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Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin (Portugal)[1]

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The Mesozoic and Cenozoic sedimentary record of the western Portuguese passive margin is about 5 km thick. In the Mesozoic deposits, several unconformity-bounded stratigraphic units (UBS) are defined: UBS1 Triassic-Callovian; UBS2 middle Oxfordian-Berriasian; UBS3 Valanginian-lower Aptian; UBS4 upper Aptian-lower Campanian and UBS5 upper Campanian-Maastrichtian. Onshore, the Cretaceous northern sector of the Lusitanian Basin is up to 500 m thick, and developed mainly in terrestrial siliciclastic facies. Three stages are recognised in its tectonic and sedimentary evolution. (1) During the late Berriasian to early Aptian, marine and terrestrial sedimentation was restricted to central and southern sectors of the basin. (2) The late Aptian-early Campanian stage began with tectonic activity corresponding to the uplift of the western and eastern borders of the basin, along with an important enlargement the area of the sedimentation. Siliciclastic facies derived from the intense erosion of the Hesperic Massif are interpreted as coalescent wet alluvial fans passing southwestwards into marginal marine sediments and a carbonate platform. Local drainage to the east is related to the uplift of the Berlenga Horst during the late Aptian. An important fall in sea-level followed the long term Albian-Cenomanian transgression resulting in progradation and, later, strong incision of the depositional systems. The top of the siliciclastic record of this stage (UBS4) is marked by an important silcrete, indicating weathering during a long period of non-deposition (Santonian ?—early Campanian). (3) The late Campanian–Maastrichtian period is marked by the main Mesozoic reactivation of the Nazaré-Lousã Fault, significant volcanic activity (emplacement of subvolcanic complexes, basaltic extrusives and associated dykes) and diapirism. Onshore, UBS5 consists of yellowish quartzarenites and red mudstones, interpreted as a meandering fluvial system draining to the northwest, changing distally to transitional and marine environments. The fluvial sediments are interpreted as second cycle, with the main provenance being previous Cretaceous sediments (UBS4) whose erosion can be related to uplift of the southern block of the Nazaré-Lousã fault. Correlative diapiric reactivations built up coalescent peridiapiric alluvial fans, transverse to N–S diapiric ruptures, that consist of calcareous conglomerates and red mudstones. Offshore, very shallow marine fine clastics and dolostones are the main facies.

KEY WORDS: Lusitanian Basin; central Portugal; Cretaceous; unconformity-bounded stratigraphic units; sedimentary evolution; tectonics; diapirism; basin analysis.

1. Introduction

The Lusitanian Basin is located on the Portuguese part of the western Iberian margin (Figure 1). The basin is nearly 130 km wide and about 340 km long; its onshore area totals over 23 000 km^2. The basin connects southward with the Algarve Basin and northward, via a basement ridge, to the Oporto (or Galicia) Basin, bounded by the Porto and Vigo seamounts and by the Galicia bank.

Surface outcrop of the Cretaceous sections is relatively widespread. The outcrop pattern of the basin is dominated by a NNE–SSW trending strip of Mesozoic rocks about 50–100 km wide, which corresponds to an inverted zone (Estremenho Calcareous Massif and Arrábida chain) separating two Tertiary sub-basins (Mondego and Lower Tagus) (Figure 2). Towards the northeast

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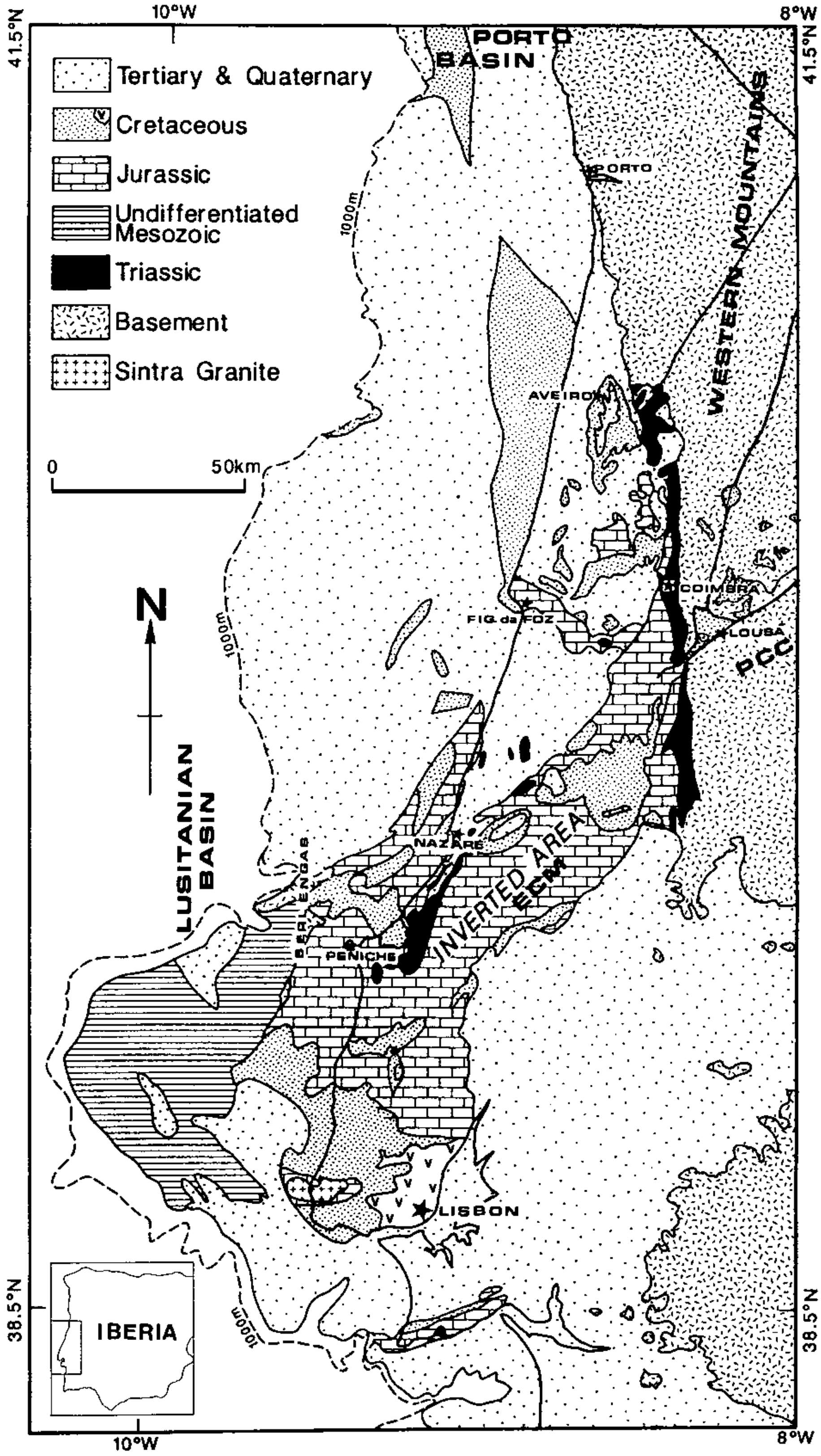
10°W
8°W
41.5°N
38.5°N
Tertiary & Quaternary
Cretaceous
Jurassic
Undifferentiated Mesozoic
Triassic
Basement
Sintra Granite
0
50km
N
PORTO BASIN
PORTO
WESTERN MOUNTAINS
AVEIRO
COIMBRA
LOUSÃ
PCC
FIG. da FOZ
1000m
LUSITANIAN BASIN
BERLENGAS
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(Portugese Central Cordillera) and north-northeast (Western Mountains), the basement is also uplifted and faulted against Cretaceous-Pliocene cover (Ferreira, 1991; Cunha, 1992).

In the northern sector of the Lusitanian Basin several detailed stratigraphic and sedimentologic studies of the siliciclastic Cretaceous (the main facies) have been undertaken (Pena dos Reis, 1983; Daveau (*et coll.*) 1985; Dinis, 1990; Cunha, 1992), and modern interpretative studies on a regional scale are also available (Pena dos Reis & Cunha, 1989a, b; Pena dos Reis *et al.*, 1991; Cunha, 1992, 1993; Cunha & Pena dos Reis, 1992, 1993; Pena dos Reis *et al.*, 1992; Dinis *et al.*, in press) but Cretaceous sequence stratigraphy and regional eustatic curves have not yet been published. This paper reviews the most recent lithostratigraphic and sedimentologic data on the Cretaceous in this region and summarizes present knowledge of the tectonic and sedimentary evolution of this sector of the Lusitanian Basin during this period.

The methodology of the synthesis was based on modern techniques of basin analysis, especially the conceptual background derived from the tectono-sedimentary basin analysis (Megías, 1982) as well as the development of sequence stratigraphy (Mitchum *et al.*, 1977; Vail *et al.*, 1984). Later contributions on this topic may be found in Riba (1989) and Pardo *et al.* (1989), among others. Like Chang (1975) we use the designation of unconformity-bounded stratigraphic unit (UBS). The sedimentary breaks that are the boundaries of the UBS are outlined either by sharp erosional surfaces, unconformities, palaeokarst surfaces or significant changes in the evolutionary trend of the sedimentary filling in the basin. Overall, they constitute major sedimentary discontinuities that can be recognized throughout the basin and which we relate to tectonic activity in the basin. One UBS could comprise one or more depositional sequences in the sense of Vail *et al.* (1977).

2. Structure and igneous activity

The deepest and greater part of the Lusitanian Basin is broadly defined by a deep Mesozoic and Cenozoic north-trending trough containing a sedimentary succession up to about 5 km thick. It is bordered on its western and eastern flanks by thinner Mesozoic and Cenozoic sequences. The basin is bounded to the east by extensive Hercynian basement rocks of the Hesperian Massif. The western offshore boundary is also a basement marginal horst system, which is exposed on the Berlengas archipelago as well as on submarine hills. Basin development was separated from the main Atlantic-margin rift basin which is preserved today in deep water west of the continental shelf break.

The Lusitanian Basin exhibits two main tectonic styles: one dominated by halokinetic structures, and the other by faulting. These structures show dominant NNE–SSW and NE-SW trends, identical to the trends of Hercynian basement faults. Near the present coast line, where Hettangian evaporites are thicker, diapiric structures developed over reactivated Hercynian basement faults (Zbyszewski, 1959; Wilson *et al.*, 1990). Salt movements were significant during

Figure 1. Geological map of the onshore part of the Lusitanian Basin and adjacent continental shelf (modified from Wilson *et al.*, 1989; simplified from Boillot *et al.*, 1975, and Boillot & Mougenot, 1978). The northeast to southwest-trending strip of Mesozoic sediments, which resulted from late Miocene inversion, separates two Tertiary sub-basins: Lower Tagus (south) and Mondego (north). Legend: ECM; Estremenho Calcareous Massif; PCC, Portuguese Central Cordillera; VVV, Lisbon volcanic complex.

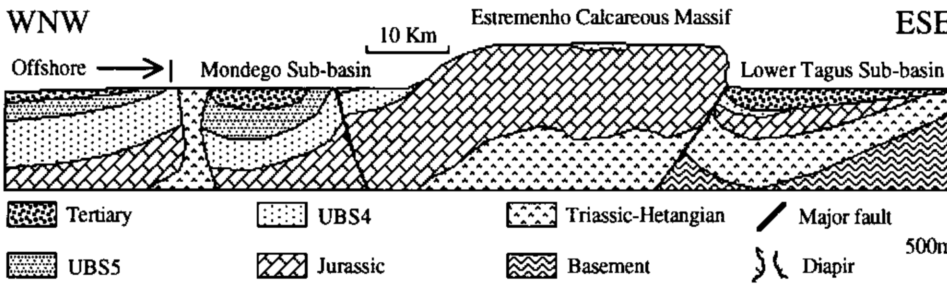

Figure 2. Schematic geological section of central Portugal.

several periods. They were possibly initiated in Sinemurian times, continued during the Middle Jurassic according to Guéry (1984), and reached a maximum at the beginning of the Late Jurassic. Diapiric structures were reactivated before the deposition of the upper Aptian, and more dramatically in the late Campanian (Pena dos Reis, 1983). Significant later compressive reactivations of the diapirs, with significant uplift, occurred during the late Tortonian-Quaternary.

From Triassic to Late Cretaceous times, the basin subsided because of E–W extension related to subsequent spreading in the nearby Atlantic (Montenat *et al.*, 1989; Wilson *et al.*, 1990). The formation and evolution of the Tertiary basins are closely related to the upbuilding of the Pyrenean and Betic orogens and the internal deformation which affected the Iberian microplate (Vegas & Banda, 1982; Anadón *et al.*, 1989). From Paleogene to middle Tortonian times, secondary extension within the Eurasian plate produced two grabens oriented SW–NE in the west Iberian margin. Although extensional structures dominate the fabric of the western Iberian passive margin, they have been modified to varying degrees by the late Tortonian–Quaternary compressional events (Betic orogeny) which led to the structural inversion of the basin. According to Ribeiro *et al.* (1990), continental collision in the Betic Chain induced foreland detachment in basement and cover rocks. Younger sediments were uplifted by as much as 1 km. Both on- and offshore, evidence of thrusting and reverse faulting of this age has been demonstrated (Pena dos Reis & Cunha, 1989a; Wilson *et al.*, 1989; Ribeiro *et al.*, 1990; Ferreira, 1991; Cunha, 1987, 1992).

The low rate of subsidence during the Cretaceous and Tertiary, is reflected by a very thin sedimentary record containing several unconformities (Cunha, 1992). During Late Jurassic and post-Ypresian times, several sub-basins were created, between which communication was either restricted or non-existent.

Two main phases of igneous activity occurred and are only recorded south of the Nazaré Fault. The older phase, ranging from Oxfordian to Valanginian in age (160–133 ma; Ferreira & Macedo, 1979, 1983), is represented by basalts, teschenites and diabase dykes trending either NNE–SSW or ESE–WNW. The second episode (late Campanian–Maastrichtian) is expressed by intrusive alkaline complexes (Sintra, Sines and Monchique) which were emplaced between 83–70 ma; the basaltic extrusives and associated dykes in the Lisbon-Nazaré region yield similar dates (Ferreira & Macedo, 1979; MacIntyre & Berger, 1982). Uraninites from dykes that cross-cut metasediments in the Beira Alta region (northeastern central Portugal) were dated at 80–100 ma (Stieff & Stern, 1960) and could also be related with this distensive event.

3. Stratigraphic setting

The sedimentary record of the Lusitanian Basin can be subdivided into major tectono-stratigraphic sequences which are related to events in the evolution of the Iberian plate and can be correlated with the stratigraphies of other basins (Hiscott *et al.*, 1990). In the Lusitanian Basin, despite discrepancies in the relative ages of several formations, probably reflecting poor biostratigraphic control, there is a close similarity in major stratigraphic elements of several areas.

In the pre-upper Aptian deposits, three unconformity-bounded stratigraphic units (UBS) were defined (Wilson, 1988; Wilson *et al.*, 1989): UBS1, Upper Triassic-Callovian; UBS2, middle Oxfordian-Berriasian; UBS3, Valanginian-lower Aptian. Cunha (1992) recognized ten UBSs in the post lower Aptian record of central Portugal, as shown on Figure 3.

A summary of the tectonic and sedimentary development of the northern sector of the Lusitanian Basin during the Cretaceous is given below. Lithostratigraphic nomenclature has not yet been agreed, because many local names have been introduced by different authors. Detailed description of the Cretaceous UBSs was presented by Cunha (1992), including information about the age and lithofacies of their constituent formations. Regional lithostratigraphic synthesis were presented by Soares *et al.* (1982, 1985), among others.

3.1. *Valanginian–early Aptian*

The UBS3 (Valanginian–lower Aptian) is not documented in the northern sector of the basin (area north of Peniche parallel). This 200 m sequence consists of siliciclastic fluvial sediments in the north interdigitating southwards with shallow-marine limestones and marls, with rudist limestones (Rey, 1972). Within the southern sector of the basin, the base is probably a gradual transition from the Tithonian carbonates; elsewhere in the basin where UBS3 is represented by siliciclastic facies, Rey (1972) suggested that Berriasian strata are missing, and that siliciclastics of UBS3 rest unconformably on older strata.

3.2. *Late Aptian–early Campanian*

In the northern sector of the basin the lower boundary of UBS4 is an angular discordance over Upper Jurassic siliciclastics, Middle and Lower Jurassic limestones and marls, Triassic siliciclastics and Palaeozoic/Precambrian metamorphic rocks (Figure 4). The sediments infill karst features developed on the Middle Jurassic limestones (Gomes, 1965; Soares, 1966; Cunha & Soares, 1987) and Lower Jurassic dolostones/dolomitic limestones (Carvalho, 1955; Soares *et al.*, 1985). Despite a small change in thickness along the NNW–SSE trending basin axis, a significant onlap is documented in the northeastern border of the basin (Cunha, 1992; Figure 4). UBS4 has a maximum thickness of about 450 m in the offshore of the Lusitanian Basin, and also extends across the platform area separating the Lusitanian and Oporto Basins (Figure 1).

Coarse siliciclastic sediments were widely deposited in the late Aptian–Albian along with an important enlargement of the sedimentation area (Figure 5A). Enormous amounts of siliciclastic detritus were furnished from the eastern uplifted Hesperian Massif. Local drainage to the east was related to the uplift of the Berlenga Horst during the late Aptian (Rey, 1972, 1979). Later development of carbonate marine sedimentation was influenced by the long term Albian–Cenomanian transgression. The decreasing influence of the Berlenga hills controlled the SSW–NNE trend of the marine incursion until the Cenomanian;

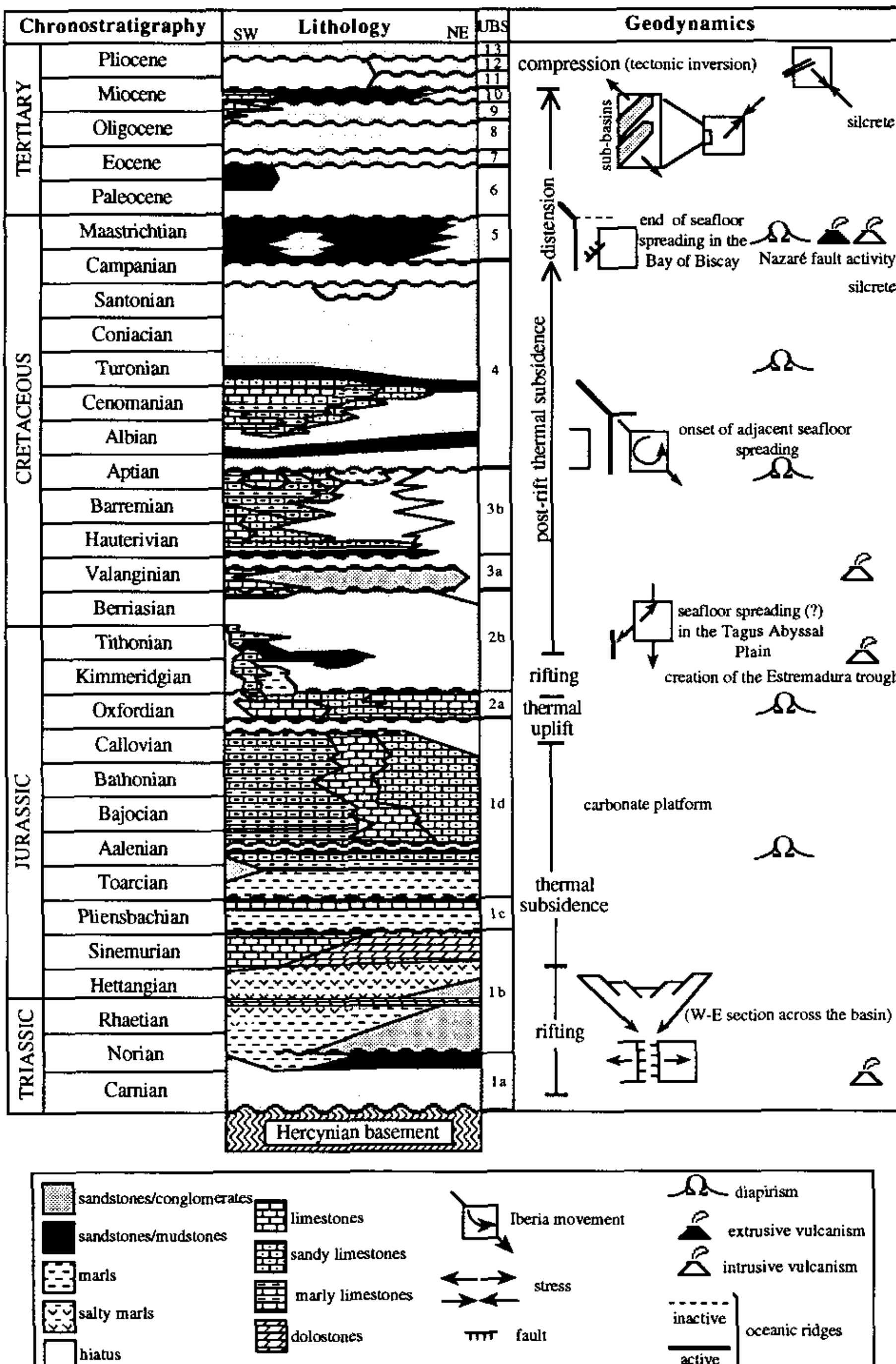

Figure 3. Summary of the Mesozoic lithological framework in the onshore part of the Lusitanian Basin (modified from Pena dos Reis *et al.*, 1992), showing the unconformity-bounded units (UBS): UBS1, Triassic–Callovian; UBS2, middle Oxfordian–Berriasian; UBS3, Valanginian–lower Aptian; UBS4, upper Aptian–lower Campanian; UBS5, upper Campanian–Maastrichtian; UBS6, Paleocene–lower Lutetian; UBS7, upper Lutetian–Bartonian; UBS8, Priabonian–Chattian; UBS9, uppermost Chattian–Burdigalian; UBS10, Langhian–lower Tortonian; UBS11, upper Tortonian–Messinian; UBS12, uppermost Messinian–Zanclean; UBS13, Piacenzian.

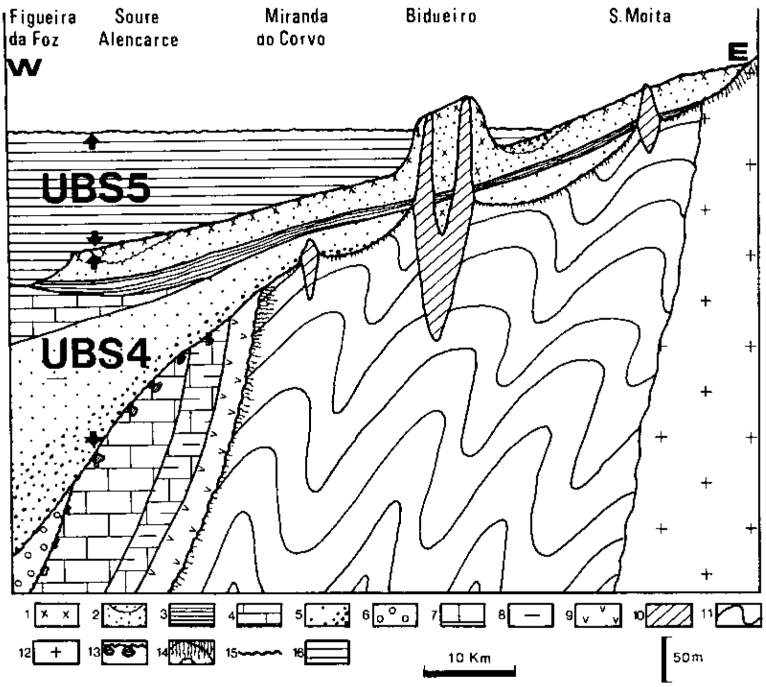

Figure 4. Schematic geological section of the Figueira da Foz–Coimbra–Oliveira do Hospital region, showing UBS4 and UBS5; later units are not represented. Legend: 1, silcrete at the top of the UBS4; 2, coarse sandstones and conglomerates; 3, micaceous fine sandstones; 4, limestones and marls; 5, conglomerates and arkoses; 6, Upper Jurassic; 7, Middle Jurassic; 8, Lower Jurassic; 9, Triassic; 10, Ordovician; 11, Cambrian and Precambrian; 12, granitic rocks; 13, karsification on Jurassic limestones; 14, purple kaolinitic palaeoweathering of the basement; 15, unconformity; 16, clays and quartzarenites (UBS5).

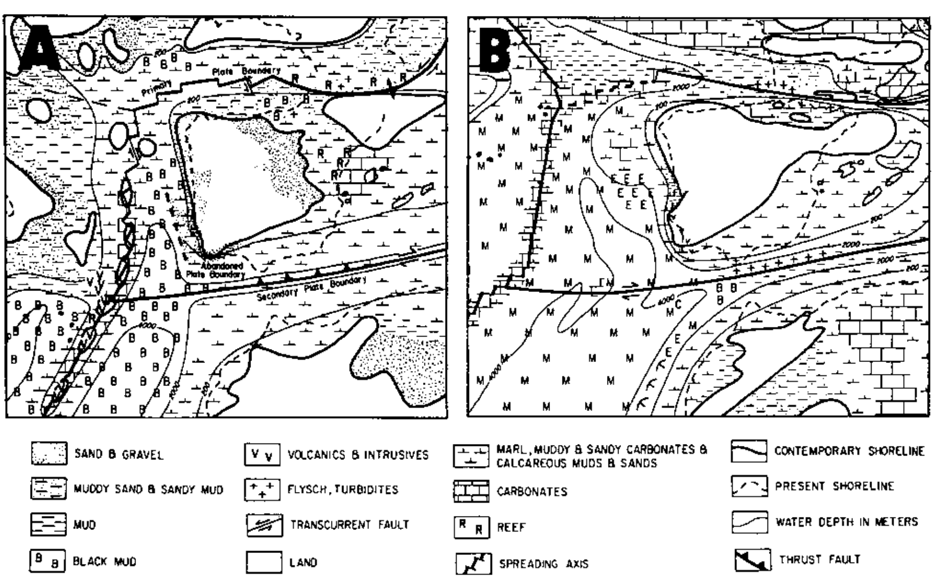

Figure 5. Palaeogeography of (A) Aptian (118 Ma) and (B) beginning of the late Campanian (80 Ma) (modified from Uchupi, 1988).

during the Cenomanian, platform carbonates covered the Berlenga Horst (Vanney & Mougenot, 1981). The lower part of the carbonate formation consists of interbedded calcareous shales and limestones/dolomitic limestones representing tidal flat/lagoonal environments; the upper part consists of shallow shelf limestones with some interbedded pelagic limestones, and is representative of the maximum transgression and subsequent regressive facies with some rudistic build-ups (Berthou, 1973; Witt, 1977; Soares, 1980).

The long term transgression was followed by progradation of the depositional systems. At the NE margin of the basin, siliciclastic facies are interpreted as coalescent wet alluvial fans passing to the SW progressively to transitional systems and to the carbonate platform (Soares, 1966, 1980; Berthou, 1973, 1984; Berthou *et al.*, 1981, 1982; Pena dos Reis & Cunha, 1986b; Dinis & Pena dos Reis, 1989; Dinis, 1990; Cunha, 1992; Dinis *et al.*, in press). Subsequently, a major fall in the sea level induced deep fluvial incision. In the Lousã region (NE proximal part of the basin) fluvial incision is estimated to be as much as 100 m (Cunha, 1992; Figure 4).

Boillot *et al.* (1972, 1975), Berthou (1973, 1978) and Berthou & Lauverjat (1979) stated that at the end of the Cenomanian the reactivation of the Nazaré fault led to the progressive emergence of the southern sector and the northward displacement of the marine sedimentation area during the Turonian. However, this is not documented by drainage, source-area and thickness changes of the successive siliciclastic systems (Daveau (*et coll.*) 1985; Pena dos Reis & Cunha, 1986). Regional fluvial drainage to the NW, with provenance from the southern block of the Nazaré-Lousã fault, is only apparent during the deposition of the UBS5 (upper Campanian-Maastrichtian) (Pena dos Reis, 1983; Cunha, 1992). Consequently, we believe that the important Mesozoic reactivation of the Nazaré-Lousã fault was later; at the Via Longa location (near Lousã village) Daveau (*et coll.*, 1985) also proved that the reactivation of the Nazaré-Lousã fault is younger than UBS4 and pre-dates the deposition of UBS5 (Figure 6).

The top of UBS4 is marked by an important silcrete, indicating sub-tropical weathering during a long period of non-sedimentation (Santonian ?–early Campanian) correlating with tectonic stability (Cunha, 1992; Cunha, Pena dos Reis & Dinis, 1992).

The diapiric structures were reactivated before the deposition of UBS4, as shown by the unconformably overlying Hettangian evaporites and other pre-Cretaceous sediments, without significant thinning against diapirs at several locations on- and offshore between Peniche and Figueira da Foz (Wilson *et al.*, 1989). Dinis & Pena dos Reis (1990) inferred some diapiric control on sedimentation at the beginning of this stage. In some other diapirs (Nazaré–Vale Furado) there is evidence of some synsedimentary faulting, probably as a result of halokinesis during the Turonian (Pena dos Reis, 1993).

3.3. *Late Campanian–Maastrichtian*

In the Lusitanian Basin, the beginning of the late Campanian was marked by diapirism and reactivation of the Nazaré–Lousã fault (relative uplift of the south-eastern block) (Figures 5B and 7). Intrusion of sub-volcanic complexes (Sintra, Sines, Monchique) and basaltic extrusions in the Lisbon-Leiria region also occurred during the late Campanian–Maastrichtian.

The boundary between UBS5 (upper Campanian–Maastrichtian) and UBS6 (Paleocene–lower Lutetian) is a sedimentary discontinuity with a documented

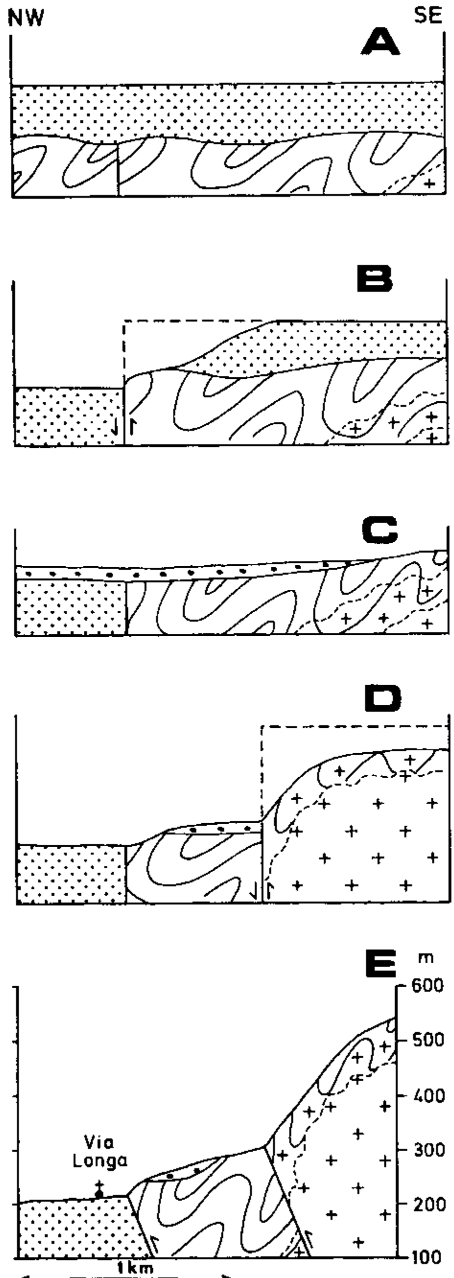

Figure 6. Evolution of the Nazaré–Lousã Fault during the Cretaceous and Tertiary at Via Longa (near Lousã). A, deposition of UBS4; B, reactivation of the Nazaré–Lousã Fault; C, deposition of UBS5; D and E, Tortonian to Quaternary compressive reactivations (adapted from Daveau *et coll.*, 1985).

stratigraphic hiatus offshore (upper Maastrichtian; Boillot *et al.*, 1973, 1975) and also probably onshore. An important reduction in the eastern extent of the basin, and tectonic quiescence occurred after the Maastrichtian.

Onshore (Figure 8), the record of UBS5 (maximum thickness, 180 m) mainly consists of yellowish quartzarenites and red mudstones (Clays and Sands of Taveiro), interpreted as deposits of a meandering fluvial system draining to

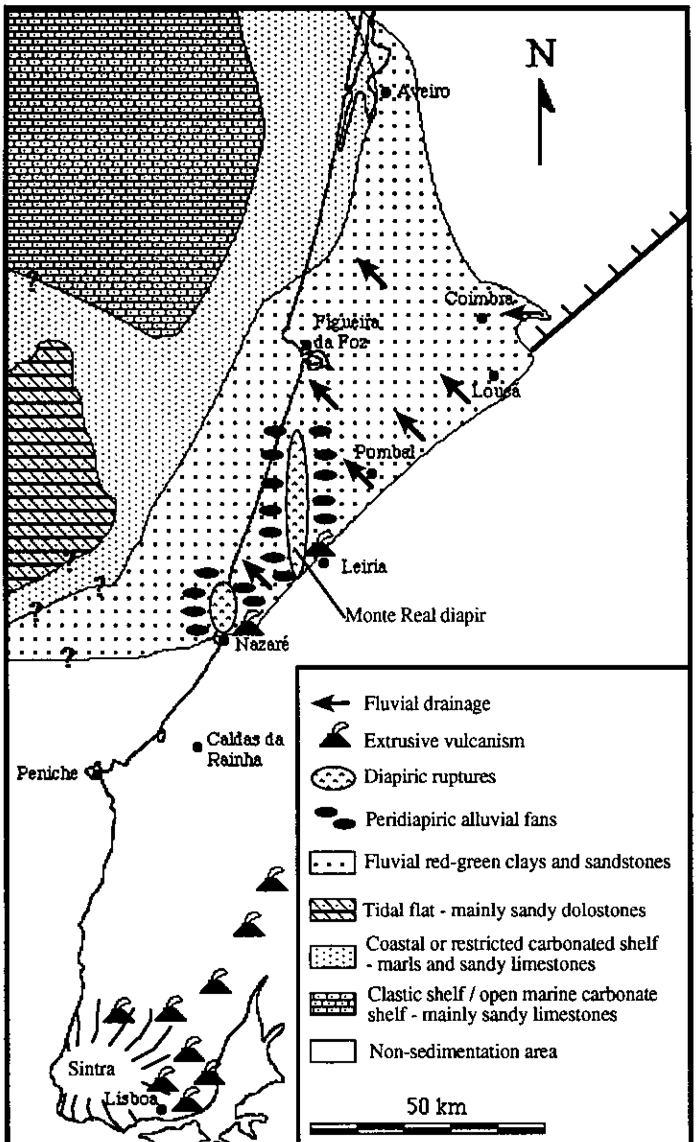

Figure 7. Palaeogeography of the Lusitanian Basin during the late Campanian–Maastrichtian (NW offshore adapted from Witt, 1977).

northwestwards, changing distally to a low coastal siliciclastic plain (barrier island–lagoonal complexes, in the Aveiro region; Pena dos Reis, 1983; Bernardes & Corrochano, 1987) and marine siliciclastic environments (Figure 7). At Mira (north of Figueira da Foz) one marine intercalation was dated as late Campanian. Antunes & Broin's (1988) analysis of the fauna and flora confirmed its upper Campanian–Maastrichtian age and indicated a tropical to subtropical climate. Sedimentological data (Pena dos Reis, 1983) also suggest such a climate with markedly seasonal rainfall.

The change from a mainly northeast granitic source-area during UBS4 deposition to a predominantly southeast arkosic provenance, indicating local erosion of the UBS4, at the beginning of this stage (UBS5) can be related to

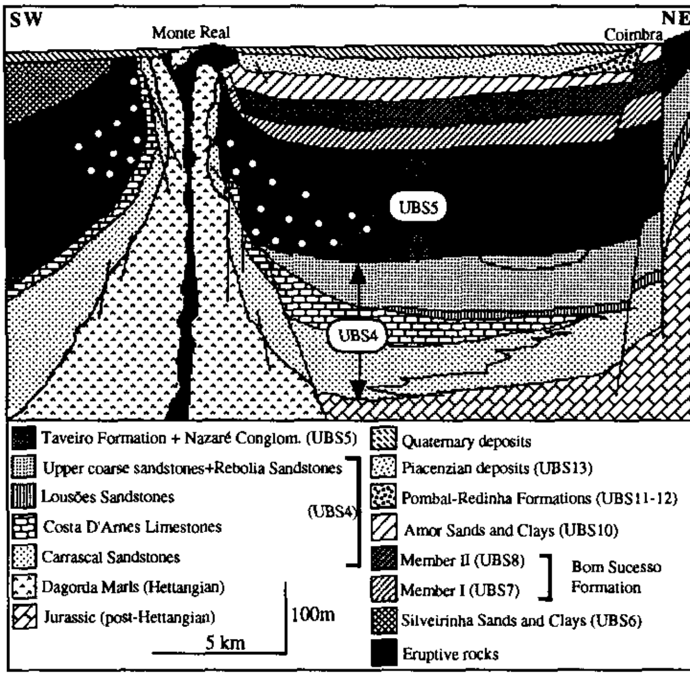

Figure 8. Geological section of the SW Coimbra region, showing the post-Jurassic unconformity-bounded units (modified from Pena dos Reis, 1983).

reactivation of the Nazaré–Lousã Fault. Near Lousã, the southern fault block was uplifted by as much as 80 m (Figure 6).

Southwest of Coimbra, the intrusion of the Hetangian gypsiferous Dagorda Marls through younger sediments, following Hercynian fault orientations, triggered the development of coalescing alluvial fans (Nazaré Conglomerates), on each side of north–south diapiric reliefs (Figure 7). The main facies are Mesozoic limestone boulder and pebble conglomerates alternating with red massive siltstones with rare carbonate concretions and some terrestrial gastropods. The fan lengths must have rarely attained 5 km. Distally, away from diapiric ruptures, these alluvial deposits interdigitate with the high sinuosity fluvial sediments of the Clays and Sands of Taveiro. The dominant upward tendency of decreasing maximum particle size and the modest thickness of these alluvial deposits (up to 40 m) do not suggest persistent diapirism (Pena dos Reis, 1981, 1983, 1984).

Offshore, very shallow marine fine clastics and dolomites are 90 m thick (Dourada Formation; Figure 7). This upper Campanian–Maastrichtian formation consists of grey-brown, dolomite-cemented quartz sandstones grading to sandy crystalline dolostones with, in the lower part, intercalations of grey to light brown marl and occasionally sandy limestone (Witt, 1977).

4. Discussion and conclusions

The Lusitanian Basin records two rifting intervals: Late Triassic and Late Jurassic. The second, is older than the synrift sediments drilled off Galicia Bank, and those of northern Spain, where the opening of the Atlantic commenced in the Aptian. The major phase of subsidence is Late Jurassic; immediately after, the extensional rift zone moved west to deep-water and effective rifting in the basin was terminated. The main phase of opening of the North Atlantic between Iberia and the Grand Banks began in the area to the south of Galicia Bank before the Aptian. The separation of North America and Europe from Iberia occurred in the Early Cretaceous and is reflected by major unconformities at sub-Neocomian and intra-Aptian levels (Wilson *et al.*, 1989). The Cretaceous succession can be related to syn- and post-rift sequences drilled on the northwest Iberian margin (Group Galice, 1979; Mougenot *et al.*, 1984, 1986; Mauffret & Montadert, 1987), but it shows a much lower rate of subsidence and deposition, mainly in terrestrial or shallow marine conditions.

The Cretaceous of the Lusitanian Basin comprises several unconformity-bounded stratigraphic units which can be related to the geodynamic events connected to the opening of the adjacent Atlantic Ocean: (1) middle Oxfordian-Berriasian, (2) Valanginian–early Aptian, (3) late Aptian–early Campanian and (4) late Campanian–Maastrichtian. Stage 1 documents rifting; the later stages corresponding to post-rift. The low rate of subsidence during the Cretaceous and mainly during the Tertiary is reflected by a thin succession (about 500 m thick in the northern sector of the Lusitanian Basin) containing several unconformities. The main sedimentary ruptures can be related to tectonic events. However, relative sea-level changes should be considered as having influenced the facies distributions during the Cretaceous.

Of the unconformity-bounded stratigraphic units recognized in the Cretaceous of the Lusitanian Basin only the Valanginian-lower Aptian is not documented in the northern sector of the basin. UBS3 is equivalent to the synrift succession that preceded ocean opening, as indicated in boreholes drilled off the northwestern margin of Iberia (Sibuet & Ryan, 1979; Boillot & Malod, 1988), but is much thinner and contains no deep-water sediments (Wilson *et al.*, 1989).

The late Aptian structural disturbance, and the generation of the important angular unconformity, coincide with the separation of the Grand Banks and Iberian margins and the onset of oceanic opening in the Atlantic sector adjacent to the Lusitanian Basin north of the Tagus abyssal plain (Sullivan, 1983; Masson & Miles, 1984; Keen *et al.*, 1987; Hiscott *et al.*, 1990; Malod *et al.*, 1992). The Iberian and European plates diverged from late Aptian to Santonian times as a consequence of triple-junction evolution and the opening of the Bay of Biscay (Malod, 1989); some late Variscan faults in the interior of Iberia (striking NNE–SSW and NE–SW) were probably reactivated with sinistral strike-slip motion (Ribeiro *et al.*, 1979). The late Aptian–early Campanian period corresponds to an important enlargement of the sedimentation area of the Lusitanian Basin. All the earlier UBSs are overstepped by UBS4, which is of relatively uniform thickness and extends across the platform area (shallow basement) separating the Lusitanian and Oporto Basins. The sediments of this stage testify a main clastic provenance from the northeastern granitic region, undergoing a thermal and isostatic uplift (Dinis *et al.*, in press). Progradation of the depositional systems followed the long term Albian–Cenomanian transgression that can be correlated with the eustatic rise during Albian and Cenomanian (Haq *et al.*, 1988); subsequently a major fall in sea level induced deep fluvial incision and later weathering of the sediments.

The beginning of the late Campanian can be related to the inversion of the movement of Iberia relative to the European plate (beginning of compression at the northern border of Iberia; Gräfe & Wiedmann, 1993). The important unconformity at the base of the record of this stage may also be related to the continental breakup between the Rockall Plateau-Greenland (European plate) and Labrador Shelf (north of American plate) (Hiscott *et al.*, 1990). The late Campanian–Maastrichtian was marked by the main Mesozoic reactivation of the Nazaré–Lousã fault, intense diapirism, and significant volcanic activity. The alkaline ring complexes were emplaced along a deep strike-slip NNW–SSE zone (Kullberg, 1985); according to Ribeiro *et al.* (1985, 1990) rift migration may have changed the stress field and deeply fractured the previously thinned continental margin. The SSW–NNE alignment of several volcanic structures of this age (Figure 7) might be related to the Lower Tagus fault, which offsets the Moho.

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References

Anadón, P., Cabrera, L. & Roca, E. 1989. Contexto estrutural y paleogeográfico de los sistemas cenozoicos de Espana. *Acta Geologica Hispanica* **24**, 167–184.

Bernardes, C. M. A. & Corrochano, A. 1987. A sedimentologia da "Formação Arenitos e Argilas de Aveiro"—Cretácico Superior, Bacia Ocidental Portuguesa. *Geociências* **2**, 9–26.

Berthou, P. Y. 1973. Le Cénomanien de l'Estrémadure portugaise. *Memórias dos Serviços Geológicos de Portugal* **23**, 308 pp.

Berthou, P. Y. 1978. La transgression cènomanienne dans le bassin occidentale portugais. *Géologie Méditerranéenne* **5** (Colloque sur le Cénomanien), 31–38.

Berthou, P. Y. 1984. Resumé synthétique de la stratigraphie et de la paléogéographie du Crétacé moyen et supérieur du basin occidental portugais. *Geonovas* **7**, 99–120.

Berthou, P. Y., Blanc, P. & Chamley, H. 1982. Sédimentation argileuse comparée au Crétacé moyen et supérieur dans le bassin occidental portugais èt sur la marge voisine (site 398D DSDP): ensaignements paléogéographiques et tectoniques. *Bulletin de la Société Géologique de France* (7) **24**, 3, 460–472.

Berthou, P. Y. & Lauverjat, J. 1979. Essai de synthèse paléogéographique du Crétacé moyen et supérieur du bassin occidental portugais. *Ciências da Terra* (Universidade Nova de Lisboa) **5**, 121–144.

Berthou, P. Y., Hasenboehler, B. & Moron, J. M. 1981. Apports de la palynologie à la stratigraphie du Crétacé moyen et supérieur du bassin occidentale portugais. *Memórias e Notícias* (*Publicações do Museu e Laboratório Mineralogico e Geológico da Universidade de Coimbra*) **91–92**, 183–221.

Boillot, G. & Malod, J. 1988. The north and north-west Spanish continental margin. A review. *Revista de la Sociedad Geologica de Espanã* **1**, 295–316.

Boillot, G., Berthou, P. Y., Dupeuble, P. A. & Musellec, P. 1972. Géologie du plateau continental portugais au Nord du Cap Carvoeiro. *Comptes Rendus de l'Académie des Sciences de Paris* **274**, 2748–2751.

Boillot, G., Dupeuble, P. A. & Musellec, P. 1973. Carte géologique du plateau continental portugais entre 39° 50′ et 41° 50′ de la latitude Nord. *Comptes Rendus de l'Academie des Sciences de Paris* **227**, 25–28.

Boillot, G., Dupeuble, P. A. & Musellec, P. 1975. Carte géologique du plateau continental nord-portugais. *Bulletin de la Société Géologique de France* (7) **14**, 462–480.

Carvalho, G. S. 1955. Sur l'âge de quelques remplissages sableux des fentes de dissolution des calcaires du Portugal. *Memórias e Notícias* (*Publicações do Museu e Laboratório Mineralogico e Geológico da Universidade de Coimbra*) **31**, 9–15.

Chang, K. H. 1975. Unconformity-bounded units. *Geological Society of America, Bulletin* **86**, 1544–1552.

Cunha, L. J. Sobral da & Soares, A. F. 1987. A carsificação no Maciço de Sicó. Principais fases de evolução. *Cadernos de Geografia* **8**, 119–137.

Cunha, P. Proença 1987. Evolução tectono-sedimentar Terciária da Região de Sarzedas (Portugal). *Comunicações dos Serviços Geológicos de Portugal* **73**, 67–84.

Cunha, P. Proença 1992. *Estratigrafia e sedimentologia dos depósitos do Cretácico Superior e Terciário de Portugal Central, a leste de Coimbra.* Unpublished PhD thesis, University of Coimbra, 262 pp.

Cunha, P. Proença 1993. Synthesis of the tectonic and sedimentary evolution of central Portugal during Cretaceous (Lusitanian Basin). *Abstracts of the 1st General Meeting of IGCP Project 362,* 44–47.

Cunha, P. Proença & Pena dos Reis, R. 1992. Síntese da evolução geodinâmica e paleogeográfica do sector Norte da Bacia Lusitânica, durante o Cretácico e Terciário. *Actas del III Congreso Geológico de Espanã e VIII Congreso Latinoamericano de Geologia* **1**, 107–112.

Cunha, P. Proença & Pena dos Reis, R. 1993. The Cretaceous unconformity-bounded sequences (Upper Aptian–Lower Campanian and Upper Campanian–Maastrichtian ?) in the Lousã–Pombal region. *Field trip guide, 1st General meeting—IGCP Project* 362—*Tethyan and Boreal Cretaceous,* 5–18.

Cunha, P. Proença, Pena dos Reis, R. & Dinis, J. 1992. A importância de um silcreto bacinal como marcador do final da etapa sedimentar Aptiano superior—Campaniano inferior, na Bacia Lusitânica; perspectivas de generalização deste modelo. *Actas del III Congreso Geológico de Espanã e VIII Congreso Latinoamericano de Geologia* **1**, 102–106.

Daveau, S. (avec la collaboration de Birot, P. & Ribeiro, O.) 1985. Les bassins de Lousã et d'Arganil. Recherches géomorphologiques et sédimentologiques sur le massif ancien et sa couverture à l'est de Coimbra. Volume 1. Le bassin sédimentaire. *Memórias do Centro de Estudos Geográficos* **8**, 450 pp.

Dinis, J. M. L. 1990. *Litostratigrafia e evolução dos sistemas deposicionais em depósitos continentais "pós-rift". Os "grés belasianos" (Cretácico) a Este de Leiria (Portugal Central).* Unpublished MSc. thesis, University of Coimbra, 242 pp., 103 fig.

Dinis, J. M. L. & Pena dos Reis, R. 1989. Litostratigrafia e modelos deposicionais nos "grés belasianos" (Cretácico inferior e médio) a Leste de Leiria (Portugal Central). *Geociências (Revista da Universidade de Aveiro)* **4**(2), 75–96.

Dinis, J. M. L. & Pena dos Reis, R. 1990. Evidences of diapiric activitie on the "grés belasianos" unit (Cretaceous) east of Leiria (Central Portugal). *Abstracts of the 6th Meeting of the European Geological Societies,* p. 21.

Dinis, J. M. L., Pena dos Reis, R. & Cunha, P. Proença (in press). Controls on vertical changes of alluvial system character. The "grés belasianos" unit—Cretaceous of the Lusitanian Basin (Central Portugal). *Cuadernos de Geología Ibérica.*

Ferreira, A. Brum 1991. Neotectonics in northern Portugal. A geomorphological approach. *Zeitschrift fur Geomorphology (Neue Folge) Supplementband* **82**, 73–85.

Ferreira, M. Portugal & Macedo, C. A. R. 1979. K–Ar ages of the Permian–Mesozoic basaltic activity in Portugal. *Abstracts of the VI European Colloquium on Geochronology, Cosmochronology and Isotope Geology,* Lillheamer, Norway, 26–27.

Ferreira, M. Portugal & Macedo, C. A. R. 1983. Igneous rocks in the diapiric areas of the western Portuguese border: the K–Ar ages and setting of the Upper Jurassic suite. *Memórias e Notícias, (Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra)* **96**, 159–181.

Gomes, C. F. 1965. On the hyperaluminous clays of Andorinha (Cantanhede–Portugal). *Memórias Notícias, (Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra)* **60**, 57–61.

Gräfe, K.-U. & Wiedmann, J. 1993. Sequence stratigraphy in the Upper Cretaceous of the Basco-Cantabrian Basin (northern Spain). *Geologische Rundschau* **82**, 327–361.

Group Galice 1979. The continental margins of Galicia and Portugal: acoustical stratigraphy, dredge stratigraphy and structural evolution. *Initial Reports of the Deep Sea Drilling Project* (eds Ryan, W. B. F., Sibuet, J. C. *et al.*) **47**, 633–662.

Guéry, F. 1984. *Evolution sédimentaire et dynamique du bassin marginal ouest-portugais au Jurassique (Province d'Estremadura, secteur de Caldas da Rainha, Montejunto).* Unpublished PhD thesis, University of Lyon 1, 477 pp., 164 figs.

Guéry, F., Montenat, C. & Vachard, D. 1986. Évolucion tectono-sédimentaire du bassin portugais au Mésozoique suivant la transversal de Peniche (Estremadura). *Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine* **10**, 83–94.

Haq, B. U., Hardenbol, J. & Vail, P. R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science* **235**, 1156–1166.

Hiscott, R. N., Wilson, R. C. L., Gradstein, F. M., Pujalte, V., Garcia-Mondéjar, J., Boudreau, R. R. & Wishart, H. A. 1990. Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic. *American Association of Petroleum Geologists, Bulletin* **74**, 60–76.

Keen, C. E., Stockmal, G. S., Welsink, H., Quinlan, G. & Mudford, B. 1987. Deep crustal structure and evolution of the rifted margin northeast of Newfoundland: results from Lithoprobe East. *Canadian Journal of Earth Sciences* **24**, 1537–1549.

Kullberg, M. C. 1985. Controlo estrutural na instalação do maciço de Sintra. *Boletim da Sociedade Geológica de Portugal* **24**, 219–223.

Macintyre, R. M. & Berger, G. W. 1982. A note on the geochronology of the Iberian Alkaline Province. *Lithos* **5**, 133–136.

Malod, J. A. 1989. Ibérides et plaque ibérique. *Bulletin de la Société Géologique de France* **8**, 927–934.

Malod, J. A., Murillas, J., Kornprobst, J. & Boillot, G. 1992. Oceanic lithosphere at the edge of a Cenozoic active continental margin (northwestern slope of Galicia Bank, Spain). *Tectonophysics* **221**, 383–393.

Masson, D. G. & Miles, P. R. 1984. Mesozoic seafloor spreading between Iberia, Europe and North America. *Marine Geology* **56**, 279–287.

Mauffret, A. & Montadert, L. 1987. Rift tectonics on the passive continental margin of Galiza (Spain). *Marine and Petroleum Geology* **4**, 49–70.

Megias, A. G. 1982. Introduccion al analisis tectosedimentario: aplicacion al estudio dinamico de cuencas. *Actas Quinto Congresso Latino-Americano de Geologia* (Argentina) **I**, 385–402.

Mitchum, R. M., Vail, P. R. & Thompson, S. 1977. The depositional sequence as a basic unit for stratigraphic analysis. In *Seismic stratigraphy—applications to hydrocarbon exploration* (ed. Payton, C. E.) *American Association of Petroleum Geologists, Memoir* **26**, 53–62.

Montenat, C., Guéry, F., Jamet, M. & Berthou, P. Y. 1988. Mesozoic evolution of the Lusitanian basin: comparison with the adjacent margin. In Boillot, G. & Winterer, E. L. *et al.*, *Proceedings of the Ocean Drilling Program, Scientific Results* **103**, 757–775.

Mougenot, D., Kidd, R. B., Mauffret, A., Regnauld, H., Rothwell, R. G. & Vanney, J. R. 1984. Geological interpretation of combined Seabeam, Gloria and seismic data from Porto and Vigo seamounts, Iberian continental margin. *Marine Geophysical Research* **6**, 329–363.

Mougenot, D., Vanney, J. R., Mauffret, A. & Kidd, R. B. 1986. Les montagnes sous-marines de la marge continental nord-portugaise: morphologie et évolution structurale. *Bulletin de la Société Géologique de France* **8**, 401–412.

Pardo, G., Villena, J. & González, A. 1989. Contribución a los conceptos y a la aplicatión del análisis tectosedimentario. Rupturas y unidades tectosedimentarias como fundamento de correlaciones estratigráficas. *Revista de la Sociedad Geologica de España* **2**, 199–221.

Pena dos Reis, R. 1981. *La sédimentation continentale du Crétacé terminal au Miocène, sur la bordure occidentale du Portugal, entre Coimbra et Leiria.* Thèse 3è cycle (unpublished), University of Nancy I, 150 pp.

Pena dos Reis, R. 1983. *A sedimentologia de depósitos continentais. Dois exemplos do Cretácico superior—Miocénico de Portugal.* Unpublished PhD. thesis, University of Coimbra, 404 pp.

Pena dos Reis, R. 1984. The sedimentology of continental peridiapiric alluvian fans. A generalized model for the Upper Cretaceous Western Basin of Portugal. *Abstracts of the 5th European Regional Meeting of Sedimentology,* IAS/ASF, pp. 351–352.

Pena dos Reis, R. 1993. Evidences of probably synsedimentary faulting on the upper boundary surface of the Lousões Fine Sandstones (Upper Cretaceous) (Nazaré Lighthouse outcrop, Lusitanian basin, Portugal). *Abstracts of the 1st General Meeting of the IGCP Project 362,* pp. 60–61.

Pena dos Reis, R. & Cunha, P. Proença 1986. The sedimentology and infill model of the Cretaceous alluvial succession in Lousã Basin (Portugal). *Abstracts of the British Sedimentology Research Group Annual Meeting* (unpaginated).

Pena dos Reis, R. & Cunha, P. Proença 1989a. Comparacion de los rellenos terciarios en dos regiones del borde occidental del Macizo Hespérico (Portugal Central). In: *Paleogeografia de la Meseta norte durante el Terciario* (ed. Dabrio, C.), Studia Geologica Salmanticensia, *Volumen Especial* 5, 253–272.

Pena dos Reis, R. & Cunha, P. Proença 1989b. A definição litostratigráfica do Grupo do Buçaco na região de Lousã, Arganil e Mortágua (Portugal). *Comunicações dos Serviços Geológicos de Portugal* **75**, 99–109.

Pena dos Reis, R., Corrochano, A., Cunha, P. Proença, Dinis, J. L. & Trincão, P. 1991. Megassequências cretácicas na Bacia Lusitaniana, a norte de Nazaré. *Abstracts of the* 3 *Congresso Nacional de Geologia,* p. 130.

Pena dos Reis, R., Corrochano, A., Bernardes, C., Cunha, P. Proença & Dinis, J. L. 1992. *O Meso-cenozóico da margem atlântica portuguesa.* Guias de las excursiones geológicas—III Congreso Geologico de España y VII Congreso Latinoamericano de Geologia, Edition Universidad de Salamanca, pp. 115–138.

Rey, J. 1972. Recherches géologiques sur le Crétacé inférieur de l'Estremadura (Portugal). *Comunicações dos Serviços Geológicos de Portugal* **21**, 477 pp.

Rey, J. 1979. Le Crétacé inférieur de la marge atlantique portugaise: biostratigraphie, organisation séquentielle, évolution paléogéographique. *Ciências da Terra (Universidade Nova de Lisboa)* **5**, 97–120.

Riba, O. 1989. Unidades tectosedimentarias y secuencias deposicionales. *Revista de la Sociedad Geologica de España* **2**, 189–198.

Ribeiro, A., Antunes, M. T., Ferreira, M. P., Rocha, R. B., Soares, A. F., Zbyszewski, G., Moitinho de Almeida, F., Carvalho, D. & Monteiro, J. H. 1979. Introduction à la géologie générale du Portugal. *Serviços Geológicos de Portugal,* 114 pp.

Ribeiro, A., Possolo, A., Silva, J., Kullberg, M. C., Cabral, J. & Dias, R. 1985. Modelos tectónicos: ensaio de aplicação em Portugal. *Boletim da Sociedade Geológica de Portugal* **24**, 145–151.

Ribeiro, A., Kullberg, M. C., Kullberg, J. C., Manuppella, G. & Phipps, S. 1990. A review of Alpine tectonics in Portugal: foreland detachment in basement and cover rocks. *Tectonophysics* **184**, 357–366.

Soares, A. Ferreira 1966. Estudo das formações pós-jurássicas na região entre Sargento-Mór e Montemór-o-Velho (margem direita do Rio Mondego). *Revista da Faculdade de Ciências da Universidade de Coimbra* **40**, 343 pp.

Soares, A. Ferreira 1980. A "Formação Carbonatada" Cenomano–Turoniana na região do Baixo Mondego. *Comunicações dos Serviços Geológicos de Portugal* **66**, 99–109.

Soares, A. Ferreira, Barbosa, B. & Pena dos Reis, R. P. B. 1982. Esboço de enquadramento cronostratigráfico das unidades líticas pós-jurássicas da Orla Meso-Cenozóica Ocidental entre os paralelos de Pombal e Aveiro. *Memórias e Notícias, (Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra)* **93**, 77–91.

Soares, A. Ferreira, Marques, J. F. & Rocha, R. B. 1985. Contribuição para o conhecimento geológico de Coimbra. *Memórias e Notícias, (Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra)* **100**, 41–71.

Stieff, I. R. & Stern, T. W. 1960. Age study of uraninites from the Urgeiriça and Lenteiros Mines, Portugal. *Junta da Energia Nuclear, Technical Paper* **27**, 11 pp.

Sullivan, K. 1983. The Newfoundland Basin: ocean-continent boundary and Mesozoic sea-floor spreading history. *Earth and Planetary Science Letters* **62**, 321–339.

Uchupi, E. 1988. The Mesozoic-Cenozoic geologic evolution of Iberia: a tectonic link between Africa and Europe. *Revista de la Sociedad Geologica de España* **1**, 257–294.

Vail, P. R., Mitchum, R. M. & Thomson, S. 1977. Seismic stratigraphy and global changes of sea level. Part 4: Global cycles of relative changes of sea level. In *Seismic stratigraphy-application to hydrocarbon exploration* (ed. Payton, C. E.), *American Association of Petroleum Geologists, Memoir* **26**, 83–98.

Vail, P. R., Hardenbol, J. & Todd, R. G. 1984. Jurassic unconformities, chronostratigraphy and sea level changes from seismic stratigraphy and biostratigraphy. In *Interregional unconformities and hydrocarbon accumulation* (ed. Schlee, S.), *American Association of Petroleum Geologists, Memoir* **36**, 129–137.

Vanney, J. & Mougenot, D. 1981. La plate-forme continentale du Portugal et les provinces adjacentes: analyse geomorphologique. *Memórias dos Serviços Geológicos de Portugal (Nova Série)* **28**, 86 pp.

Vegas, R. & Banda, E. 1982. Tectonic framework and alpine evolution of the Iberian Peninsula. *Earth Evolution Sciences* **4**, 320–342.

Wilson, R. C. L. 1988. Mesozoic development of the Lusitanian Basin, Portugal. *Revista de la Sociedad Geologica de España* **1**, 393–407.

Wilson, R. C. L., Hiscott, R. N., Willis, M. G., Gradstein, F. M. 1989. The Lusitanian basin of west-central Portugal; Mesozoic and Tertiary tectonic, stratigraphic and subsidence history. In *Extensional tectonics and stratigraphy of the North Atlantic margins* (eds Tankard, A. J. & Balkwill, H.), *American Association of Petroleum Geologists, Memoir* **46**, 341–361.

Witt, W. G. 1977. *Stratigraphy of the Lusitanian Basin.* Unpublished Shell Prospex Portuguesa report, 61 pp, (Gabinete para a Pesquisa e Exploraçãs de Petróleo (Lisboa), open-file report).

Zbyszewski, G. 1959. Étude struturale de l'aire typhonique de Caldas da Rainha. *Memórias dos Serviços Geológicos de Portugal (Nova Série)* **3**, 184 pp.