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Geologic Evolution of the Lusitanian Basin (Portugal) during the Late Jurassic

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Abstract: During the Late Jurassic, the Lusitanian Basin was located between two Hercynian basement blocks, today represented by the Berlengas islands in the west, and the Iberian block in the east. The graben in between was elongated NNE-SSW with depositional environments becoming less terrestrial and more open marine to the southwest.

A dense network of faults (NNE-SSW, WNW-ESE and NW-SE) acted as an influence on subsidence and paleogeography as proved by major regional variations in facies distribution and thickness.

A detailed analysis of the sedimentary successions across the Lusitanian Basin leads to the definition of eleven basin-wide depositional sequences (A to K) within the Upper Jurassic-Berriasian. In this analysis we consider lateral facies changes and interpreted depositional systems; the identification and classification of depositional surfaces; and the interpretation of sedimentary systems tracts.

The Late Jurassic evolution of the basin involved three major tectonosedimentary stages. Sequences A and B correspond to the onset of rifting, which resulted in widespread drowning of the basin, mainly with carbonate deposition; extensional climax was reached during sequences C, D and E (uppermost Oxfordian to Upper Kimmeridgian). The late stage (uppermost Kimmeridgian, Tithonian and Berriasian) includes sequences F to K and is interpreted as a period of thermal subsidence, sea-level changes and short tectonic pulses.

Introduction

The main goal of the paper is to critically reinterpret the Upper Jurassic sucession of the Lusitanian Basin emphasising a sequence stratigraphic approach. To achieve this goal the large amount of data collected mainly after 1940 were systematically analysed. Sequential analysis at a regional scale was based on a detailed study of every available outcrop, section and well column, as well as on seismic profiles. A significant part of the sediments record continental and transitional depositional systems. One may recognise major variations in accommodation space influenced both by episodes of intense extensional tectonic activity as well as eustatic sea level changes. In these conditions conceptual models risk being oversimplistic. For practical purposes, flooding surfaces and correlative inflection surfaces in terrestrial and deep sea systems (progradation-retrogradation) proved the best markers for bounding cycles (Plint, 1996).

Palaeontological data are integrated for palaeoecological interpretation. The chronostratigraphic framework is based essentially on ammonite biostratigraphy (Atrops and Marques, 1986; 1988a; 1988b; Mouterde et al., 1973; 1979), planktonic and benthic foraminifera (Wightman, 1990), dinoflagellate cysts (Riding and Thomas, 1988) and pollen (Du Chene, 1988; Mohr and Schmidt 1987; Mohr, 1989). For time stratigraphic analysis we used the ammonite-biozone charts of Cariou et al. (1991) for the Oxfordian; Hantzpergue et al. (1991) for the Kimmeridgian; Geyssant and Enay (1991) for the Tithonian and Erba et al. (1995) for the Berriasian. The basin was divided into sectors with different sedimentary records (Figs. 1 and 2). The position of the boundaries between sectors shifted or faded out during the period under consideration.

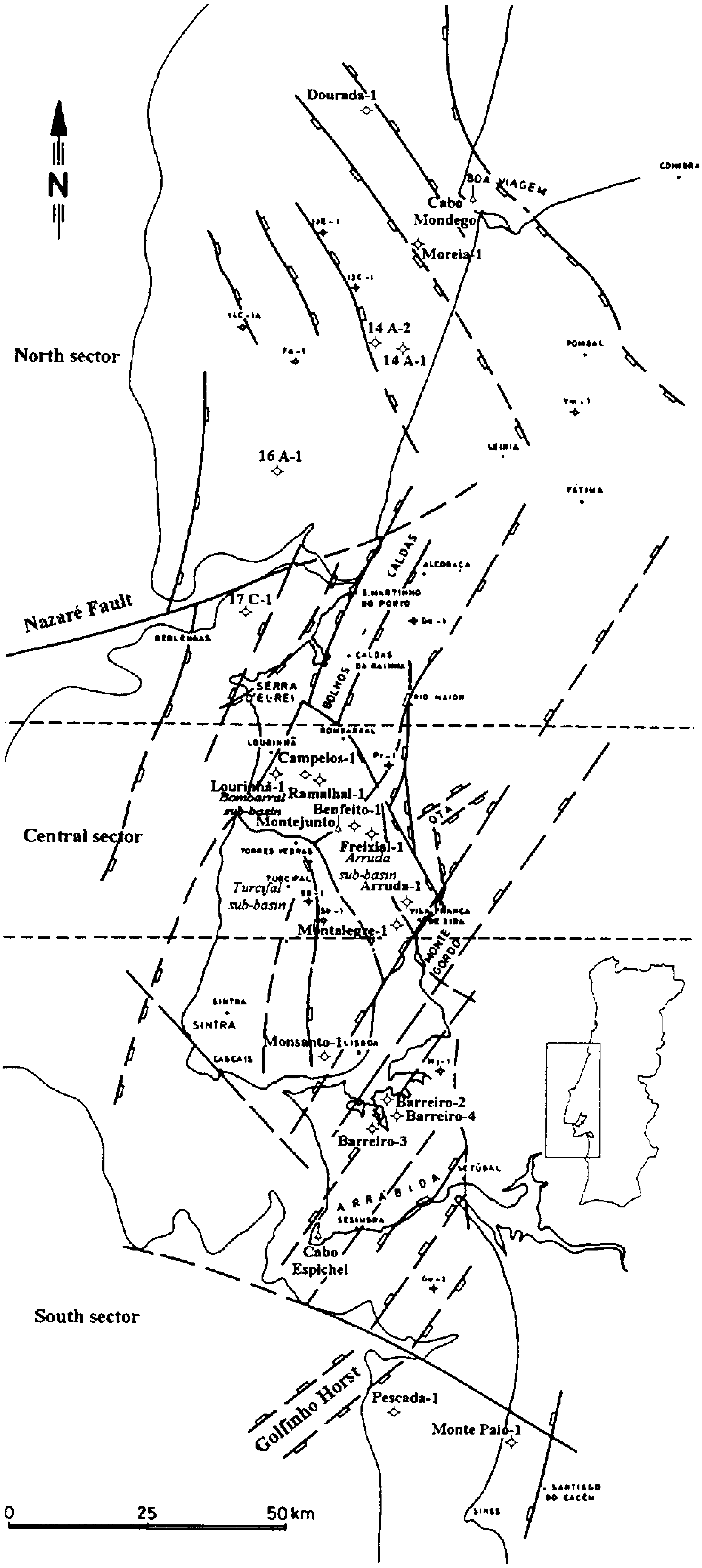
Outline of Upper Jurassic Basin Evolution

During the Late Jurassic, the Lusitanian Basin was located between two Hercynian basement blocks today represented by the Berlengas islands in the west and the Iberian block in the east. The graben in between was elongated NNE-SSW with depositional environments becoming less terrestrial and more open marine to the southwest. The rotation of the Iberian plate with a pole located to the east caused a NNE-SSW or NE-SW crustal extension (Brunet, 1992), resulting in deep fault-controlled sub-basins. A dense network of faults (NNE-SSW, WNW-ESE and NW-SE) controlled subsidence and paleogeography as proved by major regional variations in facies distribution and thickness. A significant tectonic event took place from Callovian-Oxfordian. At the end of the Middle Jurassic the Lusitanian Basin underwent a regional uplift, and erosion affected previous sediments causing karstification in some places (Guéry et al., 1986; Wright and Wilson, 1987).

During tectonic activity, in the northern part of the basin, Lower and Middle Jurassic carbonate sediments were cut into subsident blocks by NW-SE trended normal faults (Fig. 1). To the south of the Nazaré fault, the structure orientation changes to NE-SW. The granitic and metamorphic horst of Berlengas follows the Berlengas fault trend (NNE-SSW). The Caldas structure separated this sector into two subsident areas (Wilson, 1979; Canérot et al., 1995): one in the NW (S. Martinho) with moderate tectonic subsidence and another to SE (Bombarral sub-basin) with intense tectonic subsidence (Fig. 1).

During the Late Oxfordian, extensional activity strongly increased, marking the climax of rifting. According to Mauffret et al. (1988), these changes were associated with the establishment of a rift segment in the Tagus Abyssal Plain, and at the same time a dike network trending NW-SE or E-W was formed (Ferreira and Macedo, 1983; Hill, 1988; Willis, 1988). The main faults in the central area of the basin were very active (Fig. 1), intensifying the definition of blocks, tilting to SE. In the Arruda-1 well (CPP, 1956; Leinfelder and Wilson, 1989), which is next to some main active faults (Pragança, Vila Franca, etc), mixed carbonate and siliciclastic turbidites occur, reaching more than 2000m in thickness (Arruda sub-basin). Strongly subsident sub-basins are defined (Arruda, Bombarral and Turcifal) but where uplifted blocks remain (Ota, Monte Gordo), carbonate platform sediments continue to accumulate. In the southern sector of the Lusitanian Basin the extensional episode led to the establishment of a basically NNE-SSW oriented tectonic complex composed of ESE-tilted blocks in a domino fashion. In northern areas, deltaic systems prograded in highstand sea level conditions (Bernardes and Corrochano, 1992), and on the western border of central areas, alluvial fans and deltas drained to the east. Southward prograding deltaic and clastic slope depositional systems with a high proportion of turbiditic deposits (Abadia Formation), gradually reduced the area of platform slope and pelagic marl deposition (S. Pedro and Ramalhão Formations in the South sector). After the rift climax, coarse-grained siliciclastic sedimentation probably reflects erosion from the borders and subsequent expansion of the drainage basin after cessation of fault movement. The overall progradation of the siliciclastic systems (Abadia Formation) can be interpreted as a highstand-like linkage of depositional systems, created as a response to the tectonic derived relative sea-level rise. In the Late Kimmeridgian (base of Eudoxus Biozone), a short term sea-level rise (within a long term eustatic highstand (Haq et al., 1987; Ponsot and Vail, 1991)) generated an important transgressive surface, followed by widespread deposition of carbonate shelf sediments. The Amaral Formation which includes ooid grainstones and coral bioherms, overlies deeper marine sediments in the south and central sectors of the basin, indicating a decrease in bathymetry. In the north sector, southernmost area (Arrábida), and structural highs (e.g., Ota, Caldas da Rainha and Monte Gordo), the Amaral carbonates and presumed equivalents are a transgressive (deepening) event within shallow marine, marginal and continental clastic deposits. The Tithonian and Berriasian are represented in the centre and north by the Lourinhã Formation. In the axis of the basin, shallow marine marly deposition persisted, over which fluvial and fan delta systems prograded. Up to five short-term, widespread transgressions were recorded within the Lourinhã Formation. The upper beds of this unit are Late Berriasian in age (Rey, 1972; Berthou and Leereveld, 1990). Persistent carbonate deposition was restricted to shallow platform systems in the southern part of the basin (upper part of Mem Martins, Farta Pão and Porto da Calada Formations).

Figure 1. Sketch of Lusitanian basin with main structures active during Upper Jurassic times


N
Dourada-1
COIMBRA
BOA VIAGEM
Cabo
Mondego
Moreia-1
13E-1
13C-1
14C-1A
14 A-2
14 A-1
Fa-1
POMBAL
North sector
Vm-1
LEIRIA
16 A-1
FÁTIMA
CALDAS
ALCOBAÇA
Nazaré Fault
17 C-1
S. MARTINHO DO PORTO
BERLENGAS
CALDAS DA RAINHA
SERRA EL-REI
BOLHOS
RIO MAIOR
BOMBARRAL
LOURINHÃ
Campelos-1
Pr-1
Lourinhã-1
Bombarral sub-basin
Ramalhal-1
Benfeito-1
Montejunto
OTA
Central sector
TORRES VEDRAS
Freixial-1
Arruda sub-basin
TURCIFAL
Turcifal sub-basin
Arruda-1
VILA FRANCA DE XIRA
Montalegre-1
MONTE GORDO
SINTRA
CASCAIS
Monsanto-1
LISBOA
Barreiro-2
Barreiro-4
Barreiro-3
SETÚBAL
ARRABIDA
SESIMBRA
Cabo
Espichel
South sector
Golfinho Horst
Pescada-1
Monte Paio-1
SINES
SANTIAGO DO CACÉM
0
25
50 km

Sequence Stratigraphic Framework of the Upper Jurassic-Berriasian of the Lusitanian Basin

The integration at basin scale of the data analysed separately by sector made possible the establishment of a sequence stratigraphic framework for the Lusitanian Basin. The proposed chronostratigraphic distribution of facies associations, sequences and the corresponding lithostratigraphic scheme are displayed on Figure 2. Figures 3, 4 and 5 show correlation panels in the three sectors of the basin.

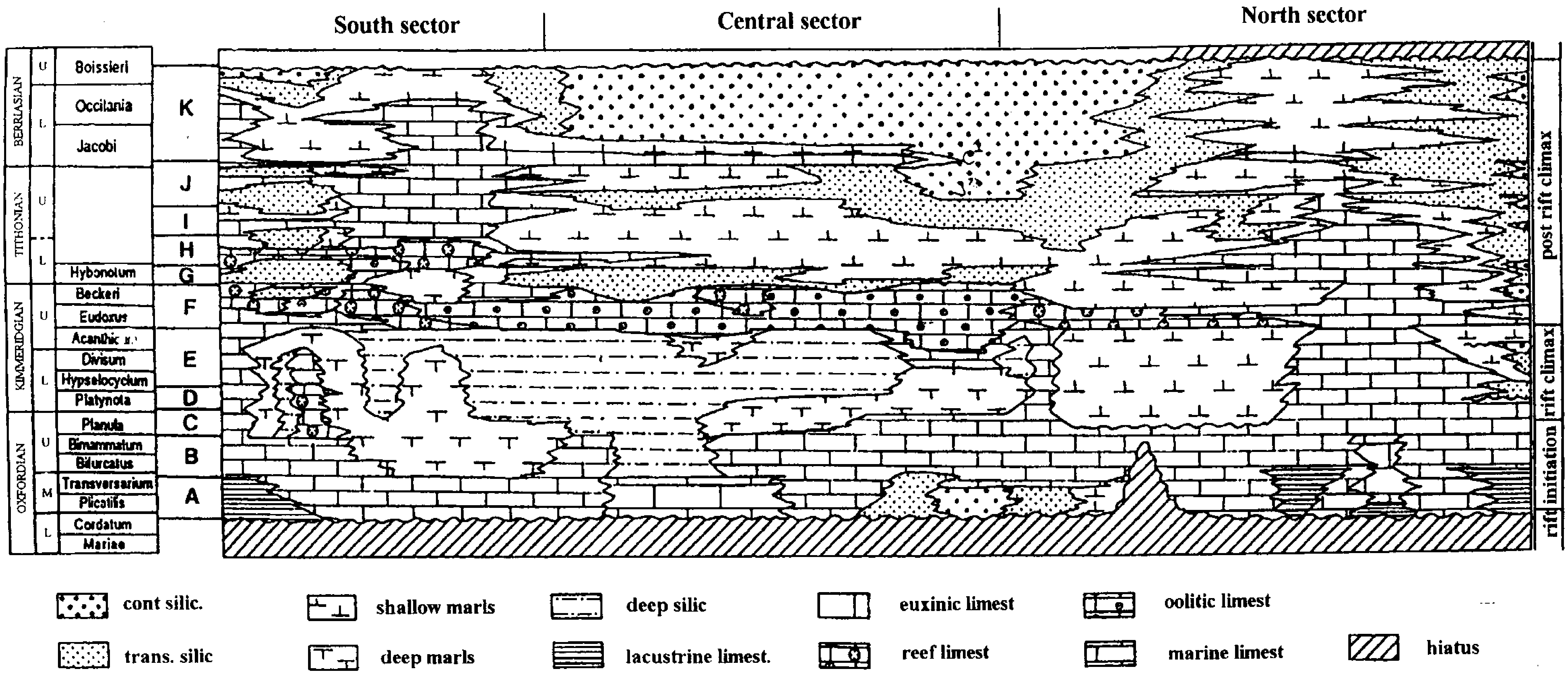
Description and Interpretation of the Depositional Sequences

Sequence A: After a long regressive hiatus that included the Callovian, sedimentation began again during the Middle Oxfordian (late Early Oxfordian?). Lacustrine carbonates (Fig. 2) are well developed in the eastern and north-eastern marginal regions. Some of these carbonates were deposited in hydrologically open shallow lakes, while others (highly bituminous) were formed in closed evaporitic lakes grading to lagoons. A shallow-marine, restricted carbonate platform is represented by a narrow N-S belt but south of Rio Maior, the environment was open marine. (Wright and Wilson, 1985). Near Cabo Mondego area and southwest of Peniche, some siliciclastics fed into the basin. Along the western border there were coastal siliciclastic systems draining to the east. To the south, sedimentation was mainly confined to carbonate systems (including lacustrine deposits) over slower subsiding blocks bounded by faults. Over the Sesimbra fault, very restricted marine environments occurred, probably due to salt flow into the structure. Subsidence of the Alentejo sub-basin appears to have been faster as that area was occupied by an open marine system. Clastic influx from the eastern margin of this sub-basin as well as along the clastic by-passing corridors related with the Arrábida and Golfinho horst was important (Fig. 5).

Sequence B (Upper Oxfordian): During deposition of this sequence, marine carbonate sedimentation occupies almost all the northern sector and siliciclastic sedimentation was restricted to a small area north of S. Martinho do Porto (fan delta and lagoon deposits). The outlines of the major sub-basins (Arruda, Bombarral and Turcifal) are defined (Fig. 2). Tectonic subsidence strongly increases within the resulting half-graben blocks. This definition is underlined by the settlement of an "arch" of carbonate platform depositional systems, with reef barriers to the north and east (Ramalhal, Montejunto, Ota and Monte Gordo buildups). Downslope of the major faults, carbonate and siliciclastic fans occur, e.g., Enxara do Bispo (Runa fault), Arruda, Montalegre (Vila Franca fault). In the Bombarral sub-basin, an unusual thickness of oolitic and biohermal limestone occurs (Ramalhal buildup), displaying a prograding geometry towards the southeast, following the Lourinhã-Ramalhal trend (Ellis et al., 1990; Wilson et al., 1990) (Fig. 4, M). Some sedimentation areas of the platform with reef barriers remained isolated e.g., the Ota and Monte Gordo horsts. Except in the eastern Arrábida, the relative sea-level rise allowed a wide distribution of marine carbonate systems and the retreat of clastic systems. The axis of maximum depth and subsidence seems to be located along the Barreiro fault and in the Alentejo sub-basin (Fig. 5). The main control over facies and thickness distribution was probably the activity of NNE-SSW faults.

Sequence C (Lower Oxfordian to lowermost Kimmeridgian): This sequence, which marks the rifting climax at a basinal scale, is difficult to identify in the northern sector. However, it is well represented at Cabo Mondego. In the central sector it is followed by rapidly deposited, thick terrigenous sediments. The activity of the structures (Vila Franca, Pragança, Runa and Caldas da Rainha faults, among others) that controlled the formation of the different sub-basins, lead to the definition of structural steps, bounding the depocenters. These steps allowed the genesis of significant amounts of terrigenous deposits (siliciclastic and carbonate) of submarine fans and canyons (Leinfelder and Wilson, 1989) (Fig. 4, Ca). Sedimentation seems to have proceeded from WNW (Hill, 1989) and ENE (from both margins of the basin) through two by-pass corridors. In general, over the whole southern sector of the Lusitanian Basin, a significant paleogeographical change is recorded, primarily reflecting increased water depth and progradation of clastic systems, mainly linked to Barreiro fault activity.

Figure 2. Biostratigraphic framework of the sequences described, and main facies associations occurring throughout the Upper Jurassic of Lusitanian Basin, (adapted from Pena dos Reis et al. 1996).


South sector
Central sector
North sector
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
U
L
U
L
U
L
U
M
L
Boissieri
Occitania
Jacobi
Hybonotum
Beckeri
Eudoxus
Acanthic.
Divisum
Hypselocyclum
Platynota
Planula
Bimammatum
Bifurcatus
Transversarium
Plicatilis
Cordatum
Mariae
K
J
I
H
G
F
E
D
C
B
A
post rift climax
rift climax
rift initiation
rift
cont silic.
trans. silic
shallow marls
deep marls
deep silic
lacustrine limest.
euxinic limest
reef limest
oolitic limest
marine limest
hiatus

Sequence D (Lower Kimmeridgian): In the area between Cabo Mondego and the Dourada-1C wells, an abrupt change from carbonates to siliciclastic sediments occurs in the top of sequence C, separated by a low angle unconformity (Bernardes, 1992). Other important aspects are the northward progradation of the Berlengas siliciclastic belt and the complete immersion of the Caldas da Rainha block which was, however, still acting as a barrier to the eastward progression of siliciclastic sedimentation. From both borders of the basin (central sector), large amounts of clastic sediments prograded over a decreasing accommodation space. These sediments define deltaic systems (Hill, 1989). In the southwest of this area, hemipelagic sedimentation occurs. In the Alentejo sub-basin, the south-eastward increase in thickness and transition from shallow marine to hemipelagic deposits points to a general tilting, probably controlled by the Santiago do Cacém fault.

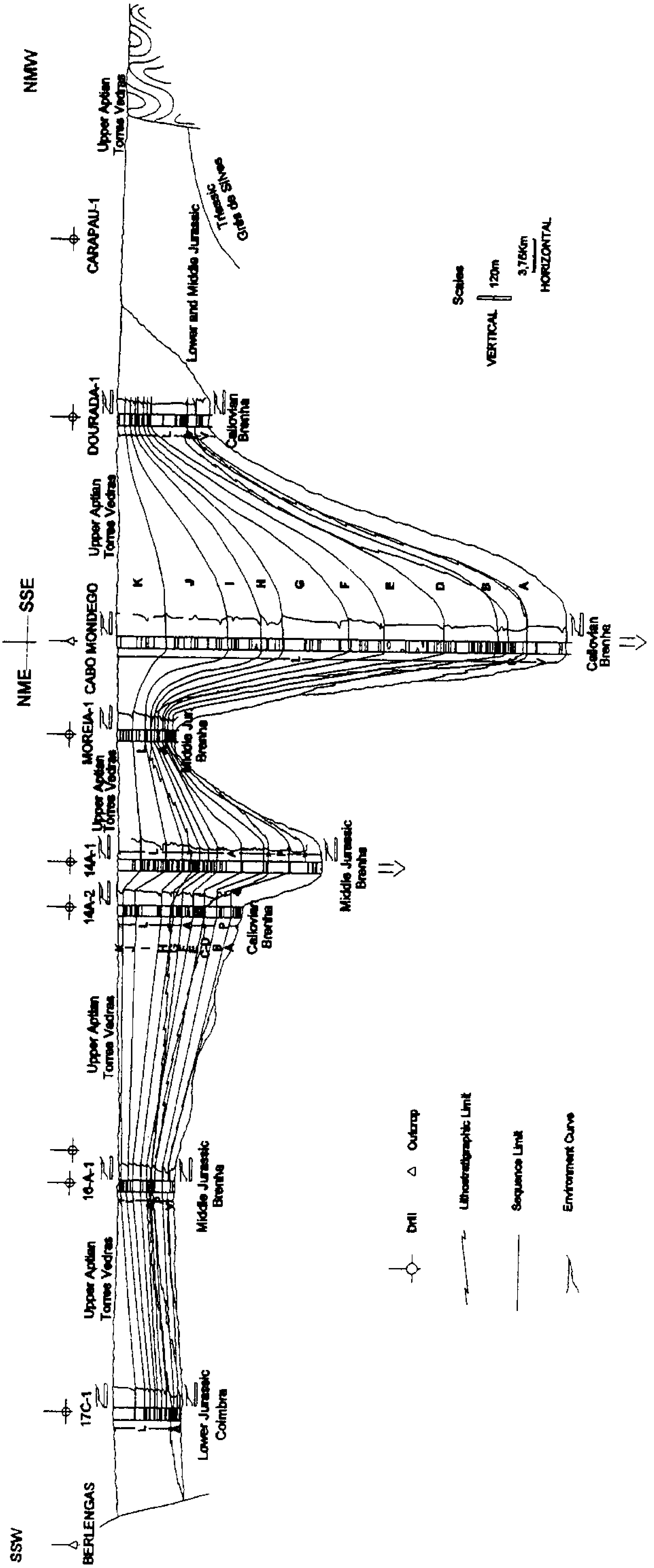
Sequence E (Lower to Upper Kimmeridgian): This sequence is similar to sequence D, displaying a more prograding geometry, and an infilling tendency due to large amounts of clastic sediments arriving into the basin. General progradation of marginal clastic systems is recorded, namely the slope siliciclastics prograding to the SE from the Turcifal and Arruda sub-basins. The axis prograded westward to the south of Barreiro and Arrábida. Compared to sequence D, the pattern of environments and isopach distribution is less complex, which is interpreted as a phase of paleogeographical homogeneity arising from a reduction of tectonic activity.

Sequence F (Upper Kimmeridgian): This sequence corresponds mainly to shallow marine deposits. They are composed of oolitic calcarenites and bioliths representing a widespread transgressive episode which caps the whole underlying succession and nearly infilled the tectonically derived accommodation space. The carbonate sediments display an onlap geometry over a major transgressive surface. They represent the marine invasion of uplifted areas such as the diapiric anticlines and the eastern horsts like Ota or Monte Gordo. Periplatform carbonate systems occupied the NNE-SSW depocenter belt west of Lisbon. Shallow marine carbonates, mainly reefs and oolitic barriers, were widespread in the central sector (Leinfelder, 1987). This facies represents the equivalent of the Amaral Formation (Fig. 4). Retrogradation of the clastic systems and a fairly uniform thickness characterises this sequence, the result of relative sea-level rise coupled with reduced tectonic activity.

Sequence G (Lower Tithonian): Relevant to the deposition of this sequence is the intense progradation of the marginal siliciclastic systems located south of Peniche. These siliciclastic systems replaced the oolitic and reefal facies belt in the northern and central sectors of the basin. At the northern border of the basin, the two marginal siliciclastic belts started to coalesce. To the south, progradation of clastic systems is more prominent on the eastern border. Progradation from the eastern part of Arrábida penetrates deeply into the Alentejo sub-basin, reducing the area occupied by shallow marine carbonates. In the basin depocenter, a shallowing trend is recorded by the onset of a shallow carbonate platform opened to the southwest (including isolated reefal buildups) and by the reduction of the slope of the ramp located south of the Sintra Massif.

Sequence H (Lower to Upper? Tithonian): This sequence is characterized by widespread retrogradation of the siliciclastic systems (except in the Alcobaça area) and the subsidence rate becomes uniform in the north sector. Most of it displays a retrogradational pattern of the clastic systems coupled with a more or less apparent restriction of carbonate systems. The deeper and more subsiding areas probably correspond to gulfs opened to the south with several axes located in the regions of Cascais, Sesimbra and the southern part of the Alentejo sub-basin. At a basin scale, the depocenter corresponds to a belt between Cascais and the Enxara do Bispo-1 well where open marine carbonate systems occur (low angle ramp to platform, including reefal facies). The transitional and continental clastic systems draining to the west still covered most of Arrábida between the Golfinho-1 well and Barreiro.

Figure 3. Correlation of sequences and lithostratigraphic units in the North sector of the Lusitanian Basin (see Fig.1 for location of sections). Strong thickness variations are shown. On the left side of each section lithostratigraphic units are identified according to the following code; Ab, Abadia Fm.; Am, Amaral Fm., C, Cabaços Fm.; Ca, Castanheira Mb.; Cb, Cabrito Mb.; Cr, Casal da Ramada Mb.; Dr, Deixa o Resto Mb.; F, Farta Pão Fm.; Fx, Freixial Mb.; L, Lourinhã Fm.; M, Montejunto Fm.; Mm, Mem Martins Fm.; P, Pholadomya Protei beds; Pc, Porto da Calada Fm.; Sb, Sobral Mb.; V, Vale Verde Fm.


SSW
BERLENGAS
17C-1
L
Lower Jurassic
Coimbra
Upper Aptian
Torres Vedras
16-A-1
Middle Jurassic
Brenha
Upper Aptian
Torres Vedras
K
J
I
H
G
E
C-D
B
A
14A-2
Callovian
Brenha
14A-1
Middle Jurassic
Brenha
Upper Aptian
Torres Vedras
MOREIA-1
Middle Jur
Brenha
NME
SSE
CABO MONDEGO
Callovian
Brenha
K
J
I
H
G
F
E
D
B
A
Upper Aptian
Torres Vedras
DOURADA-1
Callovian
Brenha
Lower and Middle Jurassic
CARAPAU-1
Triassic
Grés de Silves
Upper Aptian
Torres Vedras
NMW
Scales
VERTICAL
120m
3,75Km
HORIZONTAL
Drill
Outcrop
Lithostratigraphic Limit
Sequence Limit
Environment Curve

Sequences I and J (Upper Tithonian to lowermost Berriasian?): The sedimentation of marls (mainly prodelta and lagoonal deposits) in a N-S trending, central belt is characteristic of these sequences. In the central sector, sequences G, H, I, J and K. (Fig. 4) (Rey, 1972; Berthou and Leereveld, 1990) record fluvial and deltaic systems and represent an overall trend of progradation and basin infilling (Hill, 1989; Bernardes and Corrochano, 1992). These systems seem to have prograded from both east and west. They gradually invaded a central axial trough, mainly at the end of sequence J and during sequence K, separating two isolated areas of marginal sedimentation. This tendency appears to have undergone a temporary inversion, during sequence H, which records a moderate eastward and westward invasion of coastal and shallow marine systems. Sequence I is relatively thin in the southern sector. The local thinning over the Barreiro (Fig. 5) and Sesimbra structures can be correlated with small vertical movements. Sequence J lacks evidence of significant

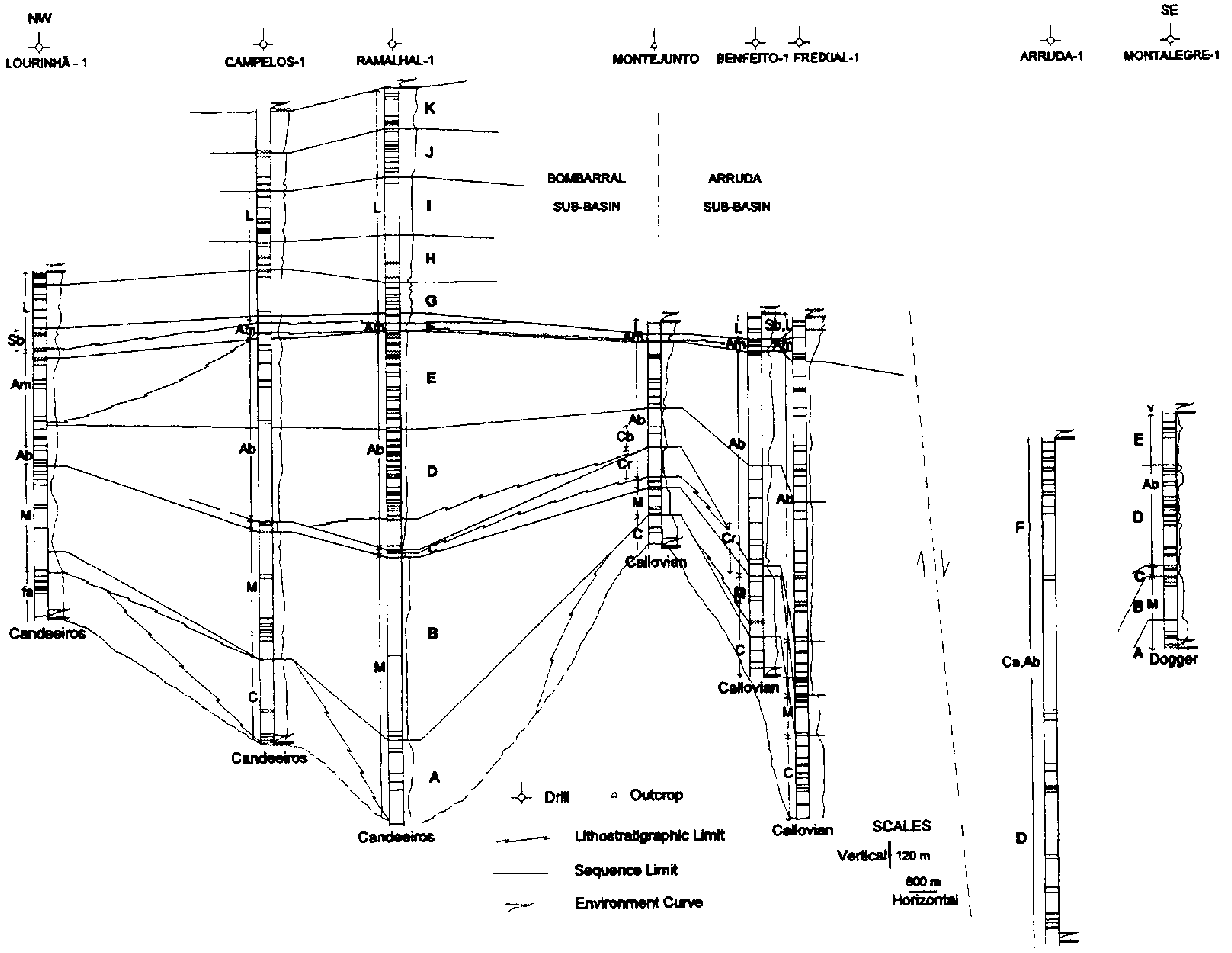
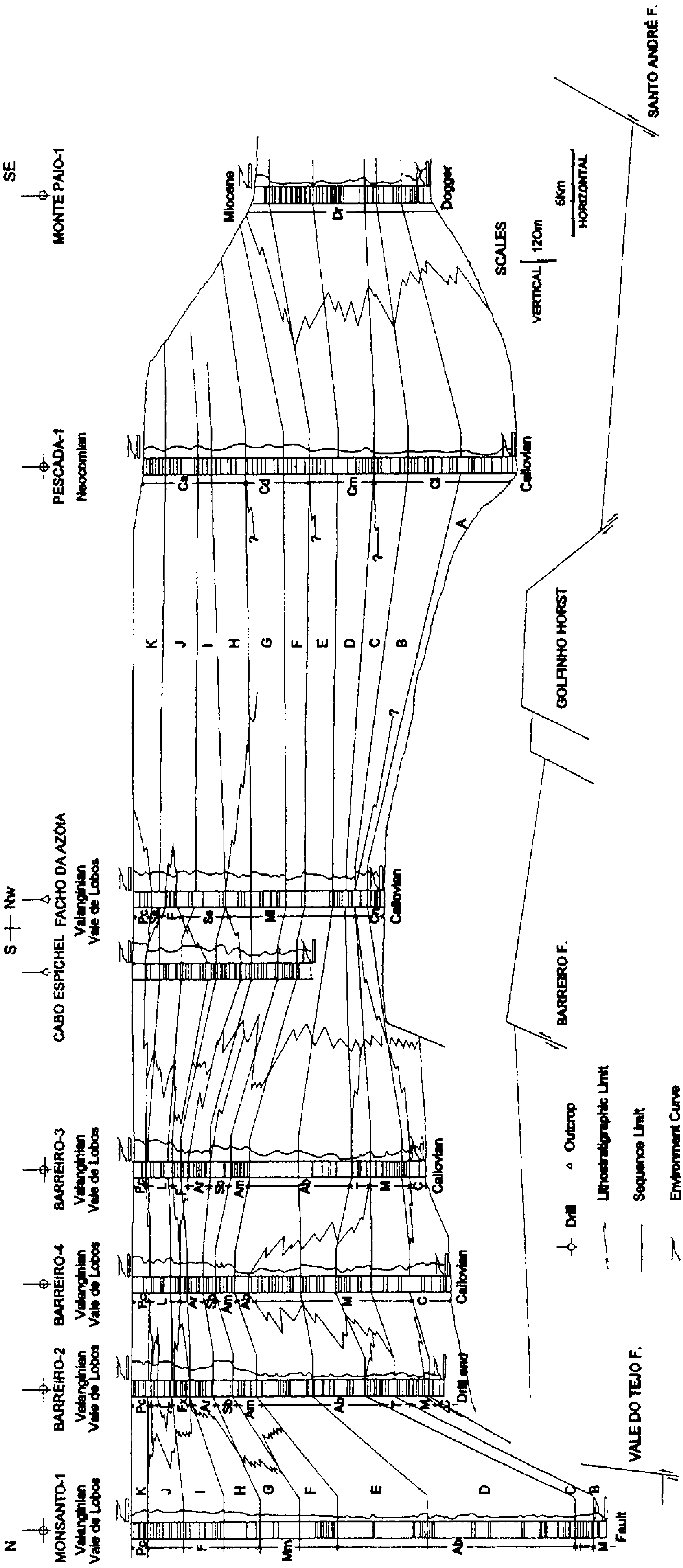


Figure 4. Correlation of sequences and lithostratigraphic units in the central sector of the Lusitanian Basin (see Fig.1 for location of sections and Fig. 3 for legend of units)

Figure 5. Correlation of sequences and lithostratigraphic units in the South sector of the Lusitanian Basin (see Fig.1 for location of sections and Fig. 3 for legend of units).


N
MONSANTO-1
Valanginian
Vale de Lobos
BARREIRO-2
Valanginian
Vale de Lobos
BARREIRO-4
Valanginian
Vale de Lobos
BARREIRO-3
Valanginian
Vale de Lobos
CABO ESPICHEL
S
Nw
FACHO DA AZÓIA
Valanginian
Vale de Lobos
PESCADA-1
Neocomian
MONTE PAIO-1
SE
Miocene
Dogger
Dr
Callovian
Drill end
Fault
Pc
F
Mm
Ab
T
M
L
Fx
Ar
Sb
Am
C
Se
Ml
Cn
Ca
Cd
Cm
Cl
K
J
I
H
G
F
E
D
C
B
A
?
SCALES
VERTICAL
120m
HORIZONTAL
5Km
SANTO ANDRÉ F.
GOLFINHO HORST
BARREIRO F.
VALE DO TEJO F.
Drill
Outcrop
Lithostratigraphic Limit
Sequence Limit
Environment Curve

tectonic movements. Maximum subsidence corresponds to the Cascais-Monsanto gulf and the southwestern Alentejo sub-basin. By this time, the clastic systems prograding from the western border of the central sector (Berlengas Islands region) reached the southern sector. In the transition between the southern and central sectors, a wide WNW-ESE belt of mixed lagoon to protected platform occurs, with a gulf defined towards the Montijo-1 well. Restricted marine carbonate sedimentation continues over a wide area with homogeneous facies distribution in the west and south of the sector.

Sequence K (Lower to Upper Berriasian): The siliciclastic sedimentation covers about two thirds of the total area of the north sector, corresponding to widespread fluvial systems. In the south sector, the highstand systems tract of this sequence corresponds to a rapid regression and is composed of the more continental deposits of the Upper Jurassic-Berriasian cycle. The westward progradation of the clastic systems occupies most of the Arrábida region and an important part of the Alentejo sub-basin. An important progradation also took place towards SW sourced in the Central sector. The thickness of the sequence is fairly uniform.

Conclusions

In the extensional model of the basin, the main features are a deep detachment (Malod, 1987) and an antithetic system of faults that created the graben that constitutes the western border of the basin. The overall sequence allows recognition of the evolution of subsidence. Trends in subsidence rate are similar in all regions of the basin. The rate increased to a maximum at the Oxfordian-Kimmeridgian transition, followed by continuous decrease until the Berriasian.

We interpret this evolution as corresponding to the following tectonic stages: rift initiation, extensional rift climax and gradual transition to post-rift thermal subsidence.

Despite recognition of the tectonic events mentioned above, subsidence rates were very different across the tectonically complex basin. Structures include pull-apart displacement (central sector, Wilson et al., 1990); half-graben (Arruda and Turcifal sub-basins, and Arrábida region) and horst/graben geometries; and halokinetic uprise and withdrawal. This implies strong variations in subsidence. Pena dos Reis et al. (1997) calculated a subsidence of 1647 m/my in the Arruda sub-basin of the Central sector (Sobral well), (Fig. 4).

In detail, a distensive episode seems to have occurred near the beginning of the Late Jurassic (Early to Middle Oxfordian), involving parts of the basin (the Arrábida, the eastern border of the Alentejo sub-basin and the western border of the central sector). On the other hand, fault reactivation under distensive stress since the Early Tithonian and during the Tithonian/Berriasian transition was recorded sedimentologically on a regional scale. The decrease in subsidence rate all over the basin and a long-term eustatic fall resulted in the general progradation of marginal siliciclastic systems. The large amount of sediment accommodation space created during the rift climax was fully infilled. During the late phase of relative tectonic quiescence, eustasy probably became the fundamental control on several recorded short-term sea-level cycles. There is no evidence of significant changes in climate, which is interpreted as generally warm and dry (Hill, 1989). During the late highstand, the progradation of clastic systems increased and the limit between sequences I and J records a peak of continental influence in the Upper Jurassic to Berriasian of the basin.

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In 1992 the Gabinete para a Pesquisa e Exploração de Petróleo (GPEP) through the Instituto Pedro Nunes (IPN) (a structure linked to Coimbra University), contracted the authors to carry out studies on sequence stratigraphy and biostratigraphy of the Upper Jurassic of the Lusitanian Basin. This paper presents a summary of the main results achieved so far. The authors are grateful to GPEP and to the consultants involved in the project.

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