alternation of sandstones, shales, and calcareous and volcanic rocks (acidic and basic) may be found on its north flank. López-Munguira *et al*. (1998) described the metamorphic evolution of these Cambrian rocks.

New data on Upper Devonian and Carboniferous materials in the Fuente del Maestre area (Valenzuela and Palacios, 1990) were collected in order to complete the metamorphic characterisation. A sequence formed by an alternation of fine-grained sandstones and quartz-rich mudstones (with coarser grain at the base of the sequence) was sampled; reef carbonates and dacite, and andesite-basalt lava-flow are also interbedded (Odriozola *et al*., 1983).

The location of the sequences is shown in Figure 1 together with the geological and geographic setting of the Ossa Morena Central Sector (modified from Expósito *et al*., 2002).

In the present work, the low-grade metamorphic conditions in the metapelites of the ZOM, are characterized in non-limiting assemblages based on the crystal-chemical parameters, chemical composition, nanostructure, and polytypes of the phyllosilicates.

## 2. Methods

X-ray analyses were made on all samples using a PW 1700 and a PW1710 powder diffractometer with Cu-Kα radiation, a graphite monochromator, and an automatic divergence slit. The <2μm and <20μm fractions were obtained by sedimentation through a column of water. The oriented aggregates were prepared by sedimentation on glass slides, treated with ethylene glycol at 60-70ºC for 3 days, and heated at 550ºC for 1 h.

In the pelitic samples, the Kubler index (KI), the basal spacing and the intensity ratios of the (00l) mica peaks were measured. Sample preparation and experimental conditions for the KI measurements followed IGPC 294 IC Working Group recommendations (Kisch, 1991). Our KI measurements (y) were transformed into C.I.S. values (x) according to the equation $y = 0.674x+0.052$, ($r=0.999$), obtained in our laboratory using the international standards of Warr and Rice (1994). The anchizone limits for C.I.S. values are 0.25 and 0.42º $\Delta 2\theta$.

The **b** parameters of the mica and chlorite lattices were obtained from the (060) peak measured on slices of rock cut normal to the sample foliation. Such slices are essentially perpendicular to the (00l) planes of phyllosilicates and thus avoid interference from peaks other than (060) (Sassi and Scolari, 1974; Guidotti and Sassi, 1976; Frey, 1987). For all the spacing measurements, quartz was used as an internal standard. The experimental conditions were: distance between measurement points = 0.005 º 2θ; measurement time at each point = 1 s; $d_{001}$ was obtained from the fifth peak of mica.

Polished thin sections, coated with carbon, were studied by back-scattered electron microscopy, using a ZEISS DSM 950 scanning electron microscope (SEM) at the Centro de Instrumentación Científica, University of Granada (C.I.C.). Minerals were recognized and chemically analysed by an energy dispersive X-ray (EDX) system LINK QX 2000.

Phyllosilicates were analysed in a four-spectrometer CAMECA-CAMEBAX SX-5020 electron microprobe at the C.I.C., with 20kV, 20nA, and a 5-8μm beam diameter as analytical conditions and with synthetic oxides as well as natural silicate minerals (albite, orthoclase, and wollastonite) as standards.

Samples for the Transmission Electron Microscopy (TEM) studies were selected from uncovered thin sections. The sections were ion-thinned using a Gatan 600 ion mill and carbon-coated. At the C.I.C., we used a Philips CM-20 scanning transmission electron microscope (STEM), operating at 200 kV with a point-to-point resolution of 0.27 nm equipped with an ultrathin-window EDX detector.

A more detailed description of the methods and techniques used can be found in López-Munguira (1987); López-Munguira *et al*. (1991, 1998, and 2002); López-Munguira and Nieto (2000).

## 3. Mica crystal-chemical parameters

The *Kübler Index* (KI) is a measure of the X-ray diffraction mica peak width at 10 Å. Its value is an indirect measure of the crystalline domain size of mica packets (see Warr and Nieto, 1998) which depends on numerous factors, temperature being the most important. It has been used to provide a good approximation to the metamorphic grade of many geological terrains (Kisch,1987; Merriman and Peacor, 1999).

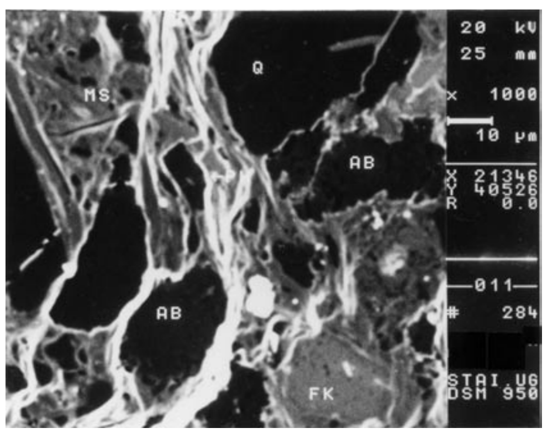


Fig. 2.- Representative backscattered image showing the texture of fine-grained sandstones of the anchizone sample (LP-6, Lower Cambrian). Q: Quartz. AB: Albite. FK: K-feldspar. MS: mica.

Fig. 2.- Imagen de barrido, representativa de las areniscas de grano fino, perteneciente a una muestra de anquizona (LP-6, Cámbrico inferior).

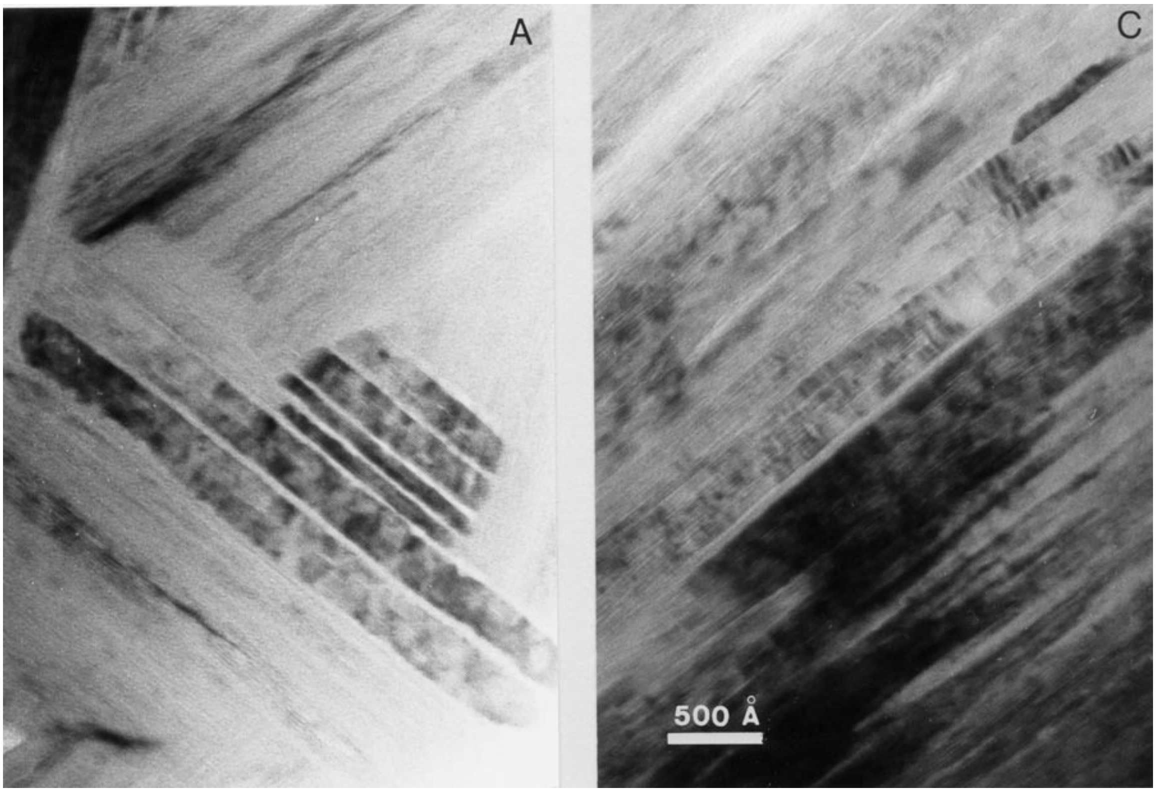


Fig. 3.-Lattice-fringe images showing typical texture of phyllosilicate of the Cambrian clastic rocks. A: Epizone sample (ZL-11, Basal Cambrian). C: Diagenetic sample (C90-7, Middle-Upper Cambrian).

Fig. 3.- Imagen reticular mostrando la textura típica de los filosilicatos en lrocas detríticas cámbricas. A: muestra de epizona (ZL-11, Cámbrico basal). C: muestra diagenética (C90-7, Cámbrico medio-superior)

The *b parameter* of a mica depends essentially on its phengite content. Phengite substitution in white micas is directly related to pressure (Massonne and Schreyer, 1987). Guidotti and Sassi (1986) calibrated the variation of this parameter in the non-limiting assemblage white-mica + albite as a semiquantitative geobarometer within the P-T field of the lower greenschist facies.

The *mica basal spacing* ($d_{00l}$) is related to the Na content, which is directly proportional to temperature. However, if the degree of paragonitization of the white-mica is very low, the mica basal spacing is basically a function of phengite content (Guidotti *et al*., 1992).

The *chemical composition of chlorite* has been also used as an indicator of temperature. The geothermometric formulae given by Cathelineau and Nieva (1985) and Cathelineau (1988) use the content in certain elements of the chlorite (Fe, Mg, Al). The chemical composition has also been used to obtain the smectite-layer proportion in the chlorite structure. However, López-Munguira *et al*. (1991, 2002) have shown that the influence of the rock composition on the chlorite composition is very pronounced in low-grade metamorphism.

## 4. Results

### *4.1 Precambrian Rocks. Serie Negra*

Quartz + muscovite + albite ± chlorite is the most usual mineral association. Matrix grains are very fine (<10 μm), but samples frequently contain grains of 20-40 μm. Phyllosilicate porphyroblasts, mica, and/or chlorite, are common with a variable size, but far larger than the matrix grains, reaching up to 200-300 μm. Generally these grains are detrital in origin. Biotite is frequently present and garnet has been recognized in some samples. The paragenesis of the interbedded basic rocks (López Munguira *et al*., 1991) includes actinolite and occasionally hornblende.

The values of KI are very homogeneous with KI = 0.22(2) º2θ, i. e., all the samples have clearly reached at least epizone conditions. No differences between air-dried and ethylene glycol samples were found either in the width of the mica peaks or in their basal-peak intensity ratios. The mean values obtained for $\mathbf{d_{001}}$ and **b** in the micas indicate their phengitic character (Table 1). Polytype of micas, determined mean XRD, are systematically 2M.

The electron microprobe data gave a Na/(Na+K) ratio ~0.05 and a $Si/Al_{total}$ ratio between 1.25 and 1.50, which indicates a very low paragonitic content of the white-micas together with a moderate but significant phengitic component compatible with the **b** values obtained by XRD. The composition of the chlorites (Mg = 2.8 and Fe = 1.6 a.f.u.) indicates that they are ferric clinochlore. At the top of the sequence, the chemical composition of the chlorites is slightly poorer in Mg than at the base of the sequence.

All the data for the Serie Negra are coherent with a minimal metamorphic grade equivalent to greenschist facies.

*4.2 Cambrian materials*

The Cambrian materials are represented by three well-differentiated tracts. At the base, the Torreárboles Formation consists of fine-grain sandstones (arkoses) with a mineral composition of quartz + plagioclase + white-mica ± haematites and occasional chlorite; their age is earliest Cambrian. The next tract (Alconera and La Lapa Formations, Early Cambrian), is formed by carbonate rocks and a terrigenous sequence of fine-grained sandstones and shales with quartz + albite + white mica + berthierine. At the top, the Playon Beds (Middle-Upper Cambrian) consist mainly of shales, with quartz + albite + white mica ± chloritic phases (berthierine and chlorite) and interbedded acidic and basic volcanic rocks.

The backscattered electron images of clastic rocks obtained by SEM showed elongated phyllosilicate crystals both surrounding quartz and plagioclase grains and in the matrix. No differences between samples corresponding to various stratigraphic levels were seen at SEM scale. Figure 2 shows the typical texture of a sample corresponding to the Lower Cambrian: large crystals of quartz, feldspar, and muscovite are very abundant. In the interstices between these detrital grains, a fine matrix, consisting of phyllosilicates, may be recognized, but it is poorly resolved.

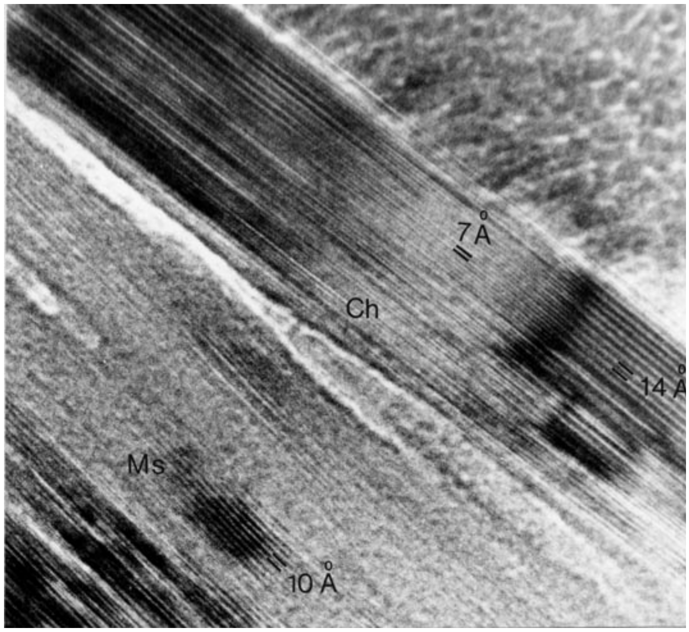


Fig. 4.- Relation between chlorite and/or berthierine (14/7 Å), and mica (10 Å) packets. Diagenetic sample (C91-25). Ms: dioctahedral K-mica. Ch: chlorite.

Fig. 4.- Relación entre paquetes de clorita y/o bertierina (14/7 Å) y mica (10 Å). Muestra diagenética (C91-25). Ms: mica potásica dioctaédrica. Ch: clorita.

| | | KI-EG | b | $d_{001}$ |
|---|---|---|---|---|
| SN | Fuente de Cantos | 0.22(2) | 9.020(23) | 9.990(6) |
| | Salvatierra | 0.22(7) | 9.021(14) | 9.980(5) |
| C | BC | 0.25(4) | 9.033(06) | 9.996(8) |
| | LC | 0.38(5) | 9.011(05) | 9.981(7) |
| | MUC | 0.50(7) | 8.997(05) | 9.993(8) |
| | Devonian* | 0.82(16) | 8.995(04) | 9.978(17) |
| | Carboniferous* | 0.98(36) | 9.002(05) | 10.001(10) |

( ): standard deviation, *: new data

Table 1.- Mean values of crystal-chemical parameters of the studied sequences. KI: Illite crystallinity. SN = Precambrian rocks. Serie Negra. C = Cambrian materials, BC: Basal Cambrian, LC: Lower Cambrian, MUC: Middle-Upper Cambrian. b and $d_{001}$ in Å. KI in Δ °2θ. EG: ethylene-glycol treatment.

Tabla 1.- Valores medios de los parámetros cristaloquímicos de las secuencias estudiadas. KI: índice de Kübler (cristalinidad de la ilita). SN: rocas precámbricas. Serie Negra. C: materiales cámbricos, BC: Cámbrico basal, LC: Cámbrico inferior, MUC: Cámbrico medio-superior. b y $d_{001}$ en Å. KI en Δ °2θ. EG: tratamiento con etilen-glicol.

The KI evolution indicates a temperature decrease from epizone at the bottom of the sequence to diagenesis conditions at the top. Pressure is intermediate in the Lower Cambrian, as deduced from the **b** parameters (Table 1).

The TEM study showed that the samples have a similar texture up to the low-magnification scale. Differences between samples are only recognized at lattice scale level: the size of the crystalline domains of micas progressively increases from diagenetic through anchizone to epizone (Fig. 3). The evolution in size of mica packets has been proved to be the main reason for the progressive change in the KI during very-low and low grade metamorphism (Warr and Nieto, 1998; Merriman and Peacor, 1999). Chlorite and/or berthierine packets are related to mica packets (Figure 4). In some cases a transformation of detrital grains (e.g. biotite) into newly-formed micas or chlorites may be recognized (Fig. 5).

Coexisting 1Md, 1M, and 2M polytypes were recognized in dioctahedral K-rich micas (Fig. 6), together with long-period polytypes composed of 4, 5, and 6 layers (Fig. 7).

| Samples | Mineralogy | | | | | | b | | $d_{001}$ | KI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Devonian** | **Q** | **Feld** | **Mica** | **Chl** | **Cc** | **CML** | **Chlorite** | **Mica** | **Mica** | **Fe Chl** | **Air** | **EG** |
| Fm1-1 | x | x | x | x | | | 9.282 | 8.998 | 9.9607 | 2.1 | 0.75 | 0.59 |
| Fm3 | x | x | x | x | | | 9.299 | 8.995 | 9.9829 | 2.6 | 0.66 | 0.58 |
| Fm6 | x | x | x | x | x | | 9.304 | 8.998 | 9.9855 | 2.8 | 1.04 | 0.43 |
| Fm8 | x | x | x | x | t | | 9.295 | 8.990 | 9.9829 | 2.5 | 0.81 | 0.38 |
| **Mean** | | | | | | | **9.295** | **8.995** | **9.9780** | **2.5** | **0.82** | **0.50** |
| **std** | | | | | | | **0.009** | **0.004** | **0.0116** | **0.3** | **0.16** | **0.11** |
| **Carboniferous** | | | | | | | | | | | | |
| Fm10 | x | x | x | x | t | | | 9.001 | 9.9958 | | 0.74 | 0.61 |
| Fm14 | x | x | x | | t | | | 9.009 | 10.0114 | | 1.11 | 0.72 |
| Fm16 | x | x | x | x | x | | | 9.001 | | | 0.56 | 0.43 |
| Fm18 | x | x | x | | x | x | | 8.995 | | | 0.72 | 0.61 |
| Fm23 | x | x | x | | x | x | | | | | 1.18 | 0.66 |
| Fm24 | x | x | x | | x | x | | | 9.9907 | | 0.89 | 0.71 |
| Fm25 | x | x | x | | x | x | | | 10.0062 | | 1.63 | 0.55 |
| Fm28 | x | x | x | | x | x | | | | | | 0.74 |
| **Mean** | | | | | | | | **9.002** | **10.0010** | | **0.98** | **0.63** |
| **std** | | | | | | | | **0.006** | **0.0095** | | **0.36** | **0.10** |

Table 2.- Mineral composition and crystalchemical parameters of Devonian and Carboniferous sedimentary rocks. Q: quartz. Feld: feldspars. Chl: chlorite. Cc: calcite. CML: chlorite mixed layers. b and $d_{001}$ in Å. KI in Δ º2θ. Air: air-dried. EG: ethylene-glycol treatment.

Tabla 2.- Composición mineral y parámetros cristaloquímicos de los sedimentos devónicos y carboníferos. Q: cuarzo. Feld: feldespatos. Chl: clorita. Cc: calcita. CML: interestratificados con clorita. b y $d_{001}$ en Å. KI en Δ º2θ. Air: muetra sin tratar. EG: tratamiento con etilen-glicol.

The chemical compositions of the white micas determined by AEM are highly variable on the sample level, i.e., from grain to grain. In the anchizone and the diagenetic zone they include both illitic (interlayer population around 0.8 a.f.u) and phengitic components (0.15 a.f.u of Mg and 0.13 a.f.u of Fe). In contrast, the illite component is absent in the epizone

Berthierine, trioctahedral chlorite (chamosite), sudoite, and corrensite coexist in one of the diagenetic zone samples. Berthierine and chamosite have the same chemical composition.

### *4.3. Devonian-Carboniferous sedimentary rocks*

Devonian-Carboniferous sedimentary rocks are pelites with a mineral association including quartz, plagioclase, illite, and chlorite at the base. At the top, the major components are quartz, plagioclase, calcite, and illite (Table 2), and pelite materials alternate with calcareous and volcanic rocks. Comparison between diagrams obtained before and after ethylene-glycol treatment showed clear differences for the mica peaks (Fig. 8 and Table 2), which indicates the presence of minor swelling layers (smectite) interstratified within the illite layers.

There are only small differences in the KI values between Devonian and Carboniferous samples (Table 1 and 2). For both cases diagenetic conditions may be deduced, with an average value = 0.82 º2θ for Devonian pelites, and = 0.98 º2θ for Carboniferous ones. There are Carboniferous samples with KI values > 1.0 °2θ, which indicates conditions in the limit between early and late diagenesis. In both the Devonian and Carboniferous samples, the scatter of the KI values is very significant (Table 2), which is characteristic of populations of micas with a very low degree of maturation. The presence of illite/smectite mixed layers together with these KI values indicates that late-diagenetic conditions have not been surpassed in these materials. The **b** parameter of the samples is coherent with low-pressure conditions in both cases.

The mean Fe content of chlorite from the Devonian samples, obtained from the **b** parameter value, is around 2.5 a.f.u.

## 5. Discussion

Most of the clastic rocks from diagenesis up to greenschist facies conditions lack grade criteria due to the absence of changes in their mineral paragenesis and non-equilibrium genetic conditions. This has precluded the use of valid geothermometers and geobarometers. However, shales, slates, and weakly metamorphosed sandstones are widely distributed in the Ossa-Morena Zone. Therefore studies based on microtextures at the mineral lattice scale are necessary in order to decipher changes in metamorphic conditions (Merriman and Peacor, 1999). Here we have integrated published information (López Munguira, 1987; López Munguira *et al*., 1991, 1993, 1996, 1998, 2002; López Munguira and Nieto, 2000) with new data from previously unstudied stratigraphic levels.

Deformation episodes in the Ossa-Morena Zone have traditionally been attributed to the Cadomian and Variscan orogenies (Apalategui *et al.,* 1990; Liñán *et al*., 1995; Bandrés *et al*., 2002; Expósito *et al*., 2002, and references therein). Devonian and Carboniferous sedimentary rocks were included in this study to clearly isolate the superimposed effects of the Variscan orogeny on previously metamorphosed materials. The results are conclusive. Mineral composition, including illite/smectite mixed-layers, KI values corresponding to a diagenetic zone, and a very low phengitic component in micas as deduced from the **b** parameter, are perfectly coherent with a lack of significant metamorphic effects. It can therefore be concluded that Variscan orogeny has not added any significant metamorphic overprint to previously metamorphosed materials in the central sector of the Ossa-Morena Zone.

In contrast, in the "Serie Negra" the metamorphic grade reached greenschists facies conditions even in the lower metamorphic grade rocks. Micas show KI values that correspond to minimum crystallinity values i. e., perfect crystallinity, and can not be discriminated from each other. Both the $Si/Al_{total}$ ratio and the **b** parameter indicate an intermediate phengite content in mica, indicative of a pressure of about 5 kb.

The empirical formulation of Cathelineau (1988) which relates octahedral Al content in chlorite to metamorphic temperature would indicate a value of around 350ºC. Nevertheless, it has been demonstrated that the decisive factor in the chemical composition of chlorite is the composition of the rock (López-Munguira *et al*., 2002) and that temperature should only be considered a modifiying factor (López-Munguira *et al*., 1991).

As a whole, Paleozoic materials show a progressive decrease of mica crystallinity from the basal Cambrian (epizone) to the Carboniferous sequence (early-to-late diagenesis). This pattern of very-low grade metamorphism, showing a progressive increase in grade with stratigraphic age, has been proposed by Merriman and Frey (1999) as characteristic of an extensional setting. They suggest that a burial pattern represents the earliest response to depth-controlled diagenetic and very low-grade metamorphic reaction progress caused by basin subsidence. Robinson (1987) distinguished two contrasting settings as responsible for the pressure-temperature-time paths that characterize the transition from diagenesis to metamorphism.

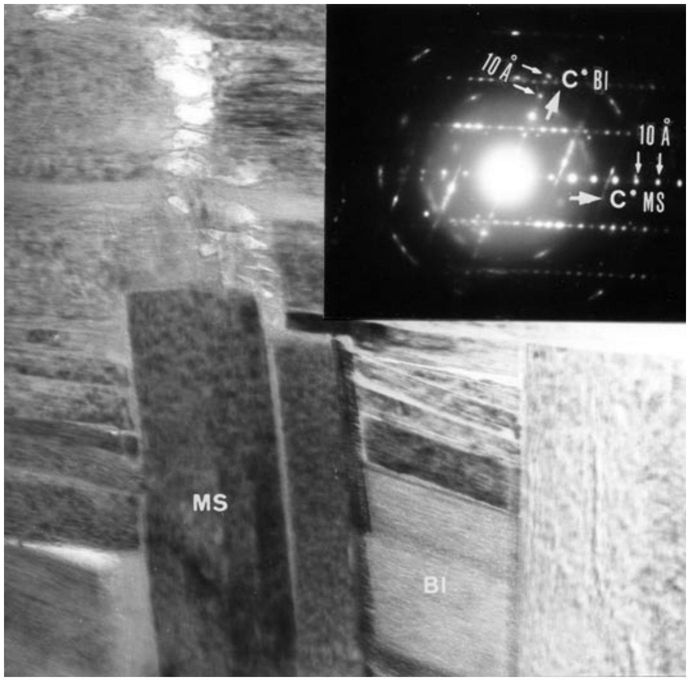


Fig. 5.- Biotite/muscovite solution/neoformation process in the anchizone sample. SAED patterns (inset) show muscovite 2M polytype and disordered biotite. Muscovite and biotite crystals were identified by AEM analysis and reflection intensities. Ms: muscovite. Bi: biotite.

Fig. 5.- Proceso de solución/neoformación de biotita/moscovita en una muestra de la anquizona. La difracción de electrones (SAED) muestra el politipo 2M de la moscovita y el desordenado de la biotita. Los cristales de moscovita y biotita se han identificado mediante microanálisis (AEM) y relación de intensidades (DRX). Ms: moscovita. Bi: biotita.

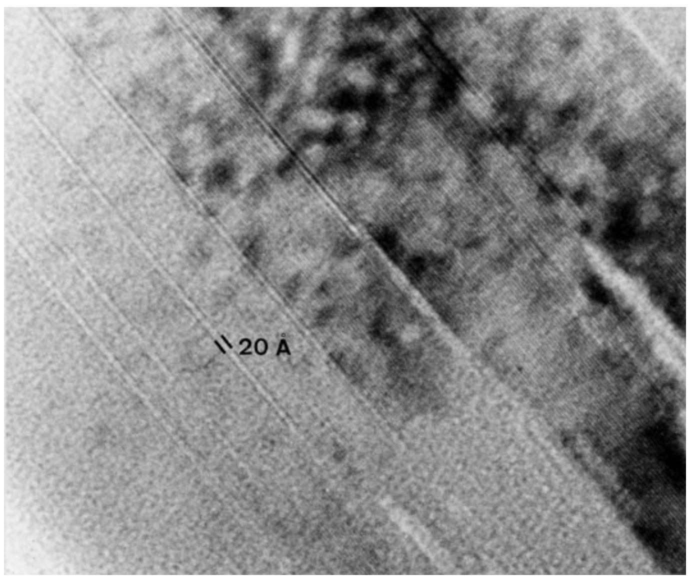


Fig. 6.- Lattice-fringe image showing 20 Å spacing (2M polytype) between 10 Å spacing (1M polytype) packets. Epizone sample (ZL-11).

Fig. 6.- Imagen reticular mostrando paquetes espaciados 20 Å (politipo 2M) entre paquetes espaciados 10 Å (politipo 1M). Muestra de la epizona (ZL-11).

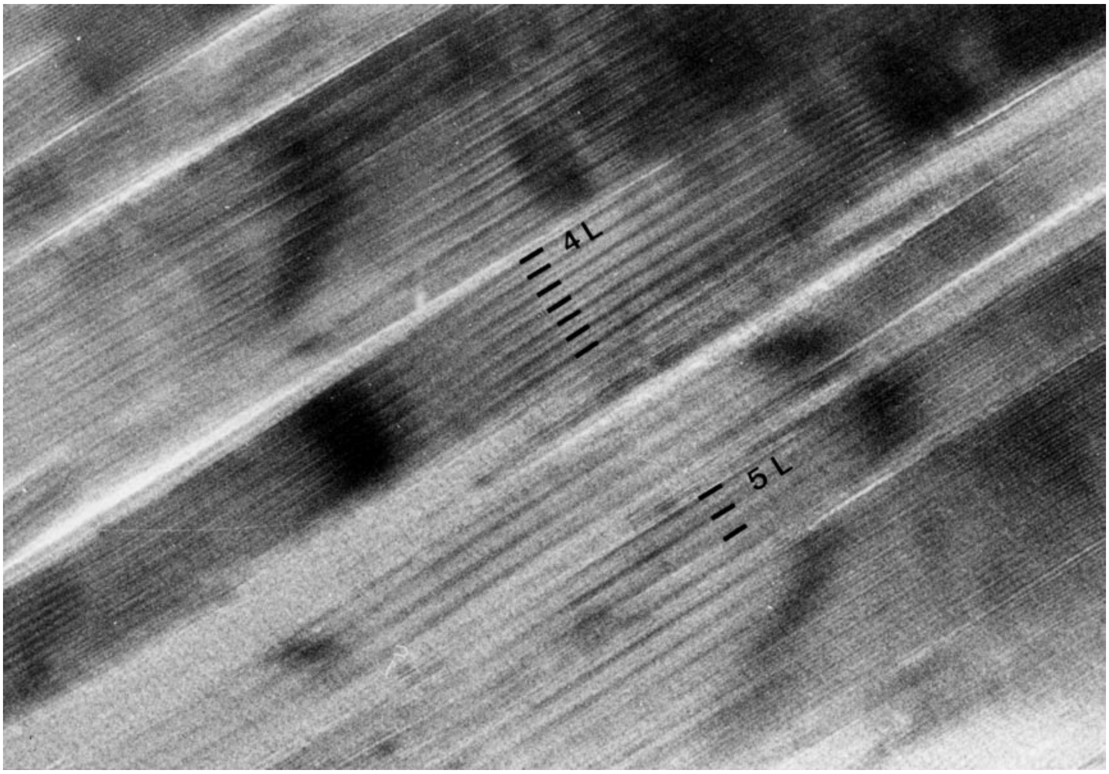


Fig. 7.- Coexistence of 4 and 5 layer polytypes with crystallographic continuity in a small area. Epizone sample (ZL-11).
Fig. 7.- Coexistencia de politipos de 4 y 5 capas con continuidad cristalográfica en áreas pequeñas. Muestra de la epizona (ZL-11).

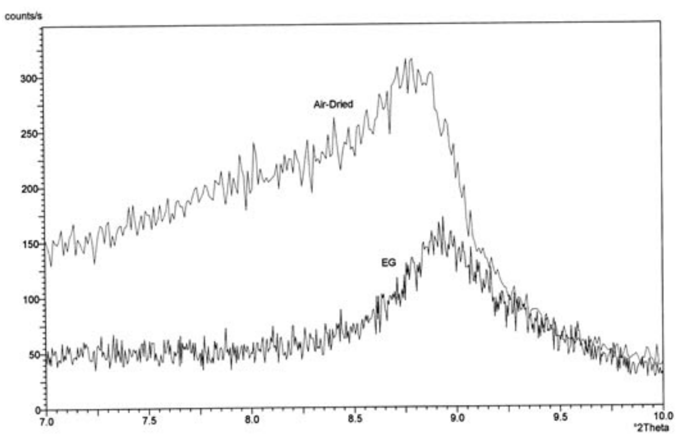


Fig. 8.- X-ray diagram of illite + illite/smectite mixed layer reflection (~10 Å), showing both the air-dried and ethylene-glycol (EG) treatments. Carboniferous sample (Fm25).
Fig. 8.- Diagramas de DRX mostrando la reflexión de ~10 Å correspondiente a ilita + interestratificado ilita/esmectita. Air-dried: muestra sin tratar. EG: muestra tratada con etilen-glicol. Secuencia carbonífera (muestra Fm25).

While collisional settings, the most widely recognized, developed in regions of crustal thickening, extensional metamorphism is associated with rift systems, including marginal and back-arc basins.

Such an extensional setting for the very low-grade metamorphism that affected the Cambrian sedimentary rocks is compatible with the characteristics of volcanism, of alkaline affinity, which has been attributed to an extensional passive continental margin setting (Sagredo and Peinado, 1992). Bandrés *et al*. (2002) suggested that the compressive Cadomian orogenic processes were rapidly followed by crustal relaxation and by thinning responsible for post-Cadomian rifting and formation of early Paleozoic sedimentary basins.

In conclusion, Cadomian deformation was responsible for the highest-grade and most significant metamorphic overprint in the Ossa-Morena Zone. This metamorphic process reached greenschist facies conditions even in the least affected rocks. Subsequently, a very-low grade extensional metamorphism or diastathermal metamorphism, affected the Cambrian materials during post-Cadomian rifting. No significant metamorphic effects were produced by Variscan orogeny; in the Devonian and Carboniferous sedimentary rocks, illite/smectite mixed layers were preserved and KI values characteristic of the early-to-late diagenesis boundary are present in Carboniferous pelites.

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