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Geobios 36 (2003) 649–663

GEOBIOS

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Tectonostratigraphy of Middle and Upper Palaeozoic black shales from the Porto-Tomar-Ferreira do Alentejo shear zone (W Portugal): new perspectives on the Iberian Massif

Tectonostratigraphie du Paleozoïque moyen-supérieur de la bande de cisaillement Porto-Tomar-Ferreira de l'Alentejo (Ouest du Portugal) : nouvelles perspectives pour le Massif Ibérique

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Received 2 October 2002; accepted 6 March 2003

Abstract

Middle/late Devonian and early Carboniferous metasedimentary sequences in the northernmost region (Porto-Espinho-Tomar) of the Ossa-Morena Zone (Portuguese Iberian Variscan Massif) contain black shales of very low to low-grade metamorphism. These metasedimentary rocks form a discrete NNW-SSE structure within a major shear zone (Porto-Tomar-Ferreira do Alentejo) and remain subparallel to the observed regional major structures (folding, thrusts or overthrusts). These black shales are overhanged and then imbricated in an upper Proterozoic metamorphic substratum. A multi-disciplinary study of these metasedimentary rocks from the Espinho-Tomar region has tectonostratigraphy, palynology, organic petrology and clay mineralogy combined methods. This approach provides new insights into the tectonic evolution and geological framework of Palaeozoic basement of the Iberian Variscides. Palaeoenvironmental and tectonostratigraphic implications on the Iberian geodynamic framework are discussed.

Résumé

À l'extrême Nord (Porto-Espinho-Tomar) de la Zone d'Ossa-Morena (Massif Ibérique des Variscides au Portugal), des successions d'âge Dévonien moyen/supérieur et Carbonifère inférieur renferment des shales noirs à métamorphisme de faible à très faible degré. Ces métasédiments forment un panneau structural NNO-SSE à l'intérieur de l'importante bande de cisaillement de Porto-Tomar-Ferreira do Alentejo, tout en demeurant sub-parallèles aux structures majeures régionales (plis, chevauchements, charriages). Ces shales noirs sont aujourd'hui imbriqués dans un substratum métamorphique d'âge Protérozoïque supérieur. L'étude multidisciplinaire (tectonostratigraphie,

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doi:10.1016/j.geobios.2003.03.002

palynologie, pétrologie organique, minéralogie des argiles, et pétrographie métamorphique) ouvre de nouvelles perspectives sur le cadre géologique et l'évolution tectonique du socle paléozoïque des Variscides Ibériques.

Keywords: Devonian; Carboniferous; Tectonostratigraphy; Palynomorphs; Porto-Tomar-Ferreira do Alentejo Shear Zone; Iberian Variscides; Western Portugal

Mots clés : Dévonien ; Carbonifère ; Tectonostratigraphie ; Palynomorphes ; Bande de cisaillement de Porto-Tomar-Ferreira do Alentejo ; Variscides Ibériques ; Ouest du Portugal

1. Introduction

Integrated studies making use of techniques from different geological disciplines (e.g., geological mapping, tectonostratigraphy, structural geology, metamorphic petrology, palynology, clay mineralogy, and organic petrology) constitute a powerful tool for understanding the geodynamic evolution of inner zones of orogens. To establish the late diagenetic to high-anchizone processes of mineral formation (ca. 200°–300° C, cf. Kisch, 1987, 1990; Merriman and Frey, 1999; Robinson and Merriman, 1999; Merriman and Peacor, 1999; Árkai et al., 2002) from metapelitic rocks is a complex task because of intergrowths of metamorphic phases (pulses), of the small grain-size, and of microstructural defects as well. Consequently, it is often very difficult to establish the relationships between the growth of metamorphic minerals and all the deformation history. Despite these difficulties, attempts have nevertheless been made to study very-low to low-grade metamorphic belts (e.g., Munhá, 1983; Lee et al., 1986; Merriman et al., 1995; López-Munguira and Nieto, 2000; Abad et al., 2001), particularly in high-strain zones (e.g., Merriman et al., 1995; Taylor et al., 1998; Merriman and Frey, 1999, and references therein).

Variscan very-low-metamorphism was reported for the first time on the Porto-Coimbra-Tomar metamorphic belt (northernmost domain of Portuguese part of the Ossa-Morena Zone) by Chaminé (2000), as indicated by the observation of monotonous black pelitic sequences. The probable age of this metamorphism is middle Palaeozoic (Fernandes et al., 2000, 2001). Chaminé et al. (2000) have presented a preliminary geological overview from mid-Palaeozoic metasediments in Albergaria-a-Velha region. The present work reviews the available geological data on metasedimentary rocks from Albergaria-a-Velha, extends their study up to Coimbra-Tomar (central Portugal), and improves it through the use of a multidisciplinary approach. Aiming at this, black shale and phyllite samples were systematically collected along a Porto-Tomar geotraverse, passing through Espinho-Ovar-Albergaria-a-Velha and Mealhada-Coimbra-Espinhal. The works by Gama Pereira (1987) and Chaminé (2000) stand an updated regional mapping and tectonostratigraphic background. The tectonostratigraphic nomenclature for the Porto-Coimbra-Tomar shear zone follows this authors. The Palaeozoic time scale of Gradstein and Ogg (1996), with updated divisions for the Devonian after Tucker et al. (1998), and Remane (2000) was used.

2. Geological and tectonic framework

In southwestern Europe, the Variscan Belt (*sensu stricto*) is recognised as a Palaeozoic orogen formed by collision of Gondwana and Laurusia in the late Devonian-early Carboniferous (e.g., Matte and Ribeiro, 1975; Badham, 1982; Lefort, 1989; Eden and Andrews, 1990; Dias and Ribeiro, 1993, 1995; Fonseca and Ribeiro, 1993; Ribeiro et al., 1995; Krohe, 1996; Martínez-Catalán et al., 1997; Matte, 1998; Fonseca et al., 1999; Matte, 2001; Gibbons and Moreno, 2002; Fernández et al., 2003). The Iberian Massif corresponds to one of the widest exposures of the SW European Variscan basement.

The western branch of the Porto-Coimbra-Tomar shear mega-domain (Gama Pereira, 1987, 1998; Chaminé, 2000), is part of a narrow NNW-SSE strip, which belongs to the Portuguese northernmost domain of the so-called Ossa-Morena Zone (OMZ) of the Iberian Massif (Lotze, 1945; Schneider, 1947; Julivert et al., 1974; Ribeiro et al., 1990). This zone has been interpreted as a tectonostratigraphic terrane that collided and was amalgamated with the Central-Iberian Zone (CIZ), either during the Variscan Orogeny (e.g., Lefort and Ribeiro, 1980; Lefort, 1989; Ribeiro et al., 1990), or during the Cadomian Orogeny (Gama Pereira, 1987, 1998). In both cases, it was juxtaposed on an earlier Cadomian structure that resulted from the merging of an arc and marginal basin complex across a dextral strike-slip shear zone. OMZ bounds to the South Portuguese Zone (SPZ) in a typical suture-zone exposed along the entire length of a belt of mid-Palaeozoic oceanic rocks, the so-called Beja-Acebuches Ophiolitic Complex (Soares de Andrade, 1972, 1978, 1983, 1985; Fonseca and Ribeiro, 1993; Quesada et al., 1994; Fonseca, 1995; Fonseca et al., 1999). This mega-domain is located alongside the western border of the Porto-Tomar-Ferreira do Alentejo [PTFA] dextral major shear zone (Chaminé, 2000; Chaminé et al., 2000; Ribeiro et al., 2001; Fernández et al., 2003). So, the PTFA major shear zone most probably connects the SW Iberian suture (Fonseca and Ribeiro, 1993; Fonseca et al., 1999) to the W-NW Iberian suture (Ribeiro et al., 1990; Dias and Ribeiro, 1995). This latter suture may represent the root zone of the NW ophiolite complexes, footwall high-pressure assemblages, and superposed Continental Allochthonous Terranes of possible Avalonian origin (Martinez-Catalán et al., 1997). The PTFA geodynamic framework is analogous, in the present, to the Pacific-North American plate boundary system of San Andreas dextral transform (e.g., Crowell, 1974; Davison, 1994), to the North Chugoku shear zone of SW Japan (Gutscher and Lallemand, 1999), and also to the late Cenozoic dextral strike-slip Alpine Fault of New Zealand orocline (Little and Mortimer, 2001).

The Porto-Coimbra-Tomar metamorphic belt (Fig. 1, Oliveira et al., 1992) comprises relative autochthonous and parautochthonous tectonostratigraphic units of low- to high-grade metamorphic rocks, as well as allochthonous units, of middle- to high-grade, assumed of upper Proterozoic times (e.g., Gama Pereira, 1987; Beetsma, 1995; Chaminé et al., 1998; Noronha and Leterrier, 2000; Chaminé, 2000; Fernández et al., 2003; and references therein). Recently, we reported for the first time in this region, mid-upper Palaeozoic black shales underlining discrete and scattered structures, N–S, parallel to major regional shear thrusts (Chaminé, 2000; Chaminé et al., 2000; Moço et al., 2001; Fernandes et al., 2001). These internal scattered basins constitute a NNW-SSE trending structure located at the Western border of the Portuguese part of the Ossa-Morena Zone, about 25-50 km from the Atlantic shoreline.

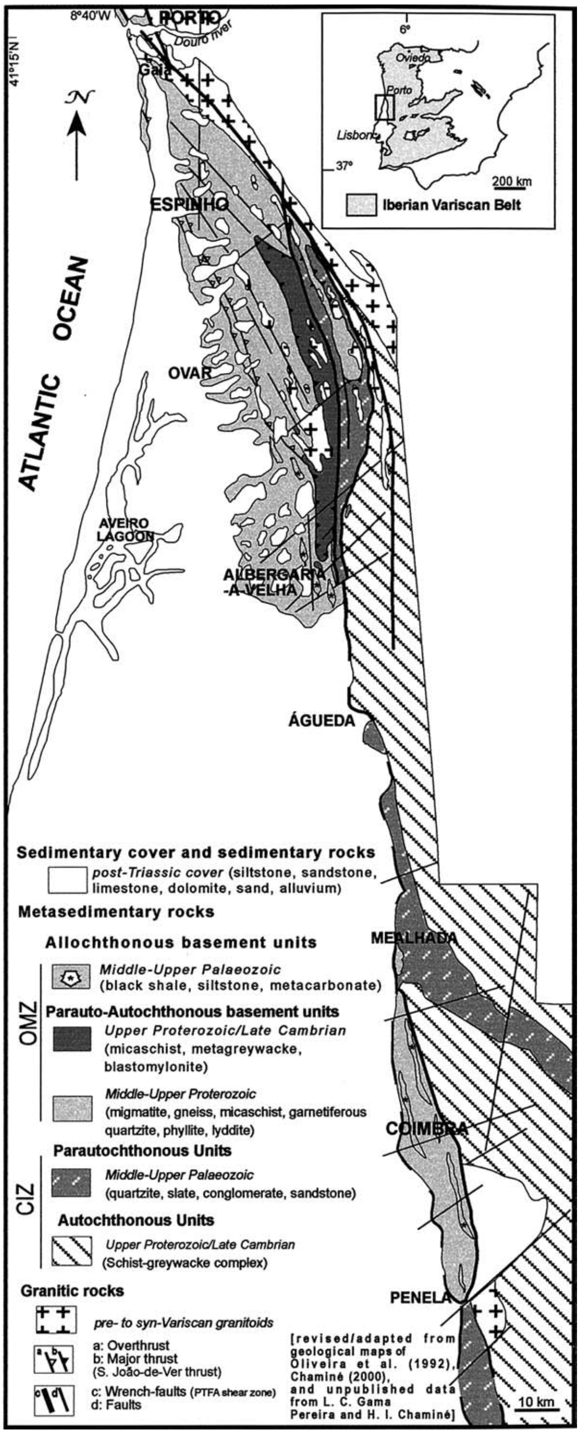


Fig. 1. Regional geotectonic framework of the Porto-Coimbra-Tomar shear zone), in Espinho-Penela sector (W Portugal).

Fig. 1. Cadre géotectonique régional de la bande de cisaillement de Porto-Coimbra-Tomar, dans le secteur d'Espinho-Penela (Ouest du Portugal).

3. Multi-disciplinary overview

For our study, the pre-Permian region, comprised between Porto and Tomar (Western Portugal), was subdivided into three major areas (Fig. 1): i) Espinho-Albergaria-a-Velha (Area I); ii) Mealhada-Coimbra (Area II); iii) Espinhal-Tomar (Area III). For laboratory analyses, 134 unaltered samples of shales, slates (phyllites) and micaschists were carefully collected in order to minimize the effects of weathering along a general W-E cross-section. The samples, representative of different metamorphic grades in the sequence, were studied by various methods, such as metamorphic petrology, palynology, organic petrology, geochemistry and clay mineralogy. The term "black shale" has been applied to shales having a broad range of shades of grey, i.e., containing varying amounts of organic matter.

4. Tectonostratigraphy

Detailed geological mapping and related work concerning the pre-Mesozoic substratum of the Porto-Coimbra-Tomar metamorphic belt (OMZ) are sparse. Main reports on this mega-domain are due to Sharpe (1849), Souza-Brandão (1914), Charnay (1962), Courbouleix (1972, 1974), Courbouleix and Rosset (1974), Severo Gonçalves (1974), Gama Pereira (1987, 1998), Chaminé (2000) and Chaminé et al. (2000).

The tectonostratigraphic framework (see Gama Pereira, 1987, 1998; Chaminé, 2000; Chaminé et al., 2000; Fig. 2) comprises a well-structured substratum composed of extremely monotonous garnetiferous black-greenish phyllites with interlayered amphibolite and lyddite lenses (Area I: Arada Unit, ArU; Area II: Vale de Canas Unit, VcU; Area III: Ribeira do Brás Unit, RbU; all related to the pre-Silurian "Série Negra" [s.l.] metasedimentary rocks). The total substratum ranges approximately 6 to 12 km wide. Radiometric dating indicated an upper Proterozoic age (Beetsma, 1995) for the Arada unit. This substratum is tectonosedimentary imbricated with middle-upper Palaeozoic black shales (Area I: Albergaria-a-Velha Unit, AvU; Area II: Portela do Ceira

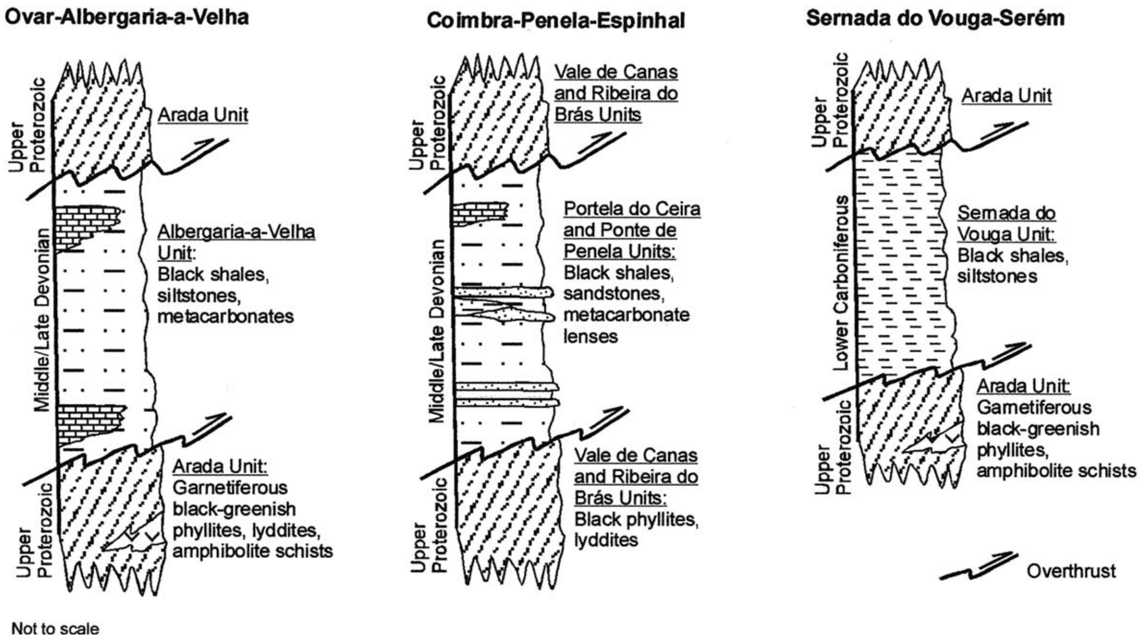


Fig. 2. Simplified tectonostratigraphic logs from Espinho-Albergaria-a-Velha-Coimbra-Tomar mid-upper Palaeozoic black metapelitic rocks (OMZ, W Portugal).

Fig. 2. Colonnes tectonostratigraphiques simplifiées des roches métapélitiques noires du Paléozoïque moyen-supérieur d'Espinho-Albergaria-a-Velha-Coimbra-Tomar (ZOM, Ouest du Portugal).

Unit, PcU; Area III: Ponte de Penela Unit, PeU) that are interbedded in laminated siltstones with interlayered metacarbonates and black metagreywackes (1-50 cm). These imbricated structures present variable thickness, ranging between 50 to 500 m. The newly mapped black shales yielded spores attributed to the middle/late Devonian and early Carboniferous (see below).

Deformation and metamorphism in the Porto-Coimbra-Tomar shear zone (OMZ) have different characteristics in each tectonostructural domain. The general features for the region point out for the existence of two regional tectonometamorphic main stages of Variscan deformation (e.g., Severo Gonçalves, 1974; Ribeiro et al., 1980; Gama Pereira, 1987; Chaminé, 2000) sometimes overprinting an earlier Cadomian blastomylonitic fabric (e.g., Gama Pereira, 1987; Chaminé, 2000; Noronha and Leterrier, 2000). The first Variscan stage produced important folding and thrusts, as well as the dominant regional schistosity. The second regional stage (related to CIZ Variscan-D_3, Dias and Ribeiro, 1995), also associated with mega-shear zones, produced a typical C-S deformation criteria and a non-coplanar cleavage schistosity with mylonitic or blastomylonitic foliation and crenulation. The metamorphic recrystallisation coincided with the first stage, and continued in the second stage, where the major event of deformation resulted in metamorphic blastesis and metasomatism (e.g., Severo Gonçalves, 1974; Gama Pereira, 1987; Chaminé, 2000).

The pre-Permian metapelitic basement is obscured mainly by Meso-Cenozoic cover deposits of the Lusitanian Basin, and bounded tectonically by medium- to high-grade metamorphic rocks of the PTFA metamorphic belt.

5. Palynology

Samples were prepared for palynological study (Fernandes et al., 2000, 2001) using standard treatment techniques involving maceration with HCl and HF, followed by oxidation of the residues with dry Schulze mixture (short oxidation times, of about 1 to 5 minutes were required, except for Ovar-Estarreja materials, which required about 30 minutes). Organic residues were systematically cleaned and concentrated during maceration procedures, thereafter strew mounts and permanent glass slides were prepared for transmitted light microscopic examination, subsequently studied and photographed. Samples, residues, and slides are stored in the archives of GIPEGO Laboratories (Department of Geology of University of Porto).

Albergaria-a-Velha (Area I) black shales provided palynomorph assemblages of late Givetian to early Frasnian age, whereas some samples from Sernada do Vouga-Serém (Area I) contained spores from the early Carboniferous (with a very large proportion of reworked Devonian palynomorphs). Black shale outcrops from Mealhada-Coimbra (Area II) provided a palynomorph association of late Famennian age, together with reworked Givetian/Frasnian forms. In the Penela-Espinhal sector (Area III) black shales yielded sporomorphs suggesting a Givetian age. A description of these assemblages follows (Fig. 3).

In the generally scarce organic residues obtained from Albergaria-a-Velha samples (Area I), a good number of palynomorphs can be found, the sporomorphs being clearly dominant over the acritarchs. Fragments of vegetal tissues are common. As a rule, palynomorphs are badly preserved,

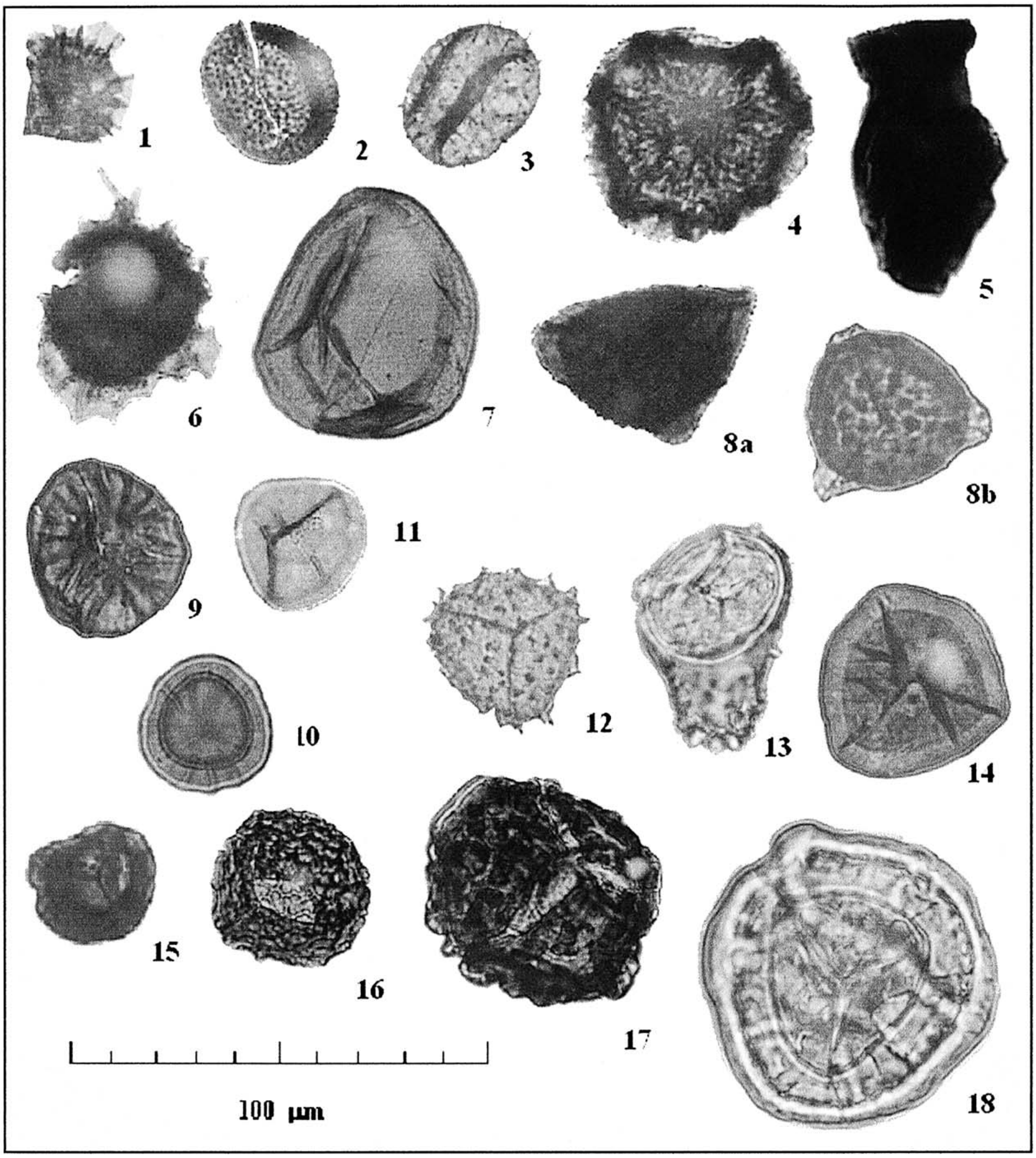


Fig. 3. Middle/late Devonian and early Carboniferous palynomorph assemblages from Espinho-Albergaria-a-Velha-Coimbra-Tomar black shales (OMZ, W Portugal). **1**. *Duvernaysphaera* sp.; **2**. *Lophosphaeridium* sp.; **3**. *Gorgonisphaeridium* sp.; **4**. *Maranhites* sp.; **5**. Chitinozoan; **6**. *Ancyrospora* sp.; **7**. *Geminospora micropaxilla*; **8a, b**. *Cristatisporites triangulatus*; **9**. *Emphanisporites rotatus*; **10**. *Emphanisporites annulatus*; **11**. *Geminospora micromanifesta*; **12**. *Grandispora famenensis* var. *minuta*; **13**. *Cyrtospora cristifer*; **14**. *Discernispotites micromanifestus*; **15**. *Densosporites anulatus*; **16**. *Microreticulatisporites microreticulatus*; **17**. *Savitrisporites nux*; **18**. *Reticulatisporites carnosus*. Early Palaeozoic: 5 (reworked); Givetian/Frasnian: 1–4; 6–11; Late Famennian/Tournaisian: 12–14; Namurian: 15–18.

Fig. 3. Associations de palynomorphes des shales noirs du Dévonien moyen/supérieur et du Carbonifère inférieur de la région d'Espinho-Albergaria-a-Velha-Coimbra-Tomar (ZOM, Ouest du Portugal). **1**. *Duvernaysphaera* sp. ; **2**. *Lophosphaeridium* sp. ; **3**. *Gorgonisphaeridium* sp. ; **4**. *Maranhites* sp. ; **5**. Chitinozoaire ; **6**. *Ancyrospora* sp. ; **7**. *Geminospora micropaxilla* ; **8a, b**. *Cristatisporites triangulatus* ; **9**. *Emphanisporites rotatus* ; **10**. *Emphanisporites annulatus* ; **11**. *Geminospora micromanifesta* ; **12**. *Grandispora famenensis* var. *minuta* ; **13**. *Cyrtospora cristifer* ; **14**. *Discernispotites micromanifestus* ; **15**. *Densosporites anulatus* ; **16**. *Microreticulatisporites microreticulatus* ; **17**. *Savitrisporites nux* ; **18**. *Reticulatisporites carnosus*. Paléozöique inférieur : 5 (remanié); Givétien/Frasnien : 1–4 ; 6–11 ; Faménnien/Tournaisien : 12–14 ; Namurien : 15-18.

the larger forms being almost invariably broken (e.g., palynomorphs with elongated ornamentation, belonging to the genus *Ancyrospora* or *Hystricosporites*, usually lack their termination). The palynomorph assemblage is characterised by the presence, among other spores, of *Cristatisporites triangulatus, Geminospora micromanifesta* and *Aneurospora* *greggsii*, as well as acritarchs: *Maranhites* sp., *Lophosphaeridium* sp. and *Duvernaysphaera* sp.. Such an assemblage corresponds to a late Givetian/early Frasnian age (*Contagisporites optivus* var. *optivus* – *Cristatisporites triangulatus* Assemblage Zone, Richardson and McGregor, 1986). Nevertheless, a slightly younger Frasnian age cannot be ruled out. In the Ovar-Estarreja sector a very badly preserved and quite poor association was found, pointing out for a similar age.

In Sernada do Vouga-Serém (Area I), although generally scarce, organic residues have been obtained, with a good number of palynomorphs. The associations observed are formed almost entirely by miospores; chitinozoans and most of acritarchs (s.l.) are interpreted as reworked. Fragments of vegetal tissues are very abundant, giving to the overall aspect of the organic residue a distinctive character, quite different from the one corresponding to the previously described Devonian outcrops; preservation is generally quite good. The distinctive character of materials originating from these samples is also indicated by their organic petrology features (see below). The palynomorph assemblage observed is characterised, mainly, by the presence of *Reticulatisporites carnosus, Savitrisporites nux, Spelaeotriletes* cf. *arenaceus, Microreticulatisporites* spp., *Lycospora* sp. and *Densosporites anulatus*, suggesting an early Namurian age (according to Smith and Butterworth, 1967; Clayton et al., 1977). Apart from reworked thick-walled acritarchs, *Tasmanites* sp. and chitinozoans, reworked spores also occur, in large amounts, as *Cyrtospora cristifer* and *Discernisporites micromanifestus* (late Famennian/Tournaisian), *Raistrikia nigra* (Visean), and *Cristatisporites triangulatus, Emphanisporites* sp. and *Ancyrospora* sp. (middle/late Devonian), among others.

Mealhada-Coimbra (Area II) organic residues, although scarce, provided a good number of palynomorphs, the sporomorphs being clearly dominant over the acritarchs. Fragments of vegetal tissues are common. As a rule, the larger palynomorphs are broken, especially in the more intensely deformed northern outcrops. Intensive reworking of Givetian/Frasnian forms almost masks the presence of a late Famennian association (e.g., Richardson and McGregor, 1986; Streel et al., 1987; Higgs et al., 1988, 1993, 2000) with *Diducites versabilis* and *Grandispora famenensis* var. *minuta*. Reworked older Devonian forms, as *Emphanisporites* sp., *Geminospora* sp. and *Cristatisporites triangulatus* (Richardson and McGregor, 1986) constitute the Givetian/Frasnian association. The limited number of the Famennian taxa identified, the tentative determination of *Verrucosisporites* cf. *mesogrumosus* (occurrence not known in Western Europe; Turnau et al., 1994), in the absence of other typical species of latest Famennian (Strunian) age, and the relatively close age of the reworked palynomorphs demand for further studies in this area, presently in progress.

A sample from Penela-Espinhal (Area III), of which several slides were studied, also yielded palynomorphs. Organic residue is scarce but palynomorph preservation is quite good. Vegetal tissues and debris are less common than in samples from Area II outcrops. The close vicinity of Triassic red sandstones and evaporites could explain the presence of gypsum as a secondary mineral resistate in the residues, creating a supplementary difficulty for sample treatment. Nevertheless, the association found, with *Cristatisporites triangulatus*, is clearly dominated by *Geminospora* spp., indicating a probable Givetian age (Richardson and McGregor, 1986). Acritarchs are very rare.

6. Organic petrology

The petrographic characterisation of the samples was performed on whole rock and light fraction (organic concentrates obtained by heavy liquid separation) polished blocks and slides, prepared according to the techniques described in Alpern et al. (1993). Microscopic examination was carried out using a microscope equipped with both reflected white and fluorescent blue light. The terminology used to identify and describe the organoclasts is the one proposed by the International Committee for Coal and Organic Petrology (ICCP). Hydrocarbons were recognised and classified following Alpern et al. (1992, 1993).

The total amount of organic matter, measured on whole rock from middle/late Devonian materials (Fig. 4), is poor. The dominant organoclasts, often-small particles, are sporinite and vitrinite with minor amounts of inertinite. The sporinites, with orange-brown fluorescence, often show their original form. Vitrinite appears as particles totally gelified, homogeneous, with small inclusions of mineral matter. Inertinite is observed mainly as debris (inertodetrinite). Zooclasts are also observed interstratified within the rock matrix. Free viscous hydrocarbons (HC) were identified, under ultraviolet light, mainly as exsudates and HC extracted by resin with no regular form. Mineral matrices are in general strongly impregnated, sometimes filling fractures and cavities. HC fluorescence colour is usually yellow, corresponding to the heavy and viscous fraction. The maturation, measured by mean random vitrinite reflectance (R_r, %), is at the level of catagenesis (ranged 1.0% and 1.3%), which is compatible with HC generation. The fluorescence colour of sporinite also agrees with this maturity level. Further studies, namely geochemical characterisation, are in progress in order to determine the correlation between the solid organic matter and HC.

The most abundant macerals of the organic assemblage from early Carboniferous materials (Fig. 5) are sporinite, followed in decreasing order of importance by inertinite and vitrinite. This suggests a very important continental contribution. Sporinites are often well preserved. We also observed rare zooclasts, probably remains of marine organisms. The organic matter observed can be classified in type II-III. Maturation was measured by distinct methods. The observation of the fluorescence colour of sporinites in organic concentrates, using transmitted white light, permitted to determine the Thermal Alteration Index (Staplin, 1969) as 3+. Mean ran-

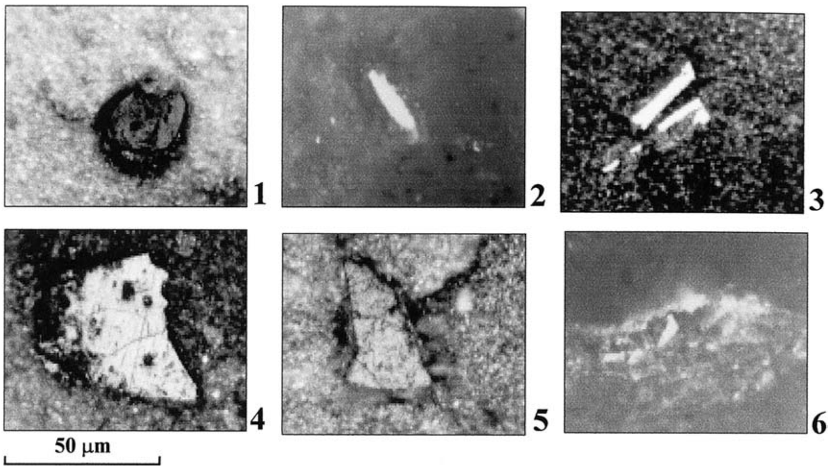


Fig. 4. Organic matter features of the middle/late Devonian black shales. (1, 2: Sporinite; 3: Organoclast; 4, 5: Vitrinite; 6: Exsudates. 1, 3, 4, 5: white reflected light, oil imersion. 2,6: ultraviolet reflected light, oil imersion).

Fig. 4. Caractérisation de la matière organique des shales noirs du Dévonien Moyen/Supérieur. (1, 2 : Sporinite ; 3 : Restes fauniques ; 4, 5 : Vitrinite ; 6 : Exsudats. 1, 3, 4, 5 : lumière blanche réfléchie, immersion d'huile. 2, 6 : lumière bleue, immersion d'huile).

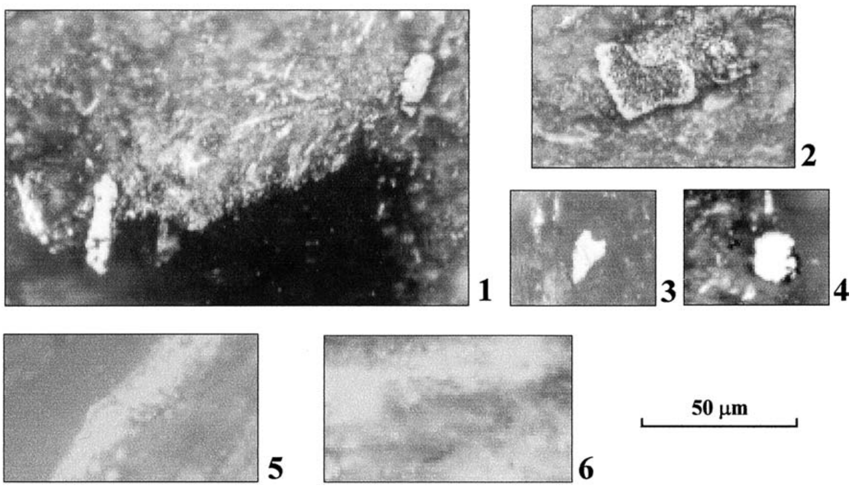


Fig. 5. Organic matter features of the early Carboniferous black shales. (1, 3, 4: Vitrinite; 2: Sclerotinite; 5, 6: HC. 1, 2, 3, 4: white reflected light, oil imersion. 5, 6: ultraviolet reflected light, oil imersion.).

Fig. 5. Caractérisation de la matière organique des shales noirs du Carbonifère Inférieur. (1, 3, 4 : Vitrinite ; 2 : Sclérotinite ; 5, 6 : Hydrocarbures. 1, 2, 3, 4 : lumière blanche réfléchie, immersion d'huile. 5, 6 : lumière bleue, immersion d'huile).

dom vitrinite reflectance is ranged 1.3% and 1.5%. Maturation is at the level of catagenesis. Following Alpern et al. (1992, 1993) methodology, we observed free HC mainly as matrix impregnations and fracture and cavity fillings.

The above results are particularly interesting. Indeed, if one considers that the west sector of PTFA major shear zone is mainly covered by Meso-Cenozoic deposits (Lusitanian Basin), with relative coarse lithology permitting migration and trapping of HC's, some Palaeozoic HC's could have been accumulated, the black shales described here acting as potential source rocks (Moço et al., 2001). These would constitute possible areas for oil or gas exploration in the Mesozoic basins as suggested in the past by Bless et al. (1977) and more recently by Uphoff et al. (2002).

Organic petrology analysis from the upper Proterozoic substratum shows a very poor organic content, lower than that of the middle/upper Palaeozoic. The organic particles, always very small, are thermally affected and consequently their classification is very difficult. They may be classified as "vitrinite-like" organoclasts. The coalification degree is always very high, corresponding to the upper epizone (low-grade metamorphism). Organic petrology data clearly indicate a distinct thermal evolution for the mid-upper Palaeozoic rocks and the basement materials. These conclusions are in agreement with previous metamorphic petrology studies, which place these materials in lower- to middle-greenschist facies, i.e., white micas + quartz + chlorite ± chloritoid ± garnet ± tourmaline ± apatite ± zircon (Severo Gonçalves, 1974; Chaminé, 2000).

7. Clay mineralogy

The mineralogical study of the samples, particularly of clay minerals, was based mainly on X-ray diffraction (XRD)

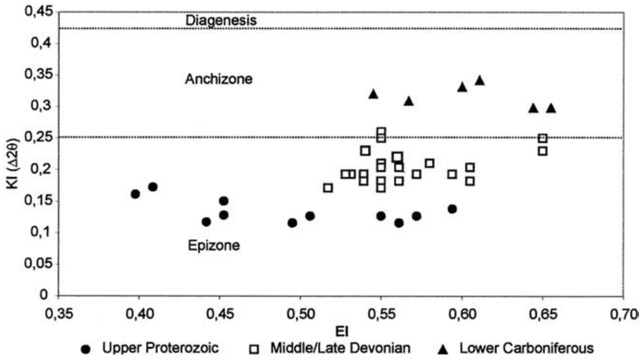


Fig. 6. KI/EI scatter diagram from the three main age groups studied (early Carboniferous, middle/late Devonian and upper Proterozoic metapelitic materials).

Fig. 6. Diagramme de dispersion KI/EI représentant les trois groupes majeurs de matériels métapélitiques étudiés (Carbonifère inférieur, Dévonien moyen/supérieur et Protérozoïque supérieur).

analyses, carried out using a Philips X'Pert PW3040/60 powder diffractometer with Cu*K*α radiation at the Aveiro University Laboratories. The terminology and recommendations suggested mainly by Kübler (1968), Thorez (1976), Kisch (1990, 1991) and Árkai et al. (2002) are followed. Several samples from Ovar-Tomar late Proterozoic and mid-upper Palaeozoic materials were studied, and organic petrology data (R_r, %) were compared with mineralogical data, namely Kübler's Illite Crystallinity Index (KI), Esquevin's Illite Index (EI) and Chlorite Crystallinity Index (CI).

Quartz, micas, chlorites and feldspars dominate the bulk mineral composition of the studied samples. Illite, chlorite and kaolinite are the most abundant minerals in the clay fraction. On the other hand, the distribution of clay minerals in the studied materials shows a differentiation according to the nature and age of the geological units. Middle/upper Devonian materials are richer in kaolinite and poorer in illite than upper Proterozoic materials, whereas early Carboniferous materials are the only ones in which chlorite is more than a simple accessory component. Therefore, we can characterise each of these materials on the basis of their clay mineral assemblages: i) early Carboniferous: KtIll(Chl) - Kaolinite + Illite + Chlorite; ii) middle/late Devonian black shales: IllKt(Chl) - Illite + Kaolinite + discrete Chlorite; and iii) upper Proterozoic materials: KtIll(Chl) - Kaolinite + Illite + discrete Chlorite.

Distribution of KI values along the sequences in the outcrops indicates, as a rule, a gradual increase of structural order within the distinguished materials, although upper Proterozoic materials have higher-structural order than those coming from mid-upper Palaeozoic materials. CI distribution is in good agreement with KI trend, in all materials.

The KI/EI scatter diagram (Fig. 6) also indicates a distinct behaviour of the three types of geological materials studied. Early Carboniferous materials exhibit KI values indicating low anchizone (KI 0.42-0.30, Merriman and Peacor, 1999) conditions, whereas those from upper Proterozoic materials (e.g., Arada Unit) indicate epizone conditions (KI < 0.25, Merriman and Peacor, 1999); middle/late Devonian (e.g., Albergaria-a-Velha Unit) show intermediate KI values, between high anchizone and epizone (KI 0.30-0.25, Merriman and Peacor, 1999). Most studied samples show EI values (0.55 to 0.65) corresponding to Al-rich (muscovitic) illites.

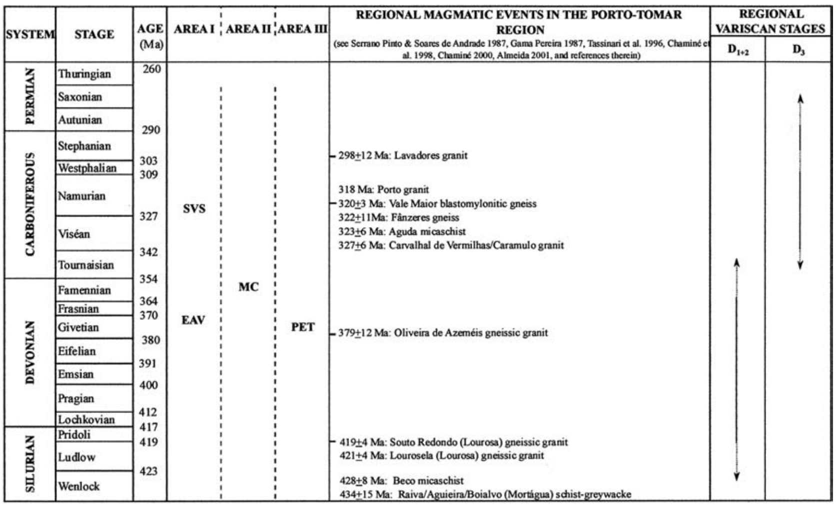
In addition, middle/late Devonian black shales commonly bear complex metacarbonates displaying white concentrations and veinlets of dickite, as well as mechanical admixture of dickite and kaolinite and mixed-layers of dickite/kaolinite that were developed as a consequence of the circulation, along the shear zones, of significant amounts of fluids that caused hydrothermal metasomatism and extensive weathering. Metasomatism related with the circulation of hot metamorphic waters, rich in CO_2 and SiO_2, is considered to be the cause of the formation of dickite. This polytype appears associated with magnesite and talc, which have been identified by XRD, under the form of thin veins crosscutting a dolomite-rich rock, with high contents in basic metals (such as Cr, Ni and Co).

Palaeothermal history deduced from clay crystallochemical, organic and metamorphic petrology data indicate very-low-grade metamorphic conditions (ca. 200°-250° C) for early Carboniferous materials, very-low to low-grade metamorphism (ca. 250°-300° C) for middle/late Devonian black shales, and low-grade metamorphism (i.e., lower- to middle-greenschist facies, ca. 300°-350° C; cf. Kisch, 1987; Bucher and Frey, 1994; Taylor et al., 1998; Merriman and Frey, 1999; Árkay et al., 2002) for upper Proterozoic basement.

8. Tectonostratigraphic and geodynamic implications

Complexity and diversity of sedimentary basins associated with strike-slip fault systems are almost as great as those observed for all other types of basins (e.g., Badham, 1982; Ingersoll, 1988; Sylvester, 1988; Davison, 1994; Woodcook and Schubert, 1994 and references therein). In fact, the major transform faults in oceanic lithosphere generally behave according to the plate-tectonic model, while strike-slip faults in continental lithosphere are extremely complex and not easily incorporated in a model involving rigid plates (e.g., Ribeiro, 2002). Moreover, strike-slip fault systems within continental crust are likely to experience alternating periods of extension and compression as slip directions adjust along major crustal faults (Crowell, 1974; Ingersoll, 1988). The occurrence of offsets and bifurcations in strike-slip fault systems can lead to the formation of either transpressional or transtensional (pull-apart) areas (Mann et al., 1983; Woodcook and Schubert, 1994; Basile and Brun, 1999). The shape of pull-aparts varies with their progressive development (Mann et al., 1983) from spindle shape, through "lazy-S" or "lazy-Z", and rhomb shapes to complex multi-rhomb shapes.

The results presented herein indicate the occurrence, in this region, of fault wedge and/or pull-apart like-basins formed at right stepping dextral of the PTFA major shear zone. Discrete metapelitic materials, with distinctive characteristics, have been observed along a strip subparallel to this shear zone, filling ancient small troughs. A large moderate to



EAV - Espinho-Albergaria-a-Velha outcrops; SVS - Sernada do Vouga-Serém outcrops; MC - Mealhada-Coimbra outcrops; PET - Penela-Espinhal-Tomar outcrops
(Ages according to the stratigraphic charts of Gradstein & Ogg 1996, Tucker et al. 1998 and Remane 2000)

Fig. 7. Stratigraphic ages of mid-upper Palaeozoic basins and geochronological dating of the regional tectonomagmatic events in the Porto-Tomar region: regional Variscan deformation stages for West OMZ.

Fig. 7. Âges stratigraphiques des bassins du Paléozoïque moyen-supérieur et datations radiométriques des événements tectonomagmatiques aux environs de Porto-Tomar : phases des déformations régionales pour les Variscides de l'Ouest de la ZOM.

high-angle normal fault borders each basin. These NNW-SSE middle/late Palaeozoic internal basins, of low- to high-anchizone metamorphism, have been interpreted as remnants of overlaying units; deposition would have occurred essentially on pre-early Palaeozoic OMZ deformed substratum of greenschist facies (Chaminé, 2000). The observed basins may thus be considered as key structures for tectonic modelling of the Portuguese northern branch of the OMZ along the PTFA major shear zone. Interestingly, Devono-Carboniferous pull-apart basins have been recognised in Brittany in dextral major shear zones (Rolet et al., 1994; Paris and Robardet, 1994a; Matte, 2001) associated with great lithospheric depths (Judenherc et al., 2002), namely, the North-Armorican Shear Zone (Châteaulin and Laval Basins) and the South-Armorican Shear Zone (Ancenis Basin).

The geometry of an elongated trough between two tectonostratigraphic mega-domains, with a long tectonic history of activity, explains the general present pattern of the Portuguese basins. Its peculiar tectonic features are in good agreement with previous interpretations of the PTFA major shear zone as a very important tectonic boundary, interpreted in general as a dextral lithospheric transform fault zone (e.g., Lefort, 1979, 1989; Lefort and Ribeiro, 1980; Dias and Ribeiro, 1993; Shelley and Bossière, 2000; Chaminé et al., 2000; Ribeiro et al., 2001; Fernández et al., 2003). It is possible to draw a preliminary sketch attempting to establish a general correlation framework. Indeed, it appears from our data that tectonic activity along the PTFA major shear zone was probably irregular and discontinuous in space and time, according to the complex heterogeneous distribution of internal basins and magmatism (Fig. 7) (Almeida, 2001 ; Tassinari et al., 1996). The structure and lithofacies of these scattered basins may now be interpreted in a tentative general model, invoking combined extension and strike-slip framework. Black shale materials would correspond to the progressively deformed syndeposition and would record large-scale influence of strike-slip during sedimentation. Scattered pull-apart and/or fault-wedge basins would have been filled with well-calibrated and fine-grained sediments proceeding from continental erosion. The combination of subsidence and lateral displacements were responsible for the fining upwards grain size motif recognised in parts of basin fillings from the Coimbra region (Area II).

Palynostratigraphic and organic petrology studies performed on middle/late Devonian black shales suggest the occurrence of marine palaeoenvironmental conditions in this region. Petrographically, a relative abundance of plant debris with small amount of faunal remains can be observed, also suggesting sedimentation in a marine environment probably close to a continental source. On the other hand, the observation of a large proportion of plant tissues and debris in the palynological residues, as well as the characteristics of the palynomorph associations (with sporomorphs clearly dominating over acritarchs, and the latter being mostly sphaeromorphs or pteromorphs with the apparent absence of polygonomorphs or acanthomorphs), again support deposition in a marine basin with a strong continental contribution. In early Carboniferous materials, sporomorphs (including frequent reworked forms) are overwhelmingly dominant, acritarchs being quite rare, usually thick-walled, and possibly reworked; plant tissues and debris are extremely abundant. In addition, our data are in agreement with a stratigraphic polarity migration of the scattered middle/late Palaeozoic basins from North to South (present coordinates), along the tectonic lineament of the PTFA.

Correlations between out-of-sequence tectonostratigraphic units described in this paper and other stratigraphic units from SW OMZ domains (or of OMZ affinities) are not simple to establish. In fact, middle/late Devonian and early Carboniferous times are very scarcely represented in the

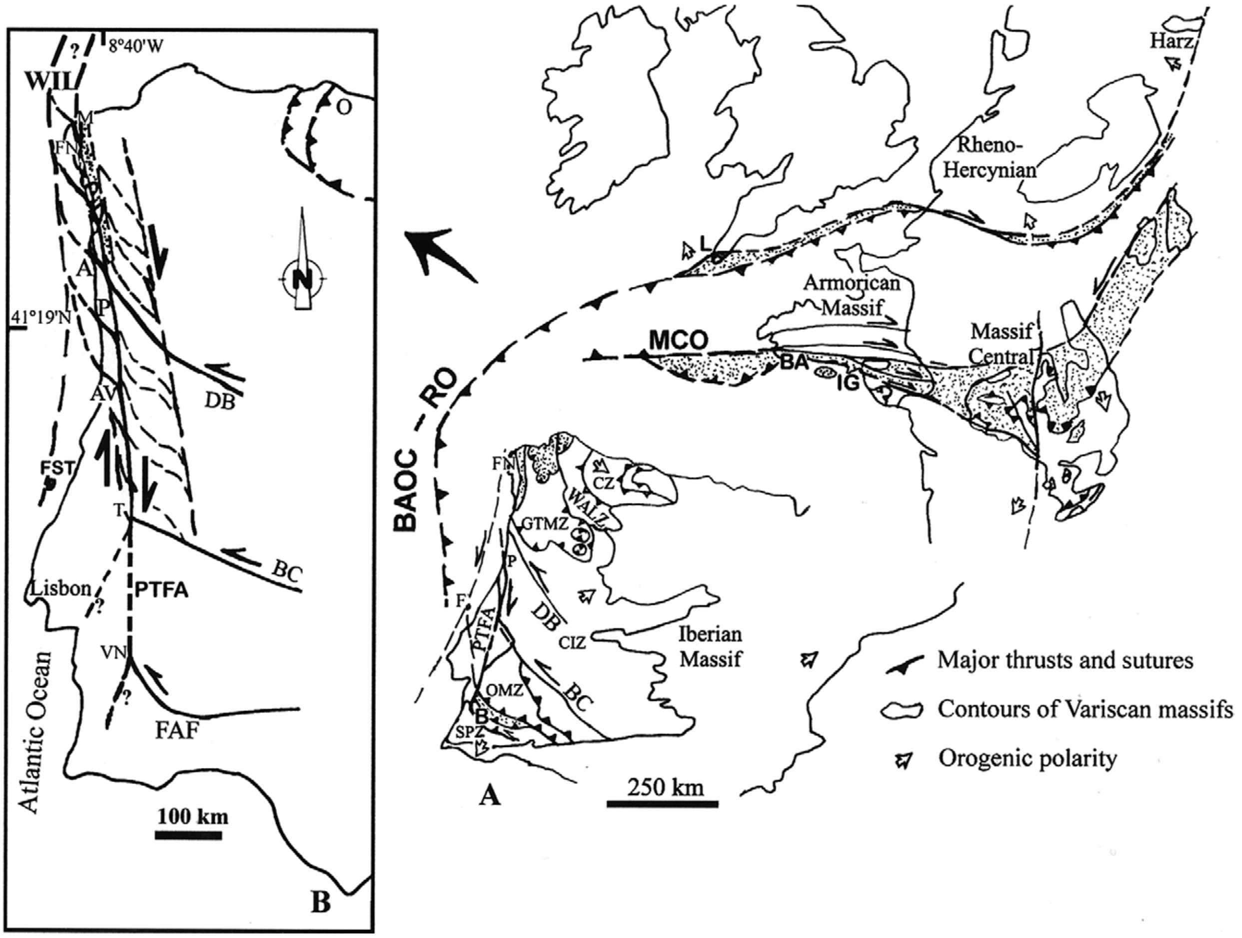


Fig. 8. Tentative geodynamic model. **A**. Correlation between Variscan sutures in western Europe (adapted from Soares de Andrade, 1978, 1985; Ribeiro et al., 1990, 1995; Matte, 1998; Fonseca et al., 1999; Franke, 2000). The stippled area corresponds to the innermost crystalline nappes, ophiolitic remnants and related root-zones. (BA: Baie d'Audierne, IG: Isle de Groix, MCO: Massif Central Ocean, BAOC–RO: Beja–Acebuches Ophiolitic Complex – Rheic Ocean; Iberian Zones: CZ: Cantabrian Zone, WALZ: West-Asturian Leonese Zone, GTMZ: Galicia–Trás-os-Montes Zone, CIZ: Central-Iberian Zone, OMZ: Ossa-Morena Zone, SPZ: South Portuguese Zone; Shear Zones: PTFA: Porto-Tomar-Ferreira do Alentejo, BC: Badajoz-Córdoba; DB: Douro-Beira Trough). **B**. Interpretative geodynamic model of the Western Iberian Line (WIL) in the OMZ framework. (Shear Zones and Terranes: PTFA: Porto-Tomar-Ferreira do Alentejo, FAF: Ferreira do Alentejo-Ficalho, BC: Badajoz-Córdoba, DB: Douro-Beira, FST: Farilhões suspect terrane; Localities: VN-Vendas Novas, T-Tomar, AV-Albergaria-a-Velha, P-Porto, A-Apúlia, FN-Finisterre, O-Oviedo.)

Fig. 8. Modèle géodynamique. **A**. Corrélation entre les sutures varisques dans l'Ouest Européen (adapté de Soares de Andrade, 1978, 1985 ; Ribeiro et al., 1990, 1995 ; Matte, 1998 ; Fonseca et al., 1999 ; Franke, 2000). L'aire pointillée correspond aux nappes cristallines internes, témoins ophiolitiques et zone de racines. (BA : Baie d'Audierne, IG : Isle de Groix, MCO : Océan du Massif Central, BAOC-RO : Océan Rhéique – Complexe Ophiolitique Beja-Acebuches ; Zones des Variscides : CZ : Zone Cantabrique, WALZ : Zone Ouest AstureLéonaise, GTMZ : Zone de la Galicia-Trás-os-Montes, CIZ : Zone Centro-Ibérique, OMZ : Zone d'Ossa-Morena, SPZ : Zone Sud-Portugais ; Bande de cisaillement : PTFA : Porto-Tomar-Ferreira do Alentejo, BC : Badajoz-Córdoba ; DB : Bassin Houiller du Douro-Beira). **B**. Modèle interprétatif proposé pour le linéament Occidental Ibérique (WIL) dans le cadre de la Zone d'Ossa-Morena (bandes de cisaillement et terrains exotiques : PTFA : Porto-Tomar-Ferreira do Alentejo, FAF : Ferreira do Alentejo-Ficalho, BC : Badajoz-Cordoba, DB : Douro-Beira, FST : Farilhões terrain exotique ; Localités : VN-Vendas Novas, T-Tomar, AV-Albergaria-a-Velha, P-Porto, A-Apúlia, FN-Finisterre, O-Oviedo).

Portuguese sector of the OMZ (see Ribeiro et al., 1990; Oliveira et al., 2000). Devonian formations have already been described in early studies of regional geology and on the palaeontological (macro and/or microfossils) record, by Pruvost (1914), van den Boogaard (1963, 1972), Conde and Soares de Andrade (1974), Soares de Andrade (1983, 1985), Ribeiro (1983), Soares de Andrade and V. Oliveira (1983) and Moutinho da Silva (1988). More recently, palynostratigraphic preliminary reports by Pereira and Oliveira (2001a, b) also point out late Devonian/early Carboniferous ages for metapelitic units (e.g., Cabrela-Vendas Novas and Toca da Moura outcrops) of the Southern domain of the OMZ (Vendas Novas-Ferreira do Alentejo-Ficalho shear zone; e.g., Soares de Andrade, 1983, 1985; Fonseca and Ribeiro, 1993; Almeida et al., 2001). An integrated geological framework requires, however, more detailed descriptions of these units. These would allow precise interpretations of the relationships between Devonian and Carboniferous internal basins and main units of similar age from the OMZ and the South Portuguese Zone (SPZ).

The continental margins of Laurusia, N-Gondwana and the mosaic of widespread intermediary microplates are known to have reached collisional stages during the latest Devonian throughout early Carboniferous times (e.g., Badham, 1982; Ribeiro et al., 1990; Rolet et al., 1994; Matte, 1998; Shelley and Bossière, 2000). It is therefore crucial, in order to understand the overall geological history, to establish the Variscan palaeogeographic position of Iberia (e.g., Paproth, 1982; Gama Pereira, 1987; Paris and Robardet, 1994b; Korn et al., 2000; Shelley and Bossière, 2000; McKerrow et al., 2000) and to identify the intervening Iberian terranes (e.g., Gama Pereira, 1987; Ribeiro et al., 1990; Martínez Catalán et al., 1997). The PTFA major shear zone stands as an essential research target to such an endeavour.

The overall skeleton structure, in the core of the emerging Variscan orogen, materialises marine pathways that intermittently connected the remaining marine like Rheno-Hercynian – South Portuguese basins adjacent to the Laurusian landmass, in the North, with the Ibero-Armorican – and Mediterranean basins juxtaposed to the main Gondwanaland coast-line (Korn and Horn, 1997; Korn et al., 2000; McKerrow et al., 2000; Franke, 2000). These linkages were maintained at least until the earliest Visean (ca. 340 Ma). Regarding that connection, Korn and Horn (1997) and Korn et al. (2000) present significant evidence based on goniatite biogeographical trends. Those faunal assemblages allow for the establishment of a general control about the timing and rate of the orogenic uplift of the Variscan belt. Korn et al. (2000) propose that a continuous transeuropean mountain barrier separated southern marine basins from northern basins at least in late Visean times (ca. 325 Ma). Interestingly, in southwestern Iberia the miospore and acritarch assemblages previously recorded (e.g., Cunha and Oliveira, 1989; Pereira et al., 1994; Pereira, 1999; Fernandes et al., 2001, and references therein) are very similar in composition to those observed from the same stratigraphic interval in other areas of southern EuroAmerica (e.g., Streel et al., 1987; Higgs et al., 1988; Higgs et al., 1993; Clayton, 1996; Streel and Loboziak, 1996; McKerrow et al., 2000).

Somehow, when a new paradigm emerges, one must give further attention to what was previously taken as being soundly established. The clear differentiation into North and South realms, in the classical OMZ (Julivert et al., 1974; Ribeiro et al., 1990), and its relationships with the northwestern prolongation of OMZ lithologies along the PTFA major shear zone (Chaminé, 2000), should considered if one hopes to understand the substratum structure. In fact, it appears as if a N–S narrow (15-35 km wide) high-deformation corridor exists, running parallel to the Galician-Portuguese shoreline for over 520 km, which bears medium- to high-metamorphic rocks and shear granitic plutons (Fig. 8). This corridor may extend from Finisterra to Tomar, passing through Muros, Vigo, La Guardia, Caminha, Apúlia, Porto, Espinho, Albergaria-a-Velha and Espinhal. In our work, this high-strain zone has been named Western Iberian Line (WIL). This westernmost deformation corridor of lithostructural out-of-sequence sheets with Ossa-Morena Zone affinity, would be subparallel to the northern portion of the Malpica-Lamego Line (Llana-Fúnez and Marcos, 2001). The WIL presents different types of micro- to macro-scale structure exposures formed at mid-crustal levels in a tectonic dextral strike-slip regime, therefore constituting a prolific imprinting of the complex tectonometamorphic events that occurred in the shoreline of West Galicia (e.g., Arps, 1970; Buiskool Toxopeus et al., 1978; Martínez et al., 1990; Martínez-Catalán et al., 1997; Llana-Fúnez and Marcos, 2001, and references therein) and/or West Portugal (e.g., Souza-Brandão, 1914; Soen, 1970; Severo Gonçalves, 1974; Ribeiro et al., 1980; Gama Pereira, 1987, 1998; Serrano Pinto and Soares de Andrade, 1987; Fernandes et al., 1998; Chaminé et al., 1998; Noronha and Leterrier, 2000; Chaminé 2000, and references therein).

9. Concluding remarks

In summary, given the complex geotectonic boundaries observed in the Porto-Coimbra-Tomar Shear Zone (Gama Pereira, 1987; Chaminé, 2000), it is natural that, at a regional scale, a single method of survey, be it geological, palynological, petrological or mineralogical, cannot yield a clear and straightforward result. Accordingly, we understand that the overall picture of this geological paradigm should be built-up on a systematic process of complementary data syntheses and crosschecks as a patchwork (e.g., Bard et al., 1980; Ribeiro et al., 1990; Krohe, 1996; McNoleg, 1996; Franke, 2000; Llana-Fúnez and Marcos, 2001; Fernández et al., 2003). Moreover, the results of such multi-disciplinary approaches may deeply significantly influence future investigations on the Iberian Variscides, especially those related to basin analysis, regional tectonostratigraphy, geodynamics, mineral resources, and hydrocarbon potential. In an even more general view, a detailed terrane analysis, as those that have been carried out along the East coasts of U.S.A. and Canada (e.g., Haworth and Lefort, 1979; Williams, 1984; Mueller et al., 1996), must be pursued, as a long term goal, on this mirror side of the North-Atlantic Ocean (e.g., Ribeiro et al., 1990, 1995; Martínez-Catalán et al., 1997). Furthermore, concerning this latter issue, one must always bear in mind a fundamental question: how can our improved knowledge of the Porto-Tomar-Ferreira do Alentejo shear zone help to the correlation between some major suture lineaments of the European Variscides, namely those of Beja-Lizard-Harz and Cordoba-Baie d'Audierne-"Massif Central" (e.g., Bernard, 1974; Bard et al., 1980; Krohe, 1996; Zeh et al., 2001) ?

Acknowledgements

This research was funded by post-doctoral and doctoral scholarships from "Fundação para a Ciência e a Tecnologia" (FCT, PRAXIS XXI) to HIC (SFRH/BPD/3641/2000, Aveiro) and to LPM (BD/2767/96, Porto), respectively. This study was supported by a grant from the MODELIB/FCT project (POCTI/35630/CTA/2000 FEDER). Thanks are also due to M.A. Marques da Silva (Aveiro) for providing deep borehole samples, and to C. Regêncio Macedo (Coimbra) for sharing unpublished results of a radiometric study in the Caramulo region. We benefited from discussions with R. Rodríguez-Gonzaléz (León), A. Ribeiro (Lisbon), A. Marcos (Oviedo), J.M. Munhá (Lisbon), F. Sodré Borges (Porto), M.J. Lemos de Sousa (Porto), M. Serrano Pinto (Aveiro), R. Baptista (Petrogal Exploration, Lisbon), G. Gutiérrez-Alonso (Salamanca), and other colleagues for critical comments provided during this investigation. Thanks are also due to Ricky Pinheiro (AfriOre, South Africa) for helpful discussions and improvement of the text. We acknowledge Michel Robardet and Alain Le Hérissé for detailed reviews that helped to improve the clarity of the manuscript.

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