Sonderdruck

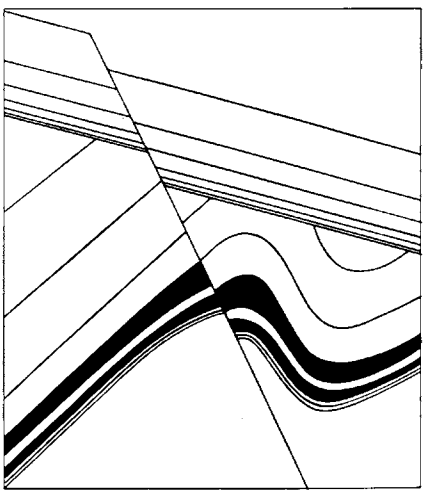
aus

Geologische Rundschau

Band 78, 1989 · Heft 1, Juli 1989

R. R. LEINFELDER and R. C. L. WILSON

Seismic and sedimentologic features of Oxfordian-Kimmeridgian syn-rift sediments on the eastern margin of the Lusitanian Basin



Ferdinand Enke Verlag · Stuttgart

Geologische Rundschau 78/1	81–104	Stuttgart 1989	© Geologische Vereinigung, Mendig

Geologische Rundschau 78/1 | 81–104 | Stuttgart 1989

Seismic and sedimentologic features of Oxfordian-Kimmeridgian syn-rift sediments on the eastern margin of the Lusitanian Basin

By R. R. LEINFELDER, Mainz and R. C. L. WILSON, Milton Keynes*)

With 17 figures

Zusammenfassung

Nach der weitverbreiteten Ablagerung mitteloxfordischer Seenkarbonate und Evaporite differenzierte sich das Lusitanische Becken in verschiedene Sub-Becken. Das Arruda Sub-Becken befindet sich ca. 30 km nördlich Lissabon und entspricht einem Halbgraben, in dem über 2.5 km mächtige Siliziklastika des Kimmeridgium zur Ablagerung kamen. Das Sub-Becken wird durch die Störungszone von Vila Franca de Xira nach Osten begrenzt. Auf Horststrukturen entlang der Störungszone wurden im Oxfordium und Unterkimmeridgium, z. T. auch bis ins Oberkimmeridgium Karbonate sedimentiert. Diese Karbonatschelfe weisen eine ausgeprägte Fazieszonierung von West nach Ost auf. Die westlichen Schelfränder sind durch höherenergetische Riffkalke (framestones) und Karbonatsande (grainstones) charakterisiert. Seismische Profile lassen eine große Lücke zwischen den Horstblöcken erkennen, durch welche Siliziklastika aus dem Hinterland ins Sub-Becken gelangten, wo sie einen submarinen Fächer aufbauten. Große Riffkalkblöcke innerhalb der Siliziklastika weisen auf Karbonatsedimentation in verlassenen Fächerbereichen hin. Die schnellen Mächtigkeits- und Fazieswechsel entlang des Ostrandes des Arruda Sub-Beckens sind durch synsedimentäre tektonische Bewegungen zu erklären, welche oftmals eine Dominanz der Lateralkomponente aufweisen.

Abstract

Following deposition of widespread middle Oxfordian lacustrine carbonates and evaporites, the Lusitanian Basin was differentiated into a number of sub-basins. The Arruda sub-basin is a half graben basin situated some 30 km north of Lisbon. It accumulated over 2.5 km of Kimmeridgian siliciclastic sediments, and is bounded to the east by the Vila Franca de Xira fault zone. Carbonate deposition persisted over horsts along the fault zone from the Oxfordian to the early Kimmeridgian, and in places to the late Kimmeridgian, and shows a pronounced west-east facies zonation, with higher energy framestones and grainstones accumulating along the exposed western margins. Seismic data indicate a major gap between the horst blocks that acted as a conduit through which basement derived siliciclastics were fed westwards into the sub-basin to form a submarine fan system. The presence of large blocks of framestone carbonates encased in siliciclastics indicates that carbonate sedimentation occurred in abandoned parts of the fan system. The rapid changes of sediment thicknesses and facies types along the eastern margin of the Arruda sub-basin are indicative of contemporaneous strike-slip movements.

Resumo

Depois da sedimentação dos calcários lacustres e depósitos evaporíticos da idade Oxfordiano médio, a Bacia Lusitánica diferenciou-se em várias sub-bacias. A sub-bacia de Arruda está situada ca. de 30 km ao norte de Lisboa e corresponde a uma estrutura «half-graben» em que mais do que 2.5 km de sedimentos foram acumulados. Para leste, a sub-bacia é limitada pela zona das falhas de Vila Franca de Xira. Entre o Oxfordiano e o Kimeridgiano, calcários desenvolveram-se em cima dos blocos elevados ("horsts") ao longo da zona de falhas. Estes calcários de tipo plataforma exibem uma distincta zonação de facies de oeste a leste. As margens occidentais das plataformas pequenas são caracterisadas por sedimentos recifais e areníticos. Cortes sísmicos indicam uma abertura grande entre os blocos elevados, pelo qual sedimentos siliciclásticos passaram de "hinterland" à sub-bacia formando um "fan" submarino. Grandes blocos recifais situados dentro dos depósitos siliciclásticos são evidências para sedimentação carbonática em várias áreas abandonadas dentro do "fan". Mudanças rápidas das espessuras e das fácies dos sedimentos ao longo da margem oriental da sub-bacia de Arruda podiam ser explicadas por uma tectónica sinsedimentária dominada por movimentos horizontais.

Краткое содержание

Лузитанский бассейн / стратиграфический ярус верхней юры, залегающий выше оксфордского и ниже киммериджского / подразделяют по широко распространенным отложениям среднеоксфордских карбонатов и эвапоритов на более мелкие бассейны. Один из них, бассейн Арруда, находится примерно на 30 км севернее Лиссабона и соответствует полуграбену, в котором отложились силикокластиты киммериджского века мощностью свыше 2,5 км. Этот небольшой бассейн ограничен на востоке у Vila Franca de

*) Authors' addresses: R. R. LEINFELDER, Institut für Geowissenschaften, Universität Mainz, Saarstraße 21, D-6500 Mainz, FRG and R. C. L. WILSON, Department of Earth Sciences, Open University, Milton Keynes, MK7 6AA, U.K.

Xira зоной сбросов. На структурах горста вдоль этой зоны сбросов в оксфордском и нижнекиммериджском веках, частично и до верхне-киммериджского века, откладывались в основном карбонаты. Эти мелководные отложения карбонатов проявляют явное разделение на фации при простирании с запада на восток. Западные края их характеризуются известняками рифов / framestones /и карбонатными песками / grainstones /. С помощью сейсмических методов удается выделить большой пробел между броками горстов, по которым силикатная кластика приносилась из тыла в эту часть бассейна, где она отлагалась под водой вееропoдобно. Большие блоки известняка рифов среди кластичессого материала силикатов указывают на отложение карбонатов в основном в впадинах этого «веера». Быструю смену мощностей и фация вдоль восточного края арруудского бассейна объясняют синседиментными тектоническими движениями, которые часто преобладают на боковых отрезках таких отложений.

Introduction

Only in basins bordering the western and northern margins of Iberia is it possible to examine at outcrop syn-rift sediments that heralded the opening of the adjacent North Atlantic Ocean. Other Mesozoic marginal basins bordering the North Atlantic (see Fig. 1 a) can only be studied by seismic methods and drilling. The Lusitanian Basin of Portugal provides a unique opportunity to integrate outcrop and subsurface data in order to study the lateral and vertical variations in syn-rift sediments. This paper discusses the eastern margin of the Basin to the north of Lisbon (Fig. 1 b).

Structural and stratigraphic setting

The Tectonic Map of Portugal (RIBEIRO et al. 1972) shows that the Lusitanian Basin has a relatively simple geometry. It depicts a Mesozoic basin trending NNE-SSW, with a width of about 100 km and a length of some 250 km, in which just over four kilometres of sediment accumulated (Fig. 1 b). To the north of Lisbon, modern seismic data has revealed that this picture is oversimplified, as a number of sub-basins can be recognized. These sub-basins were particularly active during the late Jurassic (WILSON, 1979; GUERY et al., 1986; MONTENAT et al., in press; WIL-

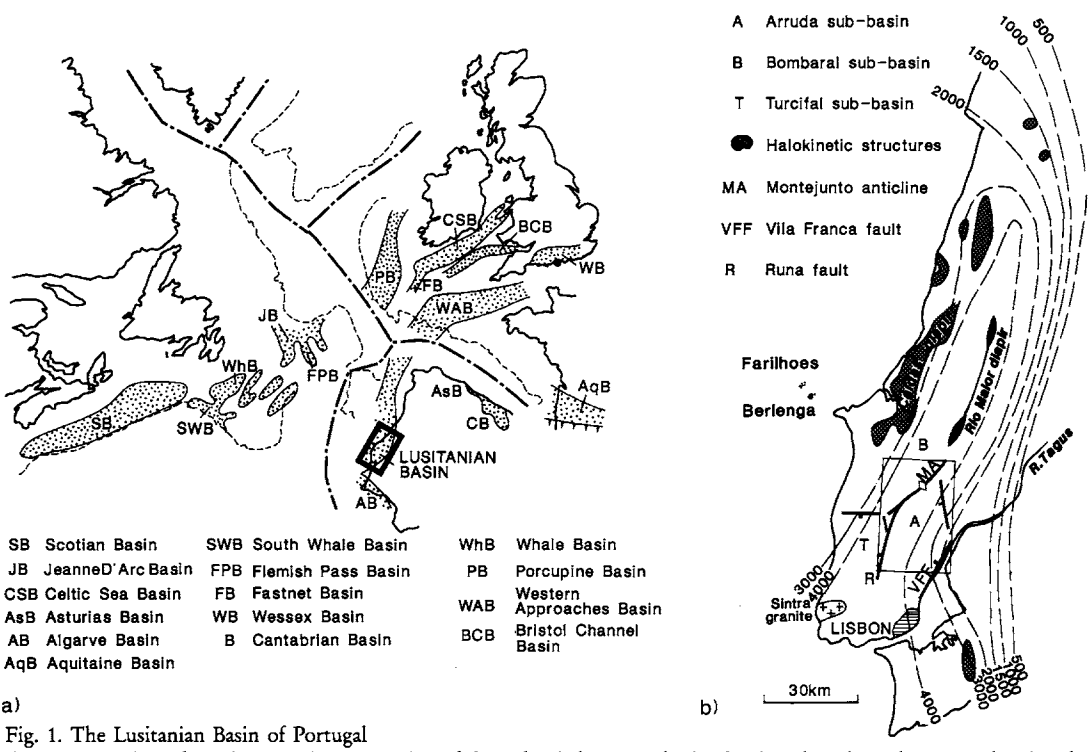


Fig. 1. The Lusitanian Basin of Portugal
a) Reconstruction of continents prior to opening of the Atlantic between Iberia, the Grand Banks and Europe, showing the location of Mesozoic marginal basins. The dashed-dotted line indicates later sites of ocean ridges.
b) Isopach map for the Mesozoic — Tertiary of the Lusitanian Basin from RIBEIRO et al. (1972): Modern seismic data reveals the presence of three sub-basins north of Lisbon. Inset indicates the location of the map of the study area shown in Fig. 3.

SON et al., in press). One of them, the Bombarral sub-basin, is flanked by diapiric structures, and subsided largely due to salt withdrawal, whereas the Arruda and Turcifal sub-basins developed as half-grabens.

The Lusitanian Basin exhibits two tectonic styles: one dominated by halokinetic structures, and the other by faulting (see Fig. 1 b). Both structural types show a dominant NNE-SSW orientation, plus a minor NE-SW trend; these mirror the trends of Hercynian basement faults. It is probable that the distribution of halokinetic and fault structures was controlled by the depositional thickness of Hettangian evaporites of the Dagorda formation. Where this formation was thick, diapiric structures developed over reactivated Hercynian basement faults, but where it was thin or absent, the faults propagated into the cover of younger sediments (WILSON et al., in press). The latter situation dominates the area discussed in this paper.

Fig. 2 summarizes the relationships between the principal stratigraphic units developed in the study area. It shows an informal nomenclature currently under discussion which aims to rationalize the confused mixture of biostratigraphic and lithostratigraphic terms used in previous literature concerning the Lusitanian Basin.

During the Triassic and Early Jurassic, movements along Hercynian basement faults produced basins that were filled with red clastics (Silves formation) and evaporites (Dagorda formation). The latter are relatively thin in the study area, but to the north were thick enough to be mobilized to produce salt structures. The Montejunto anticline, situated to the north of the study area shown in Fig. 1 b, is a salt pillow

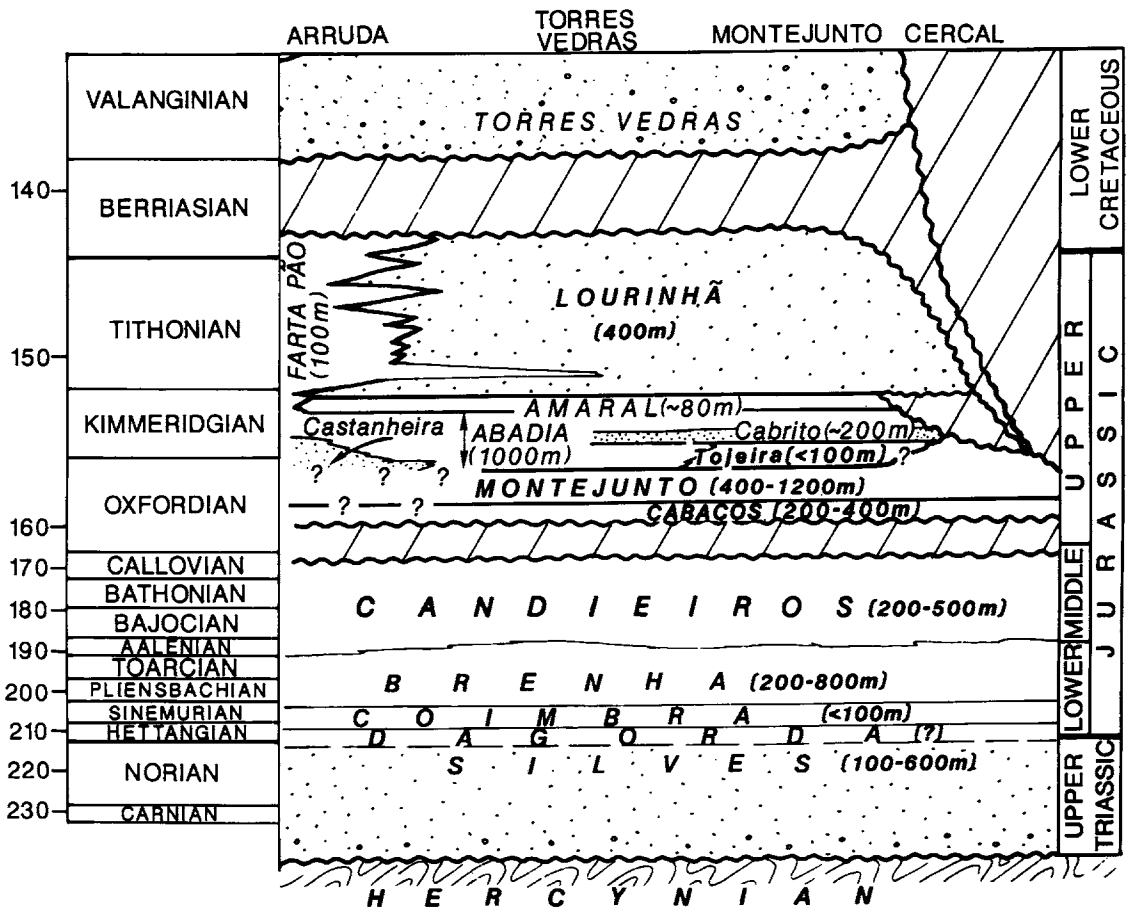


Fig. 2. Stratigraphic summary chart for the Jurassic and lowermost Cretaceous in the study area, based on an informal nomenclature currently under discussion amongst researchers working in Portugal. Note that the time scale on the left side of the diagram is doubled from the Oxfordian upwards, to accommodate the complex stratigraphy of this interval. The time scale used is that of KENT & GRADSTEIN (1985).

which was significantly modified by Miocene compressional movements (see below).

The combined effect of the progressive infilling of Triassic grabens, thermal sagging of the crust following crustal stretching and a global rise in sea-level led to more uniform sedimentation dominated by limestones and shales during the Sinemurian — Callovian interval. Localized uplift of a basement horst on the western margin of the basin occurred during the Toarcian. During the Middle Jurassic, the development of higher energy carbonates of the Candieiros formation was probably largely due to a global fall in sea-level. Minor salt movements may have commenced at this time. The widespread latest Callovian — early Oxfordian hiatus is often associated with a karst surface and is overlain by Middle Oxfordian bituminous freshwater and playa lake carbonate sediments of the Cabaços formation (LEINFELDER, 1983; WRIGHT & WILSON, 1985; WRIGHT, 1985), indicating a significant shallowing from the relatively deeper conditions of the Callovian. The stratigraphy of the post-Cabaços Upper Jurassic is discussed in more detail in the next section, where outcrop data from the study area are presented.

Surface geology

Structure

Fig. 3 shows the surface geology of the northern part of the Arruda sub-basin. The town of Arruda dos Vinhos is situated in a natural amphitheatre formed by scarp slopes capped by limestones of the Amaral formation. The roughly semi-circular outcrop pattern of this formation is produced by a domal structure, with gentle dips of only a few degrees to the north, west and south. To the southeast, the dome is cut by the Vila Franca de Xira fault zone.

The west side of the sub-basin is bounded by the Runa fault zone, the northern sector of which consists of a graben in which Upper Cretaceous sediments and Tertiary volcanics are preserved. A piercement diapir, the core of which exposes the Dagorda formation, occurs at the northern end of the graben. The northwestern margin of the sub-basin is formed by the Torres Vedras — Montejunto anticline, which trends NE-SW. The core of the northeastern portion of the structure consists of Middle Jurassic carbonates, and this part of the anticline is strongly asymmetric, with vertical to overturned strata and reverse faulting on the southern side. The Torres Vedras — Montejunto anticline was initiated during the Late Jurassic as a salt pillow structure which probably rose over a buried Triassic fault scarp defining the southeast limit of thick Dagorda evaporites (WILSON et al., in press). During the Tertiary, transpressional movements along a probable Hercynian basement fault resulted in the more complex deformation seen today.

The Ota horst defines the eastern margin of the Arruda sub-basin. This long, narrow exposure of upper Kimmeridgian shallow water carbonates is partly draped by Tertiary sediments on its eastern side, and to the west it is faulted against the Lourinhã formation.

The »standard« Upper Jurassic succession

The Upper Jurassic sequence exposed on the northwest flank of the Arruda sub-basin (see Fig. 4) is the »standard« section for the »Lusitanian« of Paul CHOFFAT (1883, 1901). The sequence begins with bituminous limestones of the Cabaços formation, which rests on a karstified surface of underlying Callovian limestones. The biota of the lower part of the formation is dominated by ostracods, cyanophytes, charophytes, and the dasyclad *Heteroporella lusitanica* which indicates a Middle Oxfordian age (LEINFELDER et al., in press). Gypsum pseudomorphs and collapse breccias indicate the former presence of evaporites. In the nearby Benfeito well (for location, see Fig. 3) the top part of the Cabaços formation contains a mixed carbonate-anhydrite sequence about 70 m thick. A variable salinity, lacustrine environment of deposition was proposed for the formation by WRIGHT & WILSON (1985) and WRIGHT (1985). The occurrence of corals and bivalves at the top of the formation indicates a transition to the fully marine environments of the overlying Montejunto formation.

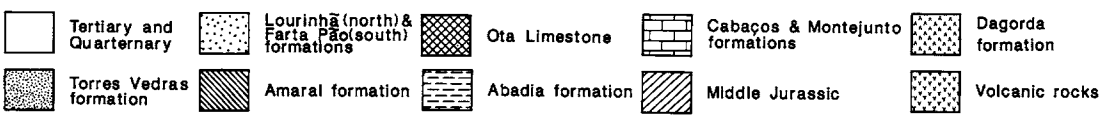
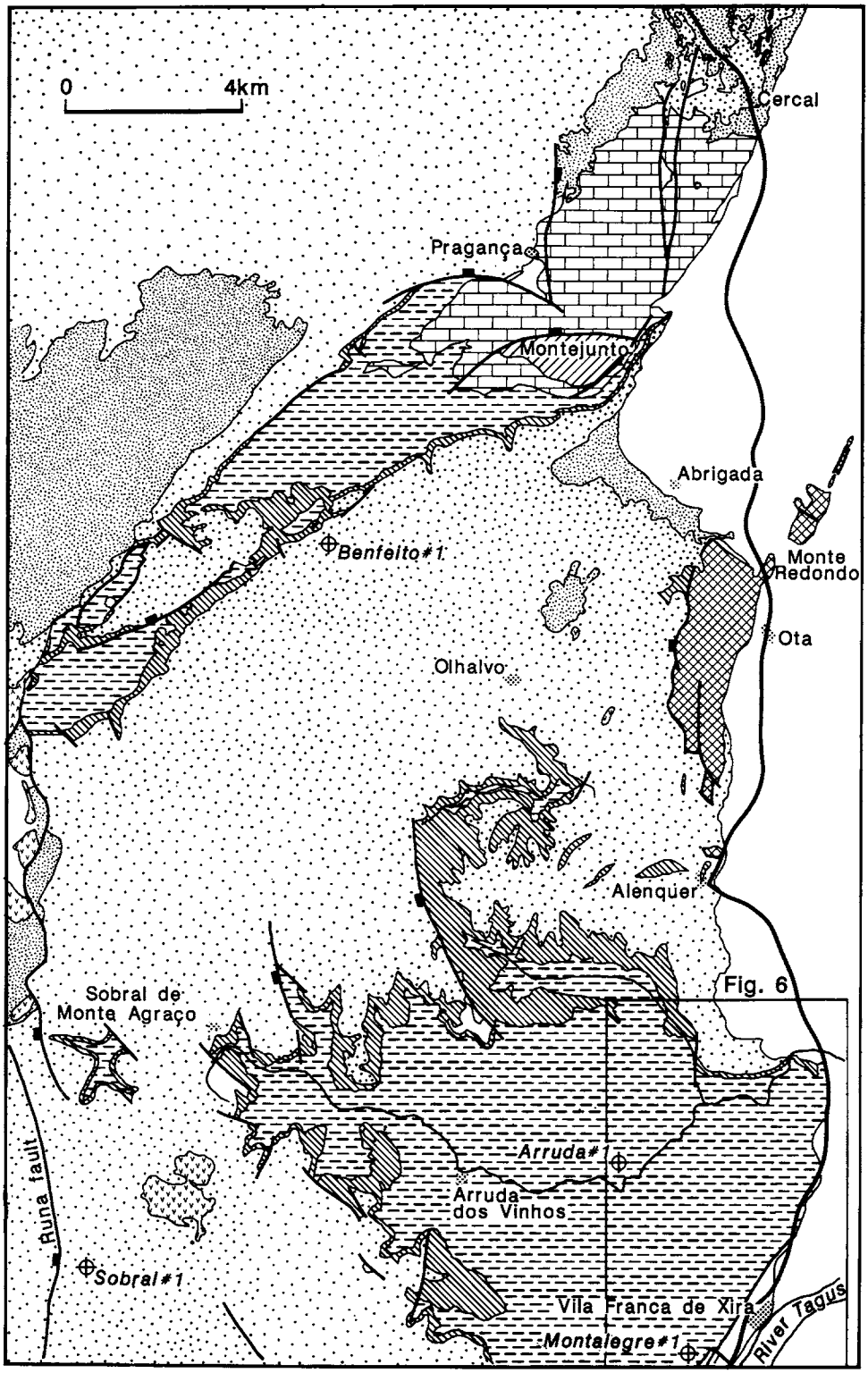


Fig. 3. Geological map of the Arruda sub-basin (after ZBYSZEWSKI & TORRE DE ASSUNÇÃO, 1965; ZBYSZEWSKI et al., 1966; with modifications). Inset indicates the area depicted in more detail in Fig. 6. The location of exploration wells discussed in the text is shown.


0
4km
Cercal
Pragança
Montejunto
Abrigada
Benfeito#1
Monte Redondo
Ota
Olhalvo
Alenquer
Fig. 6
Sobral de Monte Agraço
Arruda#1
Arruda dos Vinhos
Runa fault
Sobral#1
Vila Franca de Xira
River Tagus
Montalegre#1

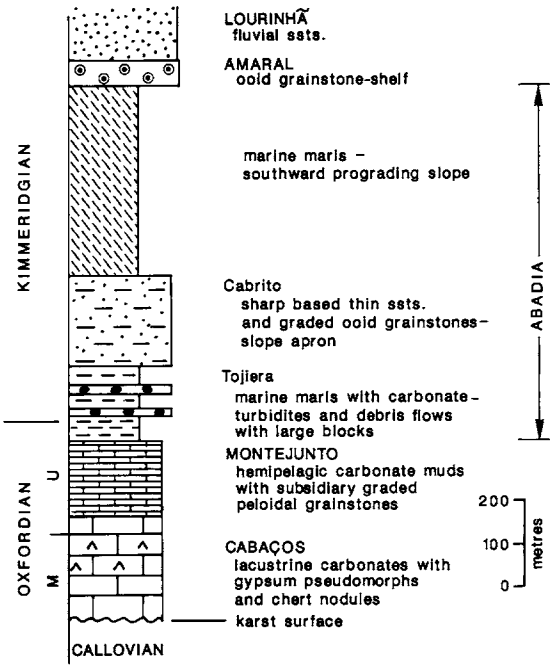


Fig. 4. Summary section showing the key features of the Upper Jurassic succession exposed in the Torres Vedras — Montejunto anticline.

In the Sobral and Benfeito wells, and at outcrops around Torres Vedras and on the southwest flank of Montejunto, the Montejunto formation consists predominantly of thick bedded, fine grained hemipelagic limestones, the ammonite fauna of which indicates a Late Oxfordian age (RUGET-PERROT, 1961).

The Abadia formation is a siliciclastic unit that is about 800 m thick. The basal Tojeira member is up to 160 m thick, and spans the Oxfordian — Kimmeridgian boundary (ATROPS & MARQUES, 1986). It consists of shales, marls, allodapic limestones and debris flows containing allochthonous blocks of karstified shallow water carbonates and pebbles of basement rocks. The limestone blocks were derived from a carbonate platform situated on the northeast flank of the Montejunto structure. The platform carbonates are laterally equivalent to the deepwater facies of the Montejunto formation (ELLIS & WILSON, 1987). The overlying Cabrito member is 200 m thick in the Montejunto area. It consists of flat bedded lensoid medium grained sandstones and graded ooid grainstones intercalated with grey silts and marls. ELLWOOD (1987) interpreted the Cabrito member as a slope apron deposit formed at the toe of the prograding slope system that deposited the 400–500 m of grey silts and marls with subsidiary turbiditic sandstones and limestones that comprise the top half of the Abadia formation.

The Abadia formation is capped by the upper Kimmeridgian Amaral formation, which is between 60 and 80 m thick. In the Torres Vedras — Montejunto area it consists almost exclusively of cross-bedded oolitic grainstones containing quartz-cored ooids. Around Arruda, medium to high-energy, biostromal coral limestones occur below the oolites and are up to 30 m thick. The biostromes are composed of coral boundstones with a highly diverse biota of baffling and massive corals and stromatoporoids, as well as molluscs, echinoids and serpulids. The boundstones grade laterally into debris facies consisting of coral-rich grainstones, packstones and nerineid packstones. Low-energy lagoonal wackestones and peloidal packstones occur occasionally (ELLIS et al., in prep.)

In the Montejunto area, the Amaral formation is overlain by the dominantly fluvial, siliciclastic Lourinhã formation of uppermost Kimmeridgian to upper Tithonian age. A horizon of freshwater oncolites occurs in the lower part of the formation to the west and southwest of the Ota horst (LEINFELDER, 1985). The base of the unit frequently exhibits marginal marine siliciclastic sediments characterized by shell beds of euryhaline molluscs such as *Eomiodon* and *Isognomon*. Towards the south, the Lourinhã formation grades laterally into the Farta Pão formation (termed the »Pteroceriano« unit in Portuguese literature, which is an invalid lithostratigraphic term as it is not based on a geographic location). The latter formation consists of lagoonal, nodular *Arcomytilus* limestones and marls, exhibiting coral biostrome developments in the middle part, and terrestrial sandstone intercalations in the upper part (LEINFELDER, 1986; 1987b).

Cretaceous sediments in the study area consist predominantly of terrestrial siliciclastics of the Torres Vedras formation.

The east side of the Arruda sub-basin exhibits Kimmeridgian successions that are markedly different from those of the »standard« succession to the west and northwest. These are described in the next two sections.

Oxfordian — Kimmeridgian carbonate shelves on the eastern margin of the Bombarral and Arruda sub-basins

The Montejunto shelf. The upper Oxfordian deepwater ammonitic lime mudstones of the Montejunto formation to the west and southwest of Montejunto grade northeastward into a shallow water carbonate

buildup (see Fig. 5 a). The transition (i.e. the slope) between the two is characterized by bioclastic wackestones with *Tubiphytes* mounds and occasional debris flows derived from coral biostromes. The shelf edge is characterized by a discontinuous and narrow sand shoal belt, behind which is a broad area of low energy lagoonal nerineid wackestones and peritidal sequences composed of lime mudstones with intercalations of laminated fenestral limestones as well as black pebble and soil horizons. The occurrence of karstified allochthonous shallow-water limestone blocks in the upper part of the Tojeira member to the southwest of the shallow water buildup indicates that the platform edge was exposed around the Oxfordian/Kimmeridgian boundary. Carbonate sedimentation may have persisted over the shelf region into the early Kimmeridgian. Later on, the shelf area underwent karstification until the Cretaceous, interrupted only by local deposition of terrestrial clastics of the Lourinhã formation (ELLIS & WILSON, 1987).

The Ota carbonate shelf. The thickness of the exposed part of the Ota limestone is about 160 metres. The top of the unit is partly draped by the uppermost Kimmeridgian Amaral formation, which transgressed over an erosional unconformity. Therefore, the Ota limestone was deposited simultaneously with the siliciclastic Abadia formation to the west (LEINFELDER et al., in press).

The Ota limestone exhibits a classic facies zonation characteristic of an aggradational shelf (see Fig. 5 b). A high-energy reefal belt, exhibiting a spur-and-grove

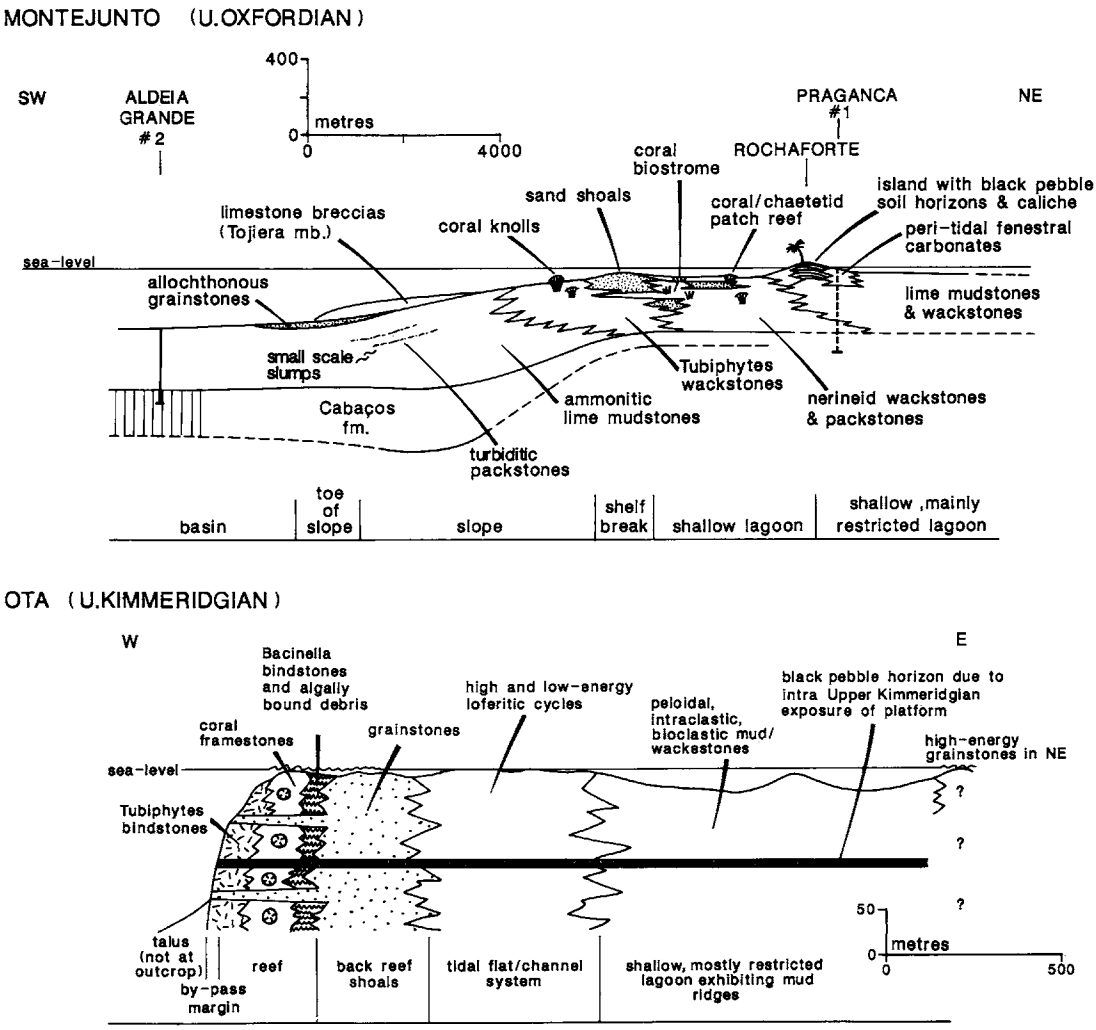


Fig. 5. Idealized cross section of the Montejunto and Ota carbonate buildups.

pattern, grades eastwards into back barrier lagoonal and shoal sands. Further east occurs a tidal zone characterized by subtidal to supratidal cycles, and a restricted low-energy lagoonal zone with mud ridge development, which grades into high-energy sands towards the northeast (LEINFELDER et al., in press; LEINFELDER, in prep.). Internal lithostratigraphic correlation is aided by a prominent, widely developed black pebble horizon (Fig. 5 b), resulting from intraformational exposure and subsequent flooding of the platform (LEINFELDER, 1987a). The position of facies zones remained stationary throughout the entire development of the unit, indicating the existence of a faulted by-pass margin to the west, which prevented progradational growth of the reef despite its very productive character. Such an interpretation is reinforced by the fact that a major fault can be seen on seismic sections (see below).

Siliciclastic fan development on the eastern margin of the Lusitanian Basin

The results of detailed mapping undertaken to the north of Vila Franca de Xira are summarized in Figs. 6 and 7. The marls and silts of the top part of the Abadia formation are replaced eastwards by coarse arkosic sandstones and conglomerates of the Castanheira member.

South of Carregado (Fig. 6) the Castanheira member represents the entire Abadia formation, and has a minimum exposed thickness of 350 metres. Close to the Vila Franca fault zone, it consists of massive, very coarse poorly sorted arkosic conglomerates. Quartz clasts range in size from 0.5 to 1.5 cm. Very fresh grains of potassium felspar are up to 3 cm across. Pebbles of Hercynian basement rocks up to 30 cm in diameter also occur, and include prophyroblastic granitoids, gneisses, amphibolite schists and phyllites. Locally, limestone pebbles are common constituents of the conglomerates; some of them may have been reworked from Oxfordian or older limestones situated to the east of the Vila Franca fault zone. The absence of limestone pebbles in many exposures of the Castanheira member may be due to postdepositional leaching rather than the absence of a limestone component to the original detrital mixture. Intraformational clasts are a significant component, and consist of pebbles of marls, clays and sandstones. Occasionally, large boulders of marls and siltstones, up to 6 m across, occur embedded in the arkoses.

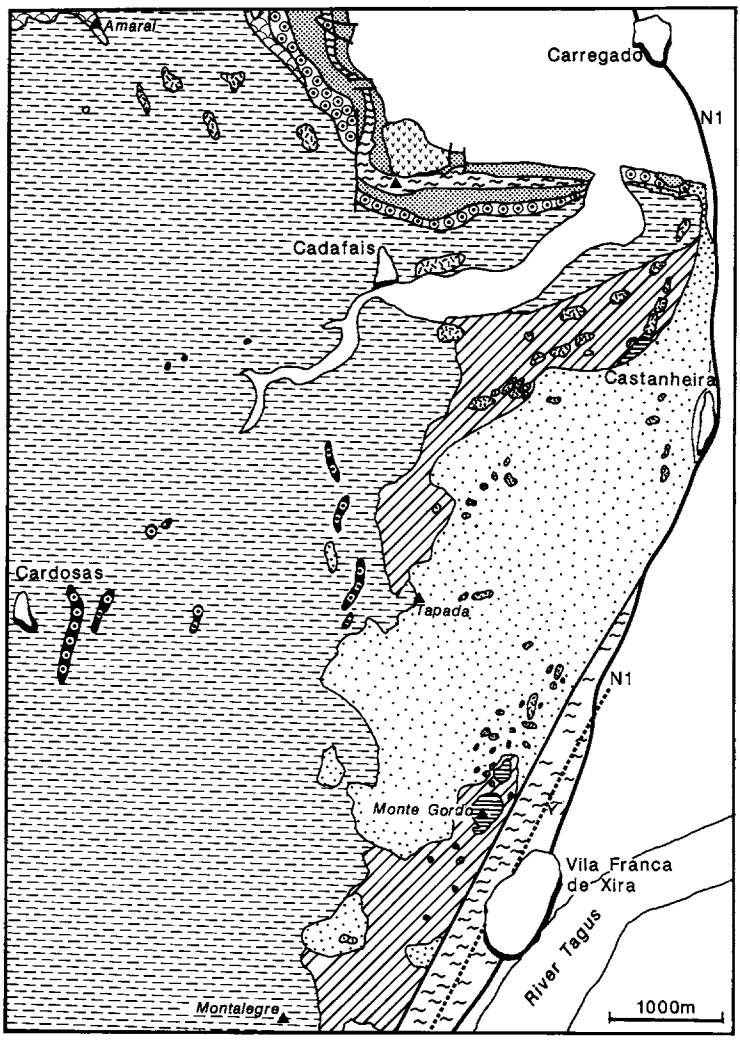
Exposures of the Castanheira member in more westerly locations away from the Vila Franca de Xira fault zone show coarse sandstones with bedding often picked out by concentrations of lignitic debris. Amalgamated channels occur in places, with individual channels up to five metres across and two metres deep. The conglomeratic sediments also die out to the south around Montalegre. At the transition between the coarse siliciclastic sediments of the Castanheira member and the marls and silts of the top of the Abadia formation, two localized sequences of interbedded marls, sandstones and limestones up to 50 m thick are developed. The sandstones are up to one metre thick; limestone beds are thinner. The sandstones sometimes exhibit grading, and the limestones consist of lithoclasts and coral breccias deposited as debris flow.

East of Arruda, thick (1–2 m) beds of ooid grainstones occur within the marls and silts of the top part of the Abadia formation. Load and flute casts, plus some burrow traces are seen on the bases of these beds, which usually fine upwards; paired graded units are common. In addition to ooids, some beds contain significant amounts of fragmented shallow water bivalves (particularly oysters) and lignitic debris. Current oriented belemnites are sometimes present. Pebbles of sideritic nodules reworked from the surrounding Abadia marls are a common constituent, indicating an early diagenetic origin for the nodules.

Allochthonous blocks of reefal limestone occur in both the fine and coarse grained facies of the Abadia formation on the east side of the Arruda sub-basin. The blocks frequently show evidence of karstification prior to transportation, with solution hollows and pockets filled with arkosic sediments. Large fields of reefal blocks (with individual blocks up to a hundred cubic metres in size) occur in the vicinity of two autochthonous masses of reefal limestone to the west of Vila Franca (Monte Gordo) and near Castanheira (Fig. 6). The limestones at Monte Gordo were first described by ANDRADE (1934). They are about 60 metres thick, with the basal few metres exhibiting lithoclastic packstones containing intraclasts, large black pebbles and detrital feldspar and quartz. This basal facies is transitional in character between the underlying arkoses and overlying coral rich reefal limestones. The southeastern margin of the Monte Gordo carbonate buildup is characterized by large para-autochthonous blocks of limestone encased in marls, and overlain by arkoses.

The presence of carbonate debris flow deposits, re-

Fig. 6. Geological map of the east side of the Arruda sub-basin between Carregado and Vila Franca de Xira (modified after MAGG 1987). ▶



LEGEND

- Volcanics
- Tertiary & Quarternary
- Farta Pão fm. (nodular lsts.&marls)
- Lourinhã fm (siliciclastics)
- a] b] Amaral fm. (a] ooid grst., b]coralgal Biostromes)

ABADIA FORMATION

- marl/siliciclastic turbidite facies
- arkosic conglomerates (Castanheira mbr.)
- marl/siliciclastic sst. facies with carbonate debris flows
- Autochthonous, partly reefal carbonates(chiefly Monte Gordo lst.)
- lithoclastic limestones with black pebbles and detrital quartz and feldspar
- Allochthonous blocks of reefal limestones
- resedimented ooid grainstones

sedimented ooid grainstones, allochthonous reefal blocks, reworked blocks of Abadia marls and sideritic concretions, and channelized and massive coarse siliciclastic sediments indicates deposition in slope and proximal submarine fan settings. The occurrence of *in situ* carbonate buildups and allochthonous reefal blocks suggests that the siliciclastic fan system aggradated close to sea-level so that carbonate sedimentation could occur over abandoned parts of it. This situation is comparable to recent reef development over siliciclastics in the Red Sea (SNEH & FRIEDMAN, 1980), although there is no evidence for alluvial sedimentation in Portugal.

Subsurface data

Borehole data

The location of petroleum exploration wells drilled in the Arruda sub-basin is shown on Fig. 3, and summary logs of Oxfordian-Kimmeridgian sections encountered are shown in Fig. 8.

In 1951, Montalegre #1 proved that the Oxfordian carbonate succession on the east side of the sub-basin is similar to that exposed in the Montejunto — Torres Vedras anticline (Fig. 8). The well entered Hercynian basement at 1714.5 m, which was shown to be faulted (at 1709 m) against Bajocian carbonates, with a few metres of Dagorda formation possibly intruded along the fault plane.

Arruda #1 was drilled in 1959 on the crest of the Arruda dome as seen at the surface, and it was expected to penetrate a sequence similar to that known at outcrop to the northwest, and from Montalegre #1. The Oxfordian carbonates were the principal reservoir target for the well, but they were never reached, despite drilling to a depth of 2137 m.

Cores from Arruda #1 show comparable features to the Castanheira member at outcrop. Fining-up sequences occur, ranging from one to four metres in thickness, with arkosic sandstones, sometimes conglomeratic, at the base, and passing up into lignite rich fine sandstones and siltstones. Limestone clasts are

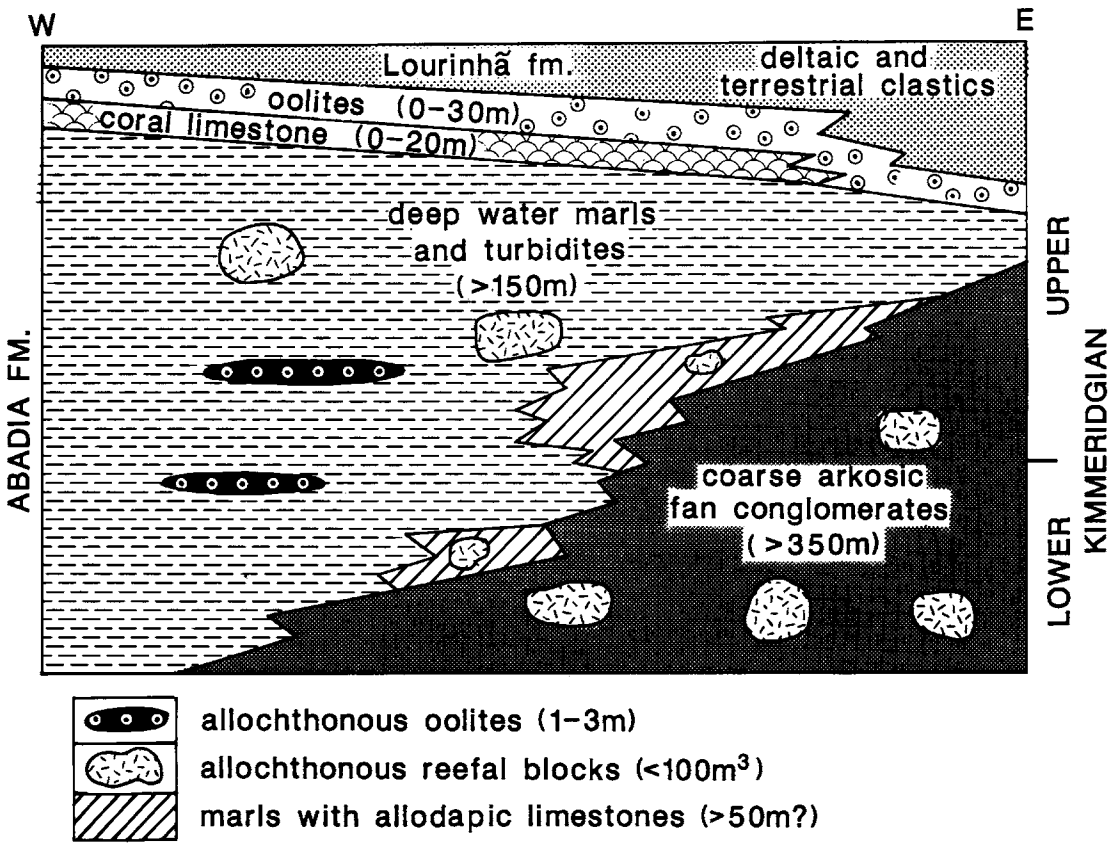


Fig. 7. Schematic cross section showing facies relationships within the Abadia and Amaral formations on the east side of the Arruda sub-basin, based on the geological map shown in Fig. 6.

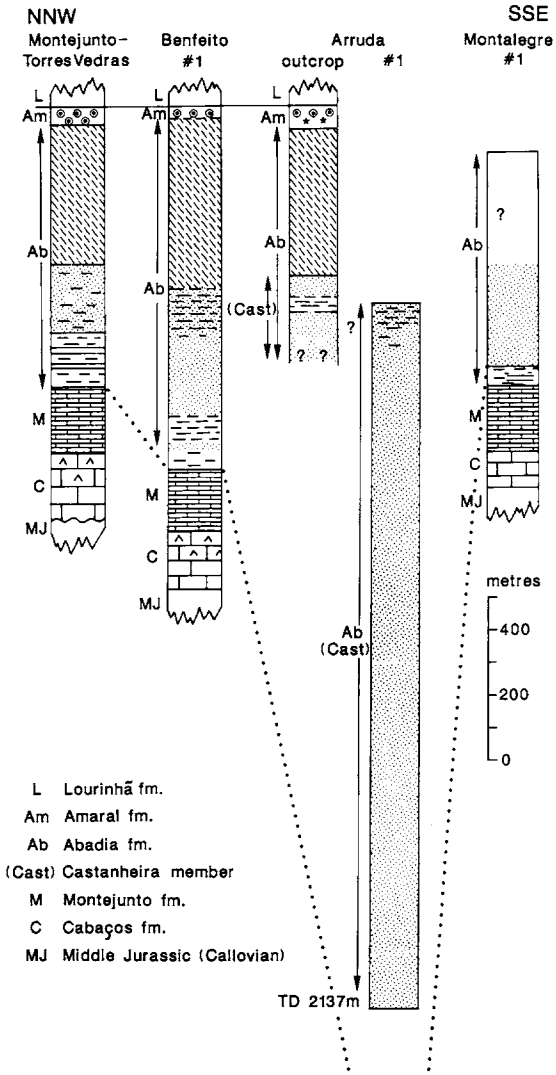


Fig. 8. Summary of successions encountered in exploration wells in the Arruda sub-basin. Outcrop data has been added above Arruda #1, and the succession exposed in the Montejunto — Torres Vedras anticline (Fig. 4) is also shown for comparison.

also quite common in the sandstones. The fining-up sequences are comparable to the amalgamated channel sandstone facies as seen at the surface. Cores taken near the bottom of the well are generally finer grained than those recovered at around 600 m; the latter commonly contain basement pebbles up to ten centimetres across. This change in grain size is accompanied by a change in palynofacies, with the lower cores containing significant microplankton, whereas the upper cores only contain rare marine palynomorphs (L. A. RILEY, pers. comm.).

In 1981, Benfeito #1 showed that the Abadia formation thickens southeastwards into the Arruda sub-basin almost entirely due to the lower sands (Cabrito member) increasing in thickness rather than the upper slope marls and silts.

The well data show that a very thick siliciclastic submarine fan sequence was deposited close to the eastern margin of the Arruda sub-basin during the Kimmeridgian. The structural setting of this fan, and its relationship to the contemporaneous carbonate buildup at Ota only became clear on examination of seismic data shot in 1980 and 1981.

Seismic data

The Arruda sub-basin seismic survey was commissioned by Petrogal, and untertaken in 1980–81 using a vibroseis source. Fig. 9 shows the location of interpretations and extracts of migrated seismic lines illustrated in Figs. 10–15. As the sections are displayed in time, no vertical exaggeration is given on the Figures: seismic velocities in the Abadia formation are around 3200–3600 msec^{-1}, those of the Castanheira and Cabrito members range between 4500–5000 msec^{-1}, whereas those in the Cabaços and Montejunto formations are 5500 msec^{-1}.

The justification of the interpretation presented on Fig. 9 will become apparent as each line illustrated is described and discussed. The examples are introduced in clockwise order around the sub-basin, starting with an west-east line passing through the location of Arruda #1.

Figure 10. This interpreted section clearly shows the half-graben nature of the Arruda sub-basin. The distance between reflectors 4 and 5 (i.e. top Dagorda to Cabaços formation) changes little, whereas the Montejunto and Abadia formations (reflectors 4 to 1) show significant thickening from east to west.

The stippled area on Fig. 10 is an area of discontinuous and chaotic reflectors that is discussed in more detail below.

Figure 11. This Figure shows that the Montejunto — Torres Vedras anticline began to develop during Oxfordian and early Kimmeridgian times, for the Oxfordian carbonates and Cabrito/Castanheira intervals thin to the northwest, whereas the underlying Lower and Middle Jurassic does not.

The division of the Abadia formation into a lower sand dominated interval, and an upper marl and silt sequence (Figs. 4, 8) is reflected in the nature of the seismic facies seen on Fig. 11. The lower part of the Abadia formation shows relatively continuous, moderate to high amplitude reflectors with some divergence southeastwards into the Arruda sub-basin. The

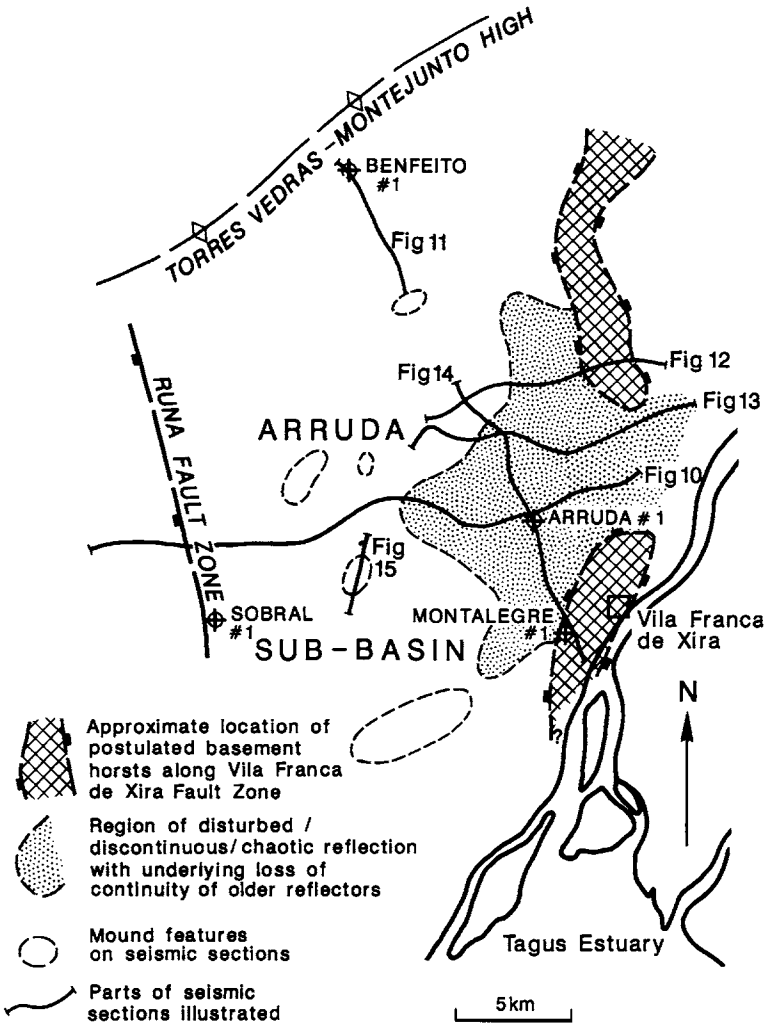


Fig. 9. Locations of seismic lines from the Arruda sub-basin illustrated in Figs. 10–15 and the distribution of the principal features interpreted from seismic data.

base of the unit onlaps the Oxfordian carbonates. The upper part shows inclined clinoforms, the true dip of which is probably to the south. This unit is largely characterized by low amplitude reflectors of poor continuity, with occasional higher amplitude continuous reflectors traversing it from top to bottom. The upper slope unit does not thin towards the Montejunto — Torres Vedras anticline, which indicates that movement of the salt pillow ceased during the Late Kimmeridgian.

Figure 12. This Figure shows part of an east-west line where it crosses the Ota carbonate buildup. Once again, the eastward thickening of the Oxfordian carbonates and the lower part of the Abadia formation can be seen. In this example, this thickening indicates syn-sedimentary movement of the fault bounding the western side of the Ota buildup.

The interpretation to the east of the Ota buildup showing Cenozoic overlying Middle Jurassic is based on drilling results to the east of the River Tagus. The fault on the east side of the Ota buildup is clearly shown on the seismic section, and that on the western side can be mapped at the surface (see. Fig. 3). Whereas there is no doubt that the Ota carbonate buildup is situated over a horst, the interpretation of the structure within the horst is very speculative.

An area of discontinuous and chaotic reflections is shown as a stippled zone on the interpretation of the seismic section. The continuous reflectors to the west marking the Oxfordian carbonates extend only a short distance eastwards beneath this zone.

Figure 13. This west-east line, though situated only a few kilometres south of Fig. 12, shows two significantly different developments. The Cabrito/Castanheira and slope intervals of the Abadia formation can be traced about five kilometres further east and appear to overlie a less prominent horst structure. A zone of discontinuous and chaotic reflectors is still evident, but its western margin is marked by a fault, the eastward inclination of which suggests it formed as an antithetic structure to the main sub-basin boundary fault. The latter fault does not cut the Abadia formation, but a flexure within this interval is developed indicating later slight reversed movement.

Figure 14. This NNW-SSE trending line traverses the location of Arruda #1, and so should reveal the setting in which the ~2.2 km sequence of arkoses penetrated by the well were deposited. Examination of Fig. 14 (a) reveals that there is an extensive zone of discontinuous and chaotic reflectors extending on either side of the location of Arruda #1. Although this zone might be the result of poor data aquisition or processing problems, the quality of the data further north along the same section is so good (see Fig. 11) that a geological explanation for the discontinuous and chaotic reflectors must be sought. Three interpretations are presented in Fig. 14.

Fig. 14 (b) is an extremely conservative interpretation of the seismic data in which seismic horizons are mapped southeastwards from the Benfeito #1 (see Fig. 11), and the lateral extent of the disturbed/chaotic reflectors at depth is shown. No attempt is made to interpret structures or seismic facies within the seismically anomalous zone.

Fig. 14 (c) is from MONTENAT et al. (in press). It explains the failure of Arruda #1 to penetrate Oxfordian carbonates by postulating a deep (over one kilometre) erosive submarine canyon cutting into Oxfordian and earlier sediments. Their interpretation is clearly based, without acknowledgement, on the interpretation of F. C. Carvalho presented in internal Petrogal reports completed in 1981. Although such a

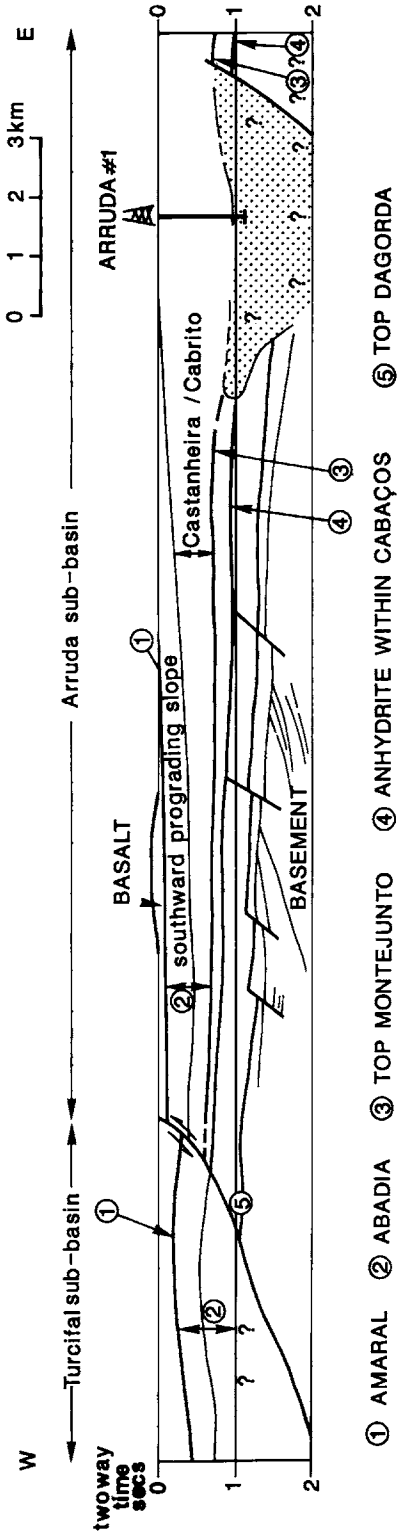


Fig. 10. Interpretation of west-east line AR 8/80 showing the half-graben nature of the Arruda sub-basin. Note how the intervals between reflectors 1–4 thicken towards the east. The stippled zone in the vicinity of the Arruda well is an area of discontinuous and chaotic reflectors illustrated in Fig. 14. The seismic expression of the southward prograding slope between reflectors 1 and 2 is illustrated in Fig. 11.

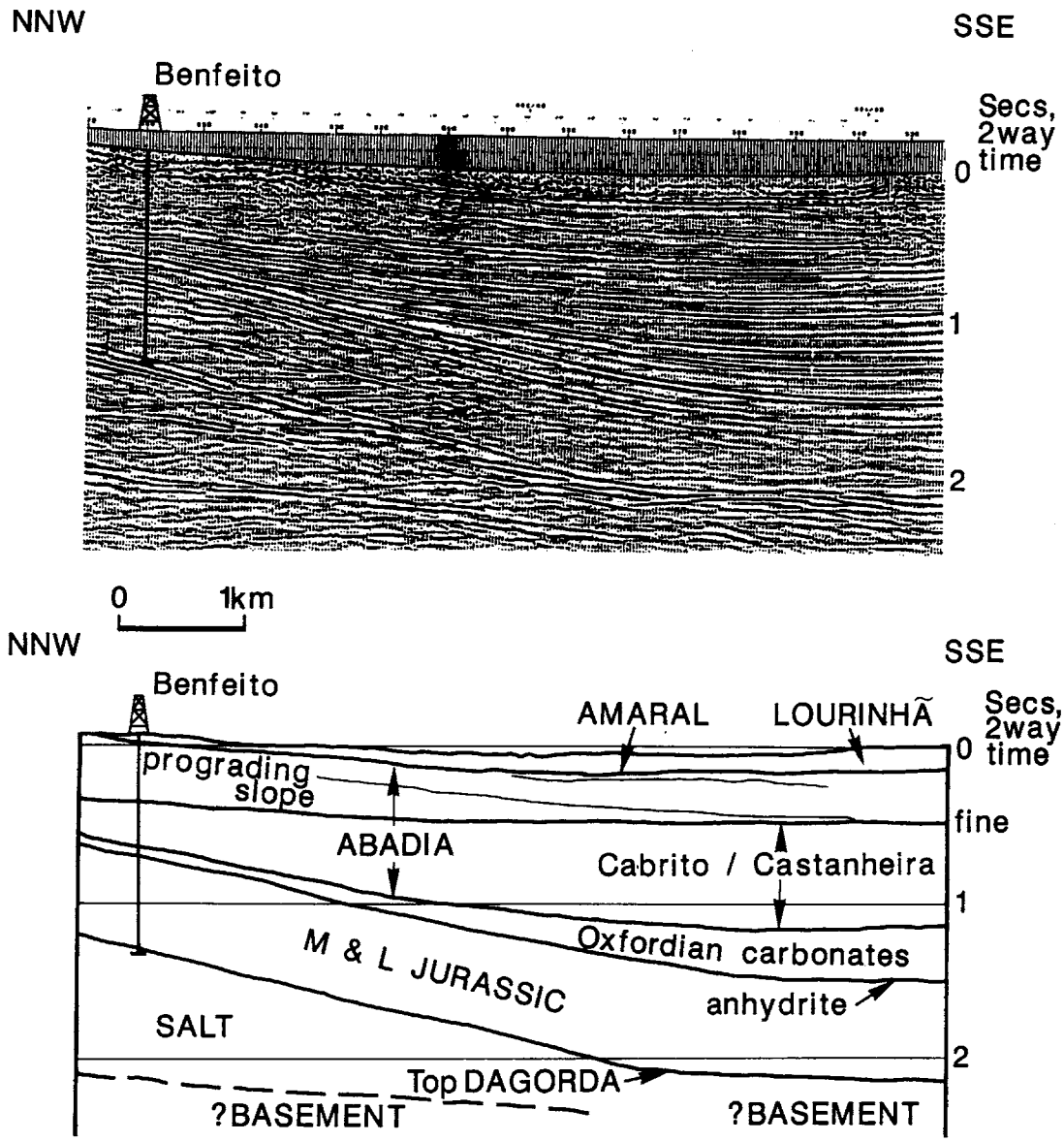


Fig. 11. Part of line AR 9/80 to the southeast of the Montejunto — Torres Vedras anticline. The structure began to develop as a salt pillow during the Oxfordian and Kimmeridgian, as demonstrated by the thinning of the Oxfordian carbonates and Cabrito/Castanheira interval to the northwest. Southward dipping clinoforms are developed at the top of the Abadia formation indicating a prograding slope. Note that this slope interval does not thin towards the northwest.

hypothesis is consistent with our interpretation of the Castanheira member as a submarine fan deposit, it is not sedimentologically consistent on a regional scale. Our examination of the seismic grid covering the Arruda sub-basin failed to reveal the erosive channel as a laterally mappable feature. Moreover, at the basinward termination of such a deep channel there should occur a very large submarine fan associated with a major break in slope both of which should easily be visible on seismic sections; no such features can be found.

Fig. 14 (d) presents what we believe to be a sedimentologically and structurally consistent interpretation. The location of a major fault in the vicinity of Montalegre #1 is not based on the seismic data, but on the fact that the well penetrated basement rocks.

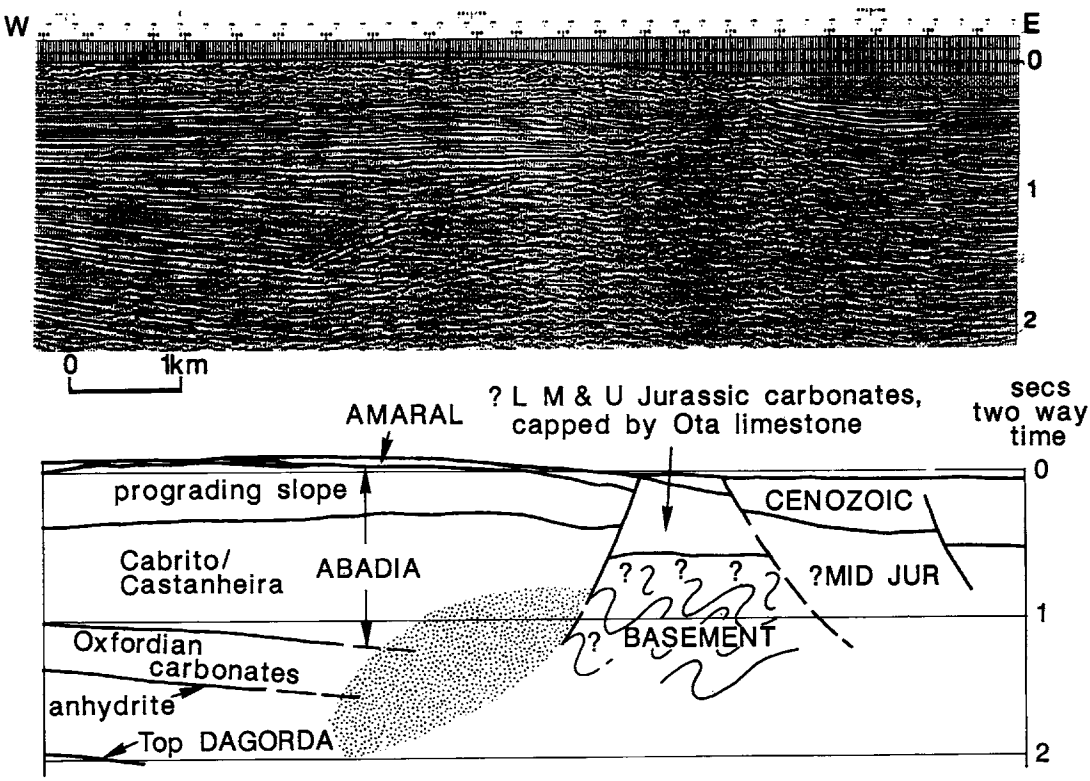


Fig. 12. Part of west-east line AR 6/81, showing the nature of the eastern boundary of the Arruda sub-basin. The stippled zone depicts an area of discontinuous and chaotic reflectors. The well defined reflectors to the west cannot be traced far into or beneath this zone.

We suggest that the zone of discontinuous and chaotic reflectors is due to both faulting and lateral facies changes within the Abadia formation. The portion of the seismic section shown on Fig. 14 (a) is situated to the south of, and almost parallel to, a fault that can be mapped at the surface immediately to the north of Arruda dos Vinhos (see Fig. 3). The convex side of this fault faces east, suggesting it is inclined in the same direction. We suggest that this fault developed as an antithetic normal fault to the major sub-basin boundary fault to the east. Normal displacement along this fault (largely contemporaneous with deposition of the Castanheira member) explains why Arruda #1 did not penetrate Oxfordian carbonates. The fault can be interpreted on other seismic sections (e.g. Fig. 13). Its surface expression today shows reversed movement (i.e. Amaral formation on the east side faulted against the younger Lourinhã formation on the west side, see Fig. 3) caused by Miocene inversion.

Figure 15. This Figure shows a mound structure developed within the Castanheira/Cabrito members. This example is about two kilometres across and about 100 milliseconds in amplitude, which suggests a geological thickness of 150 to 200 metres. The location of similar mound structures within the Arruda sub-basin is shown on Fig. 9. Given the sedimentological features of this interval seen at outcrop and in Arruda #1, the mounds seen on seismic sections indicate the presence of submarine fan lobes.

Interpretation

The lateral extent of the discontinuous and chaotic reflection zones illustrated on Figs. 12, 13 and 14 is depicted on Fig. 9. It is clearly centred on the gap between the horst structure drilled by Montalegre #1 and another horst beneath the Ota carbonate build-up. We suggest that the zone of anomalous reflection is caused largely by the massive coarse arkosic sediments of the Castanheira member, with some overprinting by faulting. Thus the zone of anomalous reflectors mapped on Fig. 9 is probably approximately coincident with the occurrence of proximal fan sands

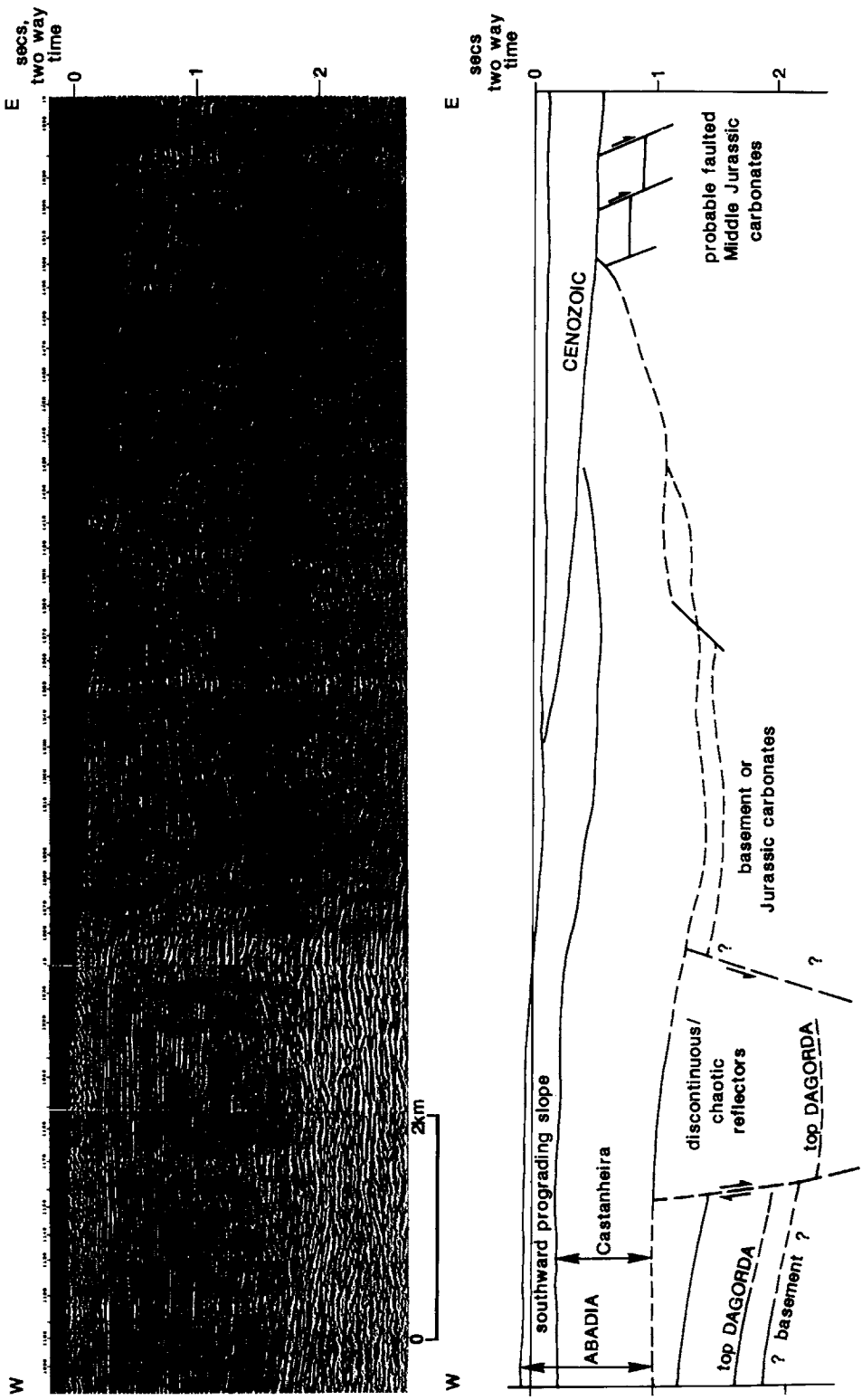
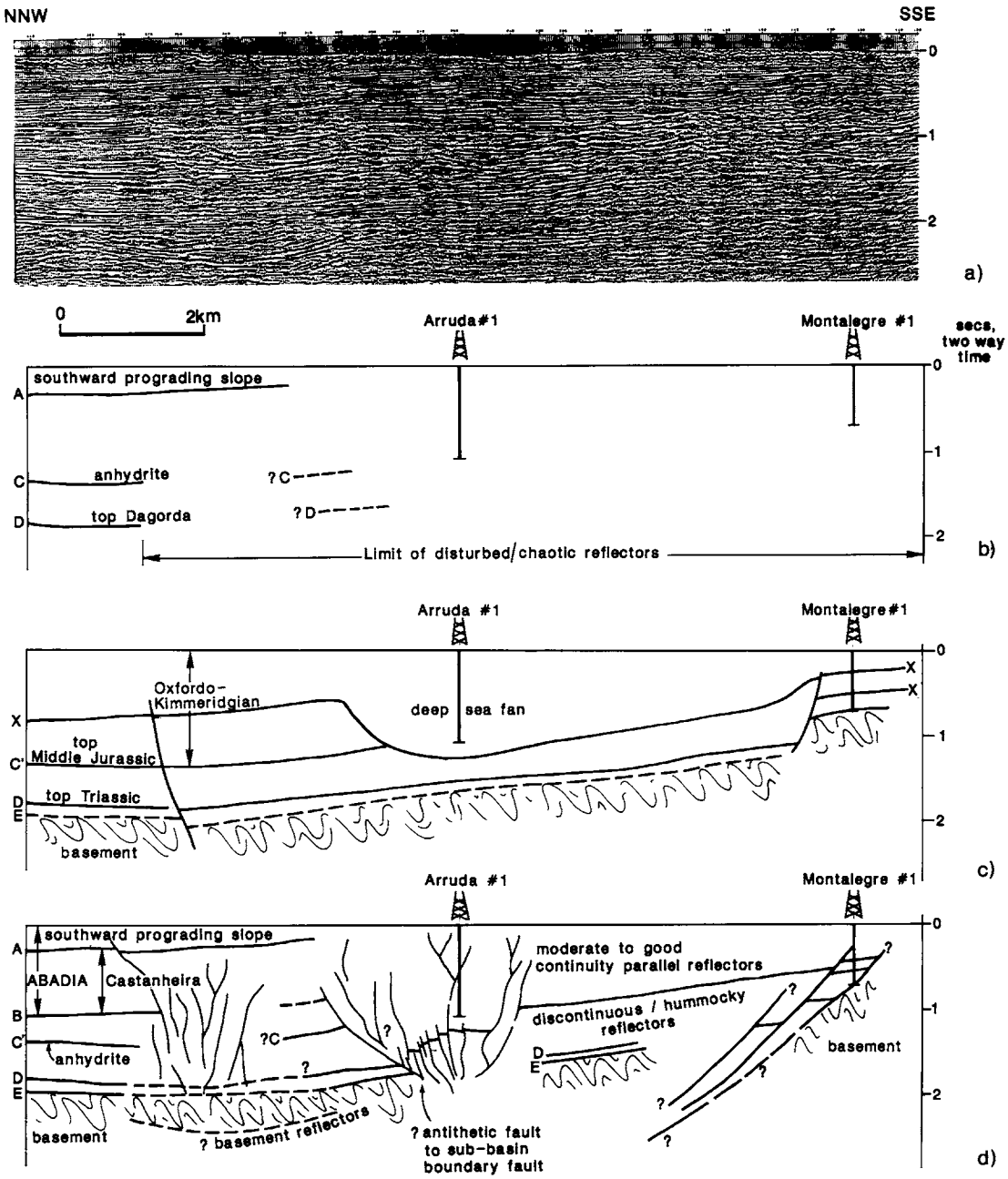


Fig. 13. Parts of west-east line AR 8/81, showing the nature of the eastern boundary of the Arruda sub-basin. Note that (1) the Abadia formation can be traced about five kilometres further east than on Figure 12, (2) the zone of discontinuous and chaotic reflectors is bounded on its western side by a fault, and (3) the sub-basin boundary fault on the west side of the horst does not cut the Abadia formation.



A base of south prograding slope unit at top of Abadia formation

B possible top of Oxfordian carbonates

C anhydrite level in Cabacos formation

C' top Middle Jurassic

D top Dagorda formation

E top basement

X not identified

Fig. 14. The southern part of line AR 9/80 showing the extensive zone of discontinuous and chaotic reflectors occurring in the vicinity of the Arruda # 1. (a) Uninterpreted seismic section. (b) Extremely conservative interpretation based on mapping principal reflectors southeastwards from Benfeito # 1 (Fig. 11). (c) The interpretation of MONTENAT et al. (in press). (d) Interpretation presented in this paper showing Arruda # 1 drilled above an antithetic fault related to the sub-basin boundary fault.

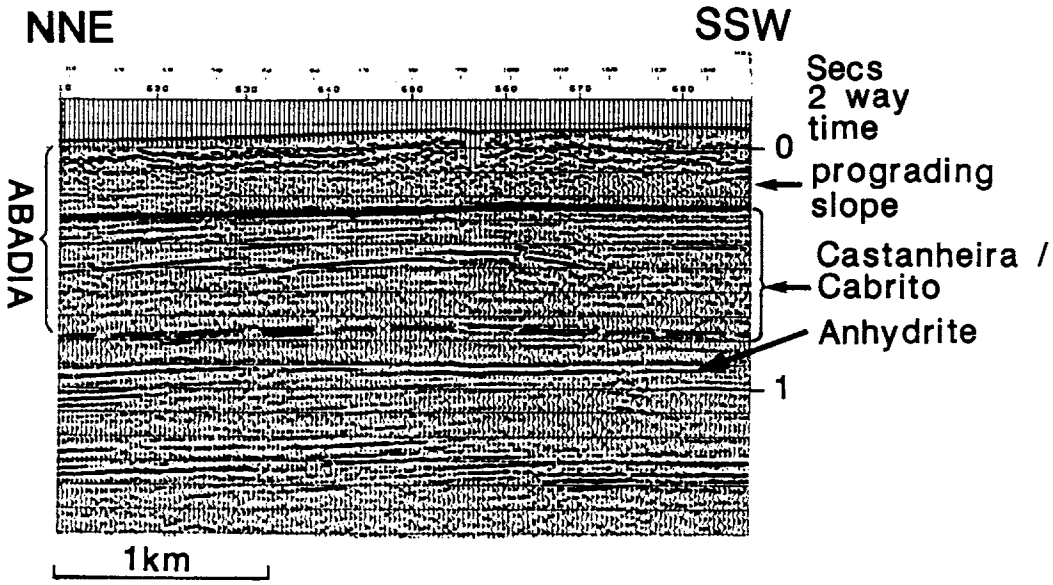


Fig. 15. Part of Line AR 5–80, showing mound structure at about 0.5 sec two way time within the Castanheira member interpreted as a submarine fan lobe.

that were fed westwards into the Arruda sub-basin through a gap in the boundary horst system. The gap is situated where the N-S Ota horst trend crosses the NNE-SSW Vila Franca de Xira fault trend. The distribution of the mound structures is consistent with the proposed submarine fan system; in fact they seem to occur opposite the three basinward projecting »lobes« of the anomalous seismic zone shown on Fig. 9.

The exceptionally thick sequence of arkosic sediments penetrated by Arruda # 1 appears to have been deposited in a small graben structure that developed between the sub-basin boundary faults and a related antithetic fault.

Conclusions

Integration of sedimentologic and seismic data

Previous sections of the paper presented evidence to suggest that a submarine fan developed on the eastern margin of the Arruda sub-basin. The sedimentologic data available is incomplete because only the top of the coarse arkosic sandstone sequence of the Castanheira member can be seen at the outcrop (Fig. 7), and because the poor exposures do not yield any reliable palaeocurrent data. The seismic data enables the geometry of the fan deposit to be mapped (Fig. 9), but the interpretation of the anomalous zone of seismic reflectors can only be made with confidence by applying the sedimentologic conclusions reached through studies made at outcrop and of Arruda # 1 cores.

Explanations for the failure of Arruda # 1 to reach Oxfordian carbonates also demonstrate the importance of applying geologically consistent models to the interpretation of seismic data. MONTENAT et al.'s (in press) suggestion that the carbonates were eroded by a huge submarine canyon (Fig. 14c) implies that such an erosive feature should be mappable across the seismic grid, and that the canyon system should traverse a break in slope beyond which a large submarine fan should be situated. No such features can be observed in the Arruda basin. Mapping of the anomalous seismic zones seen on the seismic grid shows that they are confined to the eastern margin of the Arruda sub-basin (Fig. 9), and are associated with (1) a gap in the bounding horst system (Figs. 9, 13) and (2) a moat-like graben developed between the sub-basin boundary fault and an associated antithetic fault (Figs. 13, 14d). The failure of Arruda # 1 to reach the Oxfordian carbonates is therefore best explained by displacement down to the east of the carbonates along the antithetic fault.

Kimmeridgian depositional systems

Seismic data shows that the Arruda sub-basin developed as a half-graben basin during Late Oxfordian and early Kimmeridgian times, as the Oxfordian carbonates and Cabrito/Castanheira member thicken significantly towards the eastern boundary. During the Kimmeridgian, three depositional systems occurred in the sub-basin and over its eastern margin.

1. An arkosic siliciclastic submarine fan system was supplied with basement-derived sediment from the east through a gap in the eastern horst system. It is probable that the zone of discontinuous and chaotic seismic reflectors is approximately coincident with the occurrence of massive unbedded conglomeratic arkoses as exposed near Castanheira. However, faulting, much of which is early Kimmeridgian age, also produced zones of anomalous seismic response, such as in the vicinity of Arruda #1. Small carbonate buildups developed over the shallow abandoned part of the fan system, and shed allochthonous blocks basinward.
2. Carbonate deposition over the Ota horst indicates that it was a region starved of siliciclastic sediments. The exposed carbonate buildup is Late Kimmeridgian in age, but carbonate deposition may have persisted from Late Oxfordian times (LEINFELDER et al., in press; ELLIS et al., in prep.). The bypass margin on the western side of the Ota horst probably fed carbonate debris westwards into the Arruda sub-basin, although these sediments are not visible at the outcrop, nor can their presence be detected on seismic sections.
3. During the Late Kimmeridgian, a slope system dominated by fine grained siliciclastic sediments prograded southwards across the Arruda sub-basin at the same time as the Ota carbonate buildup developed. At the foot of the slope, an apron of resedimented siliciclastic sands and carbonates was deposited to form the Cabrito member of the Abadia formation (ELLWOOD, 1987). The slope sediments are 500 m thick, and so the decompacted height of the slope must be in the order of 700 m. The slope progradation occurred during a period of relative sea-level highstand. The thinning of the Abadia marls and silts near the eastern boundary of the Arruda sub-basin (Fig. 7) suggests that the submarine fan system was still active as the slope system prograded. Therefore it is probable that though the sub-basin fill was dominantly derived from the east, a significant amount of sediment was contributed from a northerly source.

Oxfordian — Kimmeridgian history of the eastern margin of the southern part of the Lusitanian Basin

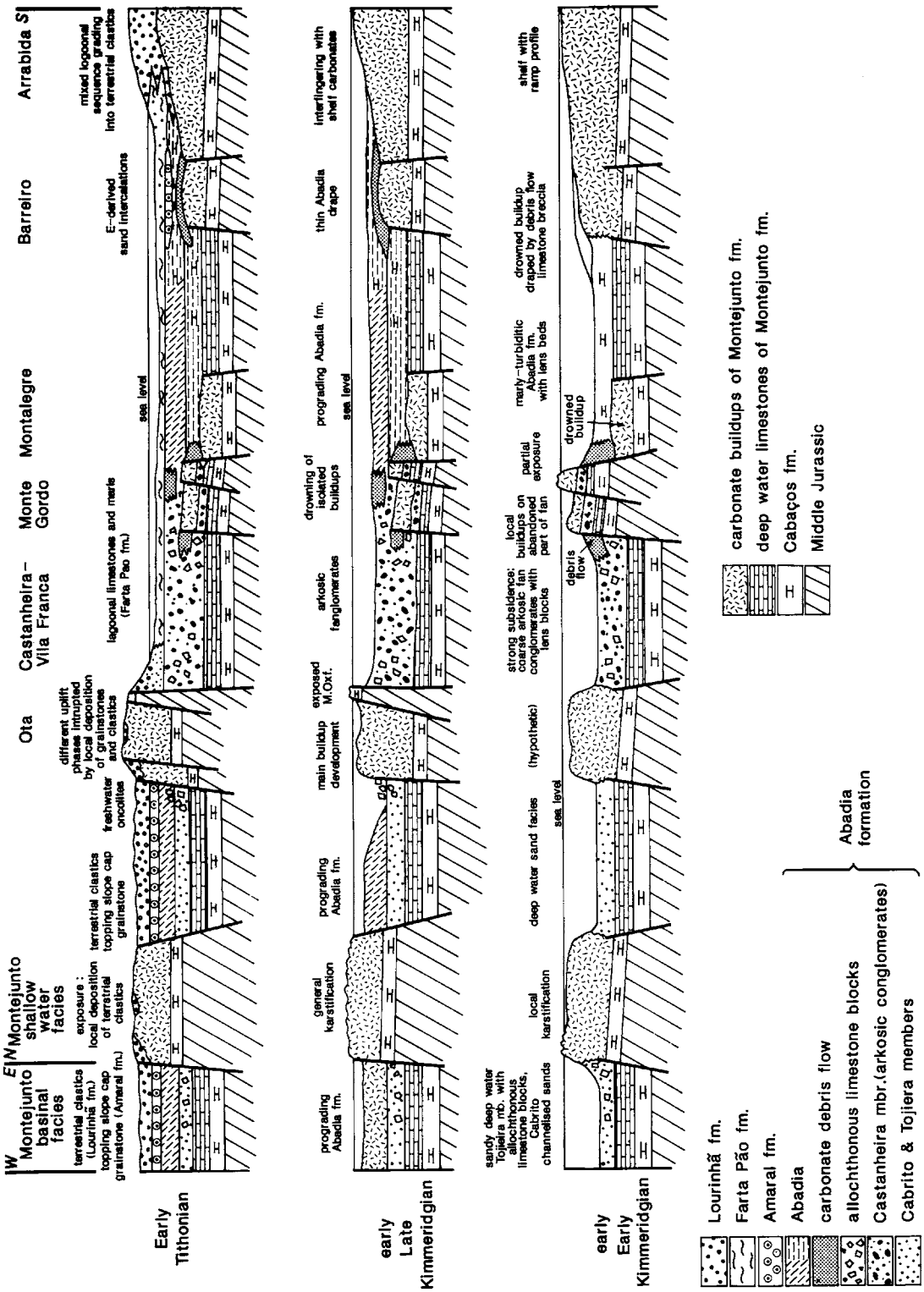
Fig. 16 shows a series of sketch sections summarizing the principal tectonic and sedimentologic events in the history of the eastern margin of the southern part of the Lusitanian Basin during the Oxfordian and Kimmeridgian. The Figure is based largely on data presented in this paper, and by ELLIS & WILSON (1987).

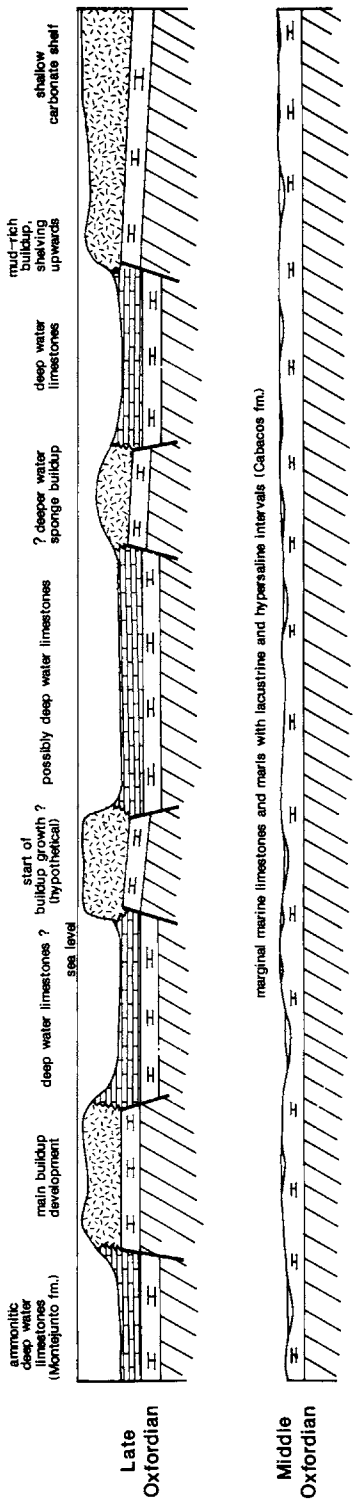
The tectonic differentiation of the Lusitanian Basin into sub-basins was heralded by a regional uplift in early Oxfordian times. This resulted in a regional hiatus and karstification of earlier Jurassic limestones, which are overlain by Middle Oxfordian lacustrine carbonates which blanket the Basin.

During the Late Oxfordian, significant deepening occurred, with localized uplift of basement blocks over which shallow-water carbonate buildups developed. Towards the end of the Late Oxfordian, the buildups at Montejunto and Barreiro were first slightly uplifted and karstified, and then drowned. These events are recorded by the Tojeira member at Montejunto (Fig. 4) which consists of shales with debris flows containing basement derived pebbles and karstified allochthonous blocks of shallow water carbonates. It is probable that the submarine fan system on the east side of the Arruda sub-basin began to develop at this time.

At the beginning of the Late Kimmeridgian, the Abadia slope system began to prograde southwards, the Castanheira member fan continued to develop, and carbonate aggradation occurred over the Ota horst. The Montejunto carbonate buildup was exposed at this time.

By early Tithonian times, the Bombarral sub-basin and northern part of the Arruda sub-basin were completely filled with sediment, so that fluvial siliciclastic sediments surrounded and partly draped the exposed Montejunto and Ota carbonate buildups. Around the Ota region, hardwater rivers flowed off the karstified limestone and resulted in the deposition of freshwater oncolites in the Lourinhã formation (LEINFELDER, 1985). Further south in the Arruda sub-basin, lagoonal marine carbonates of the Farta Pão formation accumulated, and interfingered to the south with terrestrial siliciclastics in the Arrábida area. This fairly simple pattern of shallow marine deposition occurring within an embayment extending to the northeast of Lisbon, and flanked by terrestrial siliciclastics (see LEINFELDER, 1987b, Fig. 6), continued into Early Cretaceous times, reflecting a


W
E
N
Montejunto basinal facies
Montejunto shallow water facies
Ota
Castanheira-Vila Franca
Monte Gordo
Montalegre
Barreiro
Arrabida S
terrestrial clastics (Lourinhã fm.)
exposure : local deposition of terrestrial clastics
terrestrial clastics toppling slope cap grainstone
freshwater oncolites
different uplift phases intrupted by local deposition of grainstones and clastics
lagoonal limestones and marls (Farta Pão fm.)
sea level
E-derived sand intercalations
mixed lagoonal sequence grading into terrestrial clastics
toppling slope cap grainstone (Amaral fm.)
prograding Abadia fm.
general karstification
prograding Abadia fm.
main buildup development
exposed M.Oxf.
arkosic fanglomerates
drowning of isolated buildups
prograding Abadia fm.
sea level
thin Abadia drape
interfingering with shelf carbonates
sandy deep water Tojiera mbr. with allochthonous limestone blocks, Cabrito channelised sands
local karstification
deep water sand facies
(hypothetic)
strong subsidence: coarse arkosic fan conglomerates with lens blocks
local buildups on abandoned part of fan
debris flow
partial exposure
drowned buildup
marly-turbiditic Abadia fm. with lens beds
drowned buildup draped by debris flow limestone breccia
shelf with ramp profile
Early Tithonian
early Late Kimmeridgian
early Early Kimmeridgian
carbonate buildups of Montejunto fm.
deep water limestones of Montejunto fm.
Cabaços fm.
Middle Jurassic
Abadia formation
Lourinhã fm.
Farta Pão fm.
Amaral fm.
Abadia
carbonate debris flow
allochthonous limestone blocks
Castanheira mbr.(arkosic conglomerates)
Cabrito & Tojiera members



◀ Fig. 16. Sketch sections illustrating the tectonic and sedimentologic evolution of the eastern margin of the Arruda sub-basin during Oxfordian to Tithonian times.

period of relative tectonic quiescence in the development of the Lusitanian Basin.

The origin of the Arruda sub-basin

WILSON et al. (in press) suggested that during the Oxfordian — Kimmeridgian, a pulse of NE-SW lithospheric extension occurred beneath the Lusitanian Basin. Their conclusion is based on the following observations (Fig. 17):

1. NW-SE oriented dykes occur to the north of the Arruda sub-basin, and yield dates of 140 Ma (WILLIS, 1988).
2. A set of NW-SE oriented syn-sedimentary normal faults occur in the Lourinhã formation on the coast to the northwest.
3. The exceptionally thick sequence of lower Kimmeridgian siliciclastics encountered in the Arruda sub-basin suggests that it developed as a pull-apart basin. Backstripping data from the Arruda #1 yield rates of tectonic subsidence of about 850 m per million years. Such localized rapid subsidence is also consistent with a pull-apart mechanism.

The initial effect of the NE-SW extension was to trigger salt migration above reactivated basement faults (Fig. 17). Seismic data show that salt migration began during the Oxfordian (Fig. 11), and that fault movements became extremely significant during the early Kimmeridgian (as discussed in this paper).

The period of NE-SW extension may have heralded a short period of latest Jurassic sea floor spreading postulated by MAUFFRET et al. (1988) to have occurred in the region of the present day Tagus abyssal plain. This ocean opening episode preceded the main Aptian phase of separation between Iberia and the Grand Banks. The change of facies distribution patterns from a complex to a simple configuration commented on earlier may have been linked to the onset of ocean spreading to the west.

Regional implications

It would be naive to apply the results of this study of synrift basin development in Portugal directly to formerly adjacent North Atlantic Mesozoic marginal basins (Fig. 1a). However, the complexity of facies relationships and timing of uplift and subsidence events along the eastern margin of the Lusitanian Basin suggests that conclusions drawn from sparser data sets

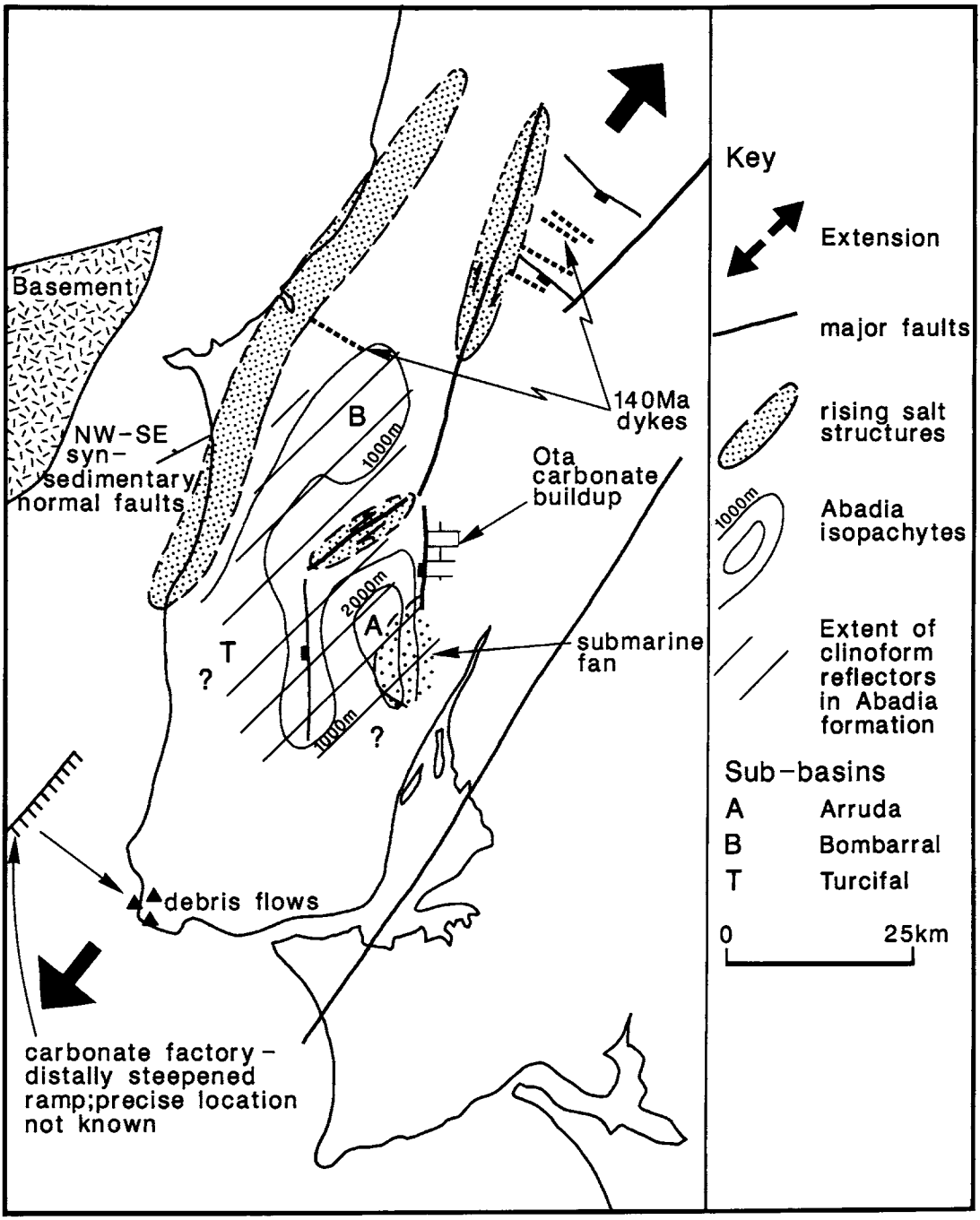


Fig. 17. Evidence for NE-SW oriented extension during the Late Jurassic: (a) NW-SE dykes dated at 140 Ma (Berriasian); (b) NW-SE syn-sedimentary faults in the Lourinhã formation; (c) the exceptionally thick lower Kimmeridgian sequence (>2.2 km) that accumulated in the Arruda sub-basin at a rate of ca. 850 m/m.y., suggesting deposition in a pull-apart basin. Reactivation of NNE-SSW basement faults triggered migration of Dagorda evaporites to produce salt pillows. The clinoform reflectors in the Abadia formation indicate southward progradation of a slope system during a period of relative sea-level still stand. The thickness of this unit is affected neither by the faults bounding the eastern and western sides of the Arruda sub-basin (Fig. 12), nor by the salt pillow to the north (Fig. 11).

in other areas may be oversimplified. For example, deep sea drilling results off northwest Iberia suggest that Tithonian to Early Cretaceous carbonate platform development was terminated by rifting during the Valanginian (BOILLOT, WINTERER et al., 1985). However, all the drilling sites were situated over structural highs. If the eastern margin of the Lusitanian Basin had been studied only through drilling over horst structures, it would appear that the area was dominated by Oxfordian — Kimmeridgian carbonate buildups!

Acknowledgements

We thank the Serviços Geológicos de Portugal for permission to undertake research in Portugal. The assistance of staff of the exploration department of Petrogal and the Serviços Geológicos in Lisbon in providing access to borehole and seismic data is gratefully acknowledged. Subsurface data in the paper is published by kind permission of the Director General da Gabinete para a Pesquisa e Exploração de Petróleo and the Director of the Exploration Department of Portugal in Lisbon.

The lithostratigraphic scheme presented in Fig. 2 was derived during discussions with Miguel Ramalho, Richard Hiscott and Peter Ellis. R.C.L.W. thanks colleagues at Petrogal, particularly Francisco Carvalho, for many stimulating discussions concerning the interpretation of seismic data.

We thank John Taylor and Andrew Lloyd for drafting the figures.

R.R.L. gratefully acknowledges financial support by the Deutsche Forschungsgemeinschaft (project nr. Le 580/1).

References

ANDRADE, F. de C. (1934): Um recife corálico no Jurássico de Vila Franca de Xira. — Bol. Mus. Mineral. Geol. Univ. Lisboa, **3**, 3–11.

ATROPS, F. & MARQUES, B. (1986): Mise en évidence de la zone a Platynota (Kimméridgien Inférieur) dans le Massif du Montejunto (Portugal); Conséquences stratigraphiques et paléontologiques. — Géobios, **19**, 537–547.

BOILLOT, G., WINTERER, E. L. et al. (1985): Evolution of a passive margin. — Nature, **317**, 115–116.

CHOFFAT, P. (1893): Déscription de la faune jurassique du Portugal. Classe des Céphalopodes. Première série: ammonites du Lusitanien de la contrée de Torres Vedras. — Dir. Trav. Geol. Portugal, 82 pp., Lisbon.

— (1901): Notice préliminaire sur la limite entre le Jurassique et le Crétacique en Portugal. — Bull. Soc. belge Geol. Paléont. Hydrol., **15**, 111–140.

ELLIS, P. & WILSON, R. C. L. (1987): Tectonic, paleogeographic and eustatic controls on Upper Jurassic carbonate buildup development in the Lusitanian Basin of Portugal (abstract). — Bull. American Assoc. Petrol. Geol., **71**, 533.

ELLWOOD, P. M. (1987): Sedimentology of the Upper Jurassic Abadia formation and its equivalents, Lusitanian Basin, Portugal. — Ph. D. Thesis, Open University, Milton Keynes, U.K. (unpublished).

FELBER, J., HOFFMANN, R., LEINFELDER, R., OSCHMANN, W. & ZIEGLER, R. (1982): Biofaziesanalyse randmariner Ablagerungsbereiche im Oberen Jura Portugals. II. Paläogeographie und Faziesverteilung in der Serra da Arrabida. — N. Jb. Geol. Paläont. Abh., **163**, 301–330.

GUERY, F., MONTENAT, C. & VACHARD, D. (1986): Evolution tectono-sédimentaire du Bassin Portugais au Mesozoique suivant la transversale de Peniche (Estremadure). — Bull. Centr. Rech. Explor. — Prof. Elf-Aquitaine, **10**, 83–94.

KENT, D. & GRADSTEIN, F. M. (1985): A Cretaceous and Jurassic Geochronology. — Bull. Geol. Soc. America, **96**, 1419–1427.

LEINFELDER, R. R. (1983): New mapping results on sheet Setubal (Sesimbra to Portinho da Arrábida, Serra da Arrábida, Portugal). — Com. Serv. Geol. Portugal, **69**, 295–324.

— (1985): Cyanophyte calcification morphotypes and depositional environments (Alenquer Oncolite, Upper Kimmeridgian?, Portugal). — Facies, **12**, 253–274.

— (1986): Facies, stratigraphy and paleogeographic analysis of Upper? Kimmeridgian to Upper Portlandian sediments in the environ of Arruda dos Vinhos, Estremadura, Portugal. — Münchner Geowiss. Abh., (A), **7**, 1–216.

— (1987a): Formation and significance of Black-Pebbles from the Ota Limestone (Upper Jurassic, Portugal). — Facies, **17**, 159–170.

— (1987b): Multifactorial control of sedimentation patterns in an ocean marginal basin — The Lusitanian Basin (Portugal) during the Kimmeridgian and Tithonian. — Geol. Rdsch., **76**, 599–651.

—, ERBENICH, A. & RAMALHO, M. (in press): Age and general facies development of the Ota Limestone (Estremadura, Portugal). — Proc. 2nd Intern. Sympos. Jurass. Strat., Sept. 1987, Lisbon, Univers. Nova Lisboa Press.

MAGG, A. (1987): Submarine Hangablagerungen des Kimmeridge (O. Jura), am Ostrand des Lusitanischen Bekkens, Portugal (Gebiet Vila Franca de Xira — Castanheira). — 21 pp; unpublished student's mapping report, Inst. f. Geowiss., University of Mainz.

MANUPPELLA, G. & BALACO MOREIRA, J. C. (1984): Os calcários da Serra de Ota. — Matérias-primas minerais não metálicas, 32 — Estud. Trabalh. Serv. Fomento Mineiro Porto, **26**, 25–34.

MAUFFRET, A. et al. (1988): An abandoned spreading centre in the Tagus Abyssal plain (west of Portugal): results of a multichannel seismic survey (abstract). — Joint Annual Meeting Geolog. Assoc. Canada and Canad. Society Petrol. Geolog., Program with abstracts, **13**, p. A80.

MONTENAT, C., GUERY, F., JAMET, M. & BERTHOU, P. Y. (in press): Mesozoic evolution of the Lusitanian Basin: comparison with the adjacent margin. — In: G. Boillot, W. Winterer et al. (eds.), Proc. ODP, Initial Reports, Leg 103.

RIBEIRO, A., CONDE, L. & MONTEIRO, J. (1972): Carta tectónica de Portugal. — Direcção Geral de Minas, Serv. Geol. Portugal, Lisbon.

RUGET-PERROT, C. (1961): Etude stratigraphique sur le Dogger et le Malm Inférieur du Portugal au Nord du Tage — Bajocien, Bathonien, Callovien, Lusitanien. — Serv. Geol. Portugal, Mem., **7**, 197 pp.

SNEH, A. & FRIEDMAN, G. M. (1980): Spur and groove pattern on the reefs of the northern gulfs of the Red Sea. — J. Sedim. Petrol., **50**, 981–986.

WILLIS, M. G. (1988): The tectonic history of the Lusitanian Basin of Portugal. — Ph. D. thesis, The Open University, Milton Keynes, U.K. (unpublished).

WILSON, R. C. L. (1979): A reconnaissance study of Upper Jurassic sediments of the Lusitanian Basin. — Ciências da Terra, **5**, 53–84.

—, HISCOTT, R. N., WILLIS, M. G. & GRADSTEIN, F. M. (in press): The Lusitanian Basin of west central Portugal: Mesozoic and Tertiary tectonic, stratigraphy and subsidence history. — In: A. J. Tankard & H. Balkwill (eds.), Extensional tectonics and stratigraphy of the North Atlantic margins, American Assoc. Petrol. Geolog., Memoir.

WRIGHT, V. P. (1985): Algal marsh deposits from the Upper Jurassic of Portugal. — In: D. F. Toomey & M. H. Nitecki (eds.), Paleoalgology, 330–341, Berlin (Springer).

— & WILSON, R. C. L. (1985): Lacustrine carbonates and source rocks from the Upper Jurassic of Portugal. — Abstracts, 6th Europ. Reg. Meeting of Sedimentol; Int. Assoc. Sedimentol., Lleida, Spain, 487–490.

ZBYSZEWSKI, G. & TORRE DE ASSUNÇÃO, C. (1965): Carta Geológica de Portugal na Escala de 1:50 000 — Notícia Explicativa da Folha 30-D, Alenquer. — Serv. Geol. Portugal, Lisbon.

—, VEIGA FERREIRA, O. da, MANUPPELLA, G. & TORRE DE ASSUNÇÃO, C. (1966): Carta Geológica de Portugal na Escala de 1:50 000 — Notícia Explicativa da Folha 30–B, Bombarral. — Serv. Geol. Portugal, Lisbon.