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Controls on Upper Jurassic carbonate buildup development in the Lusitanian Basin, Portugal

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ABSTRACT

A variety of carbonate buildups developed in the Lusitanian Basin during the late Jurassic. During an Oxfordian–Kimmeridgian rift phase evidence can be seen for both fault and diapiric control of buildup development. Fault-controlled buildups occur on the east side of the basin. They exhibit shelf profiles, are relatively thin (200–500 m), show well-developed lateral facies zonation and are dominated by lime mudstones and wackestones, with only minor amounts of packstones and grainstones. Salt-controlled buildups on the northwest margin of the basin are relatively thick (500–1500 m), show only gradual lateral facies variation with no distinct shelf break facies, and are dominated by grainstones and packstones.

During the latest Oxfordian–early Kimmeridgian, a sudden relative sea-level rise drowned or partially drowned the earlier buildups, and this was quickly followed by a major influx of siliciclastic sediments. In the centre of the basin, a thin grainstone-dominated carbonate sequence of middle Kimmeridgian age developed on top of a prograding siliciclastic slope system. In the siliciclastic-starved southern part of the basin, a prograding low-energy ramp sequence of Kimmeridgian–Berriasian age was deposited.

Carbonate facies associations described from Portugal also occur in Mesozoic carbonate bank sequences of eastern America. Data from recent US wells, and comparisons with Portugal, suggest that the eastern American Atlantic 'reef trend' is largely composed of grainstone–packstone dominated shelf-break sediments with only relatively minor amounts of biogenic reefal framework.

INTRODUCTION

Upper Jurassic carbonate buildups occur in marginal basins on both sides of the southern North Atlantic. Seismic sections show that a buried carbonate bank complex or 'reef trend' lies under the eastern US continental shelf from the Blake Plateau, northwards for a distance of over 1200 km to Georges Bank (Schlee & Grow, 1982). A similar carbonate development is known from the Nova Scotian Shelf (Eliuk, 1978). Upper Jurassic buildups also occur along the eastern Atlantic margin, including Morocco (Jansa & Wiedmann, 1982), the southern Western Approaches (Masson & Roberts, 1981) and in Portugal.

The Lusitanian Basin of Portugal provides a unique opportunity to study Atlantic margin buildups both at outcrop and in the subsurface. This paper describes the composition, structure and developmental controls of four carbonate sequences that developed in contrasting tectonic and palaeogeographic settings. Recent well data from the eastern US continental shelf are also described and commented upon in the light of information gathered from Portugal.

Figure 1 shows a palaeogeographic reconstruction of the Atlantic during the late Oxfordian. The Lusitanian Basin was not in an ocean margin location at this time, but was situated to the east of the newly opened southern North Atlantic, which was between 1300 and 1500 km wide (Jansa, 1986). The basin was located to the northeast of a postulated short segment of an ocean ridge and associated major transform that displaced spreading southeastwards into Tethys. Rifting that initiated the separation of Iberia

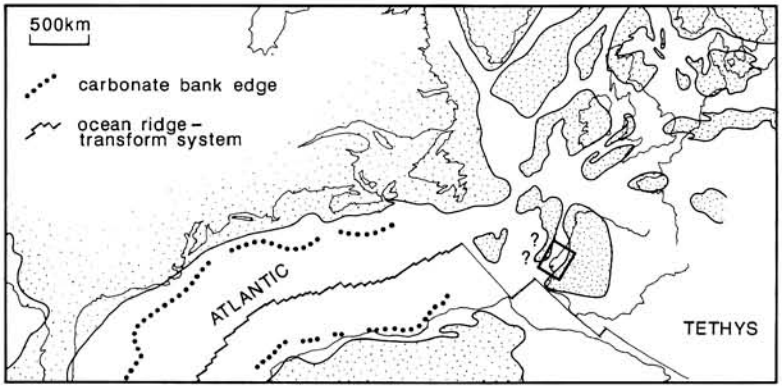

Fig. 1. Palaeogeographic sketch map for the North Atlantic region during the late Oxfordian. Box on western margin of Iberia shows the location of the Lusitanian Basin. Adapted from plate 9C of Vogt & Tucholke (1986).

from North America began in early Oxfordian times (Wilson, 1979, 1988; Wilson *et al.*, 1989), suggesting significant tectonic controls on carbonate buildup development during this period.

GEOLOGICAL SETTING AND TYPES OF BUILDUP

Stratigraphy

The Mesozoic of the Lusitanian Basin comprises four unconformity-bounded megasequences, the development of which was related to events in the evolution of the North Atlantic (Wilson, 1988; Wilson *et al.*, 1989). The first two of these megasequences, and part of the third are shown in Fig. 2 as a simplified, and as yet, informal lithostratigraphic summary chart for the southern part of the Lusitanian Basin. The three megasequences are described below.

Triassic–Callovian

This sequence is typical of the early rift–sag successions encountered in most North Atlantic margin basins. Triassic red fluvial siliciclastics (Silves formation) are capped by Hettangian evaporites (Dagorda formation) which subsequently influenced the manner in which reactivation of Hercynian basement faults affected the cover of younger sediments. Where the evaporites were thick, halokinetic structures formed above basement faults, but where they were thin, the faults propagated through younger formations. The Triassic and Hettangian sediments accumulated in grabens and half grabens, though the later Lower and Middle Jurassic sediments (Coimbra, Brenha and Candeiros formations) blanketed the basin and exhibit simple facies geometries with relatively minor indications of contemporaneous faulting.

Middle Oxfordian–Berriasian

The base of the Upper Jurassic is marked by a basin-wide hiatus, spanning the whole of the Lower Oxfordian and the early part of the Middle Oxfordian (Mouterde *et al.*, 1971). In places, this boundary is unconformable and accompanied by karst surfaces developed on the underlying Middle Jurassic limestones (Ruget-Perrot, 1961; Wright & Wilson, 1987). Throughout the basin, the earliest Oxfordian sediments consist predominantly of lacustrine ostracod–charophyte lime mudstones (Wright & Wilson, 1985; Wright, 1985) comprising the Cabaços formation. This formation contains highly bituminous horizons and is considered to be the major source for the many hydrocarbon shows in the southern part of the Lusitanian Basin.

Fully marine carbonate deposition returned to most of the southern and central parts of the Lusitanian Basin in the late Oxfordian, associated with a relative rise in sea-level. This was the main carbonate buildup phase of the basin's history, when the limestones of the Montejunto formation and its equivalents were deposited. The initiation of buildup development in the Lusitanian Basin is somewhat later than those in other southern North Atlantic-marginal basins, such as the western High Atlas Basin of Morocco and in the Nova Scotian Shelf Basin.

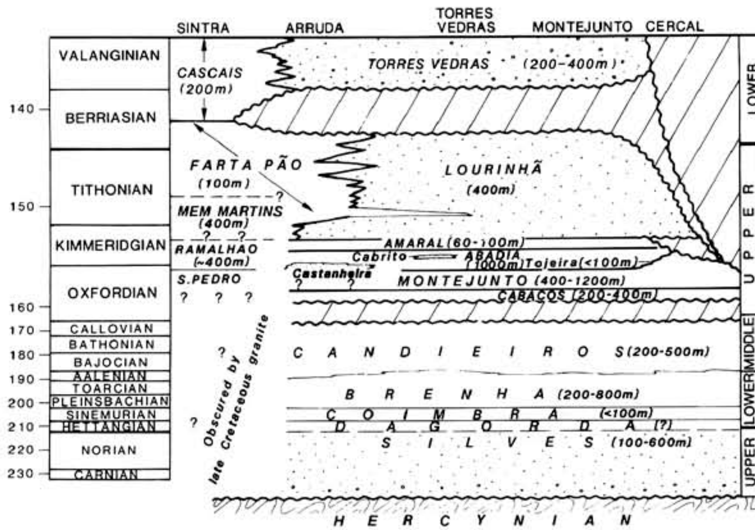

Fig. 2. Summary chart of an informal lithostratigraphic nomenclature currently under discussion for the Triassic–Lower Cretaceous of the Lusitanian Basin (as the scheme is informal, 'formation' and 'member' are not capitalized in the text). Note that the vertical time scale from Kent and Gradstein, (1985) is doubled from the base of the Oxfordian upwards in order to accommodate the Upper Jurassic units described in the paper. Formations are shown in capitals, members in lower case letters. Hiatuses are shown by diagonal ruling.

An abrupt rise in relative sea-level, accompanied by uplift of marginal basement highs during the early Kimmeridgian, ended carbonate deposition in many parts of the Lusitanian Basin and was followed by a sudden influx of siliciclastics, represented by the Abadia formation. In the central part of the basin, this event is marked by a sequence of shales and limestone breccias of the Tojeira member at the base of the clastic Abadia formation. However, on some structural highs, carbonate sedimentation continued into the Kimmeridgian.

The Abadia formation is ≈ 1000 m thick and consists predominantly of shales and siltstones. On seismic sections, the upper 550 m show southward dipping clinoforms (see Fig. 14; and Wilson, 1988, fig. 7) indicating a prograding slope deposit. Coarse sandstones of the Cabrito member accumulated at the base of this prograding slope (Ellwood, 1987). The slope deposits of the Abadia formation are capped by the Amaral Limestone formation, which contains up to 80 m of high-energy carbonates similar to the Upper Jurassic Smackover Formation of the Gulf Coast (Crevello & Harris, 1982) and is overlain by the fluvial and marginal marine clastics of the Lourinhã formation. Around salt structures, and on the eastern margin of the basin (Fig. 2), the Lourinhã formation rests unconformably on earlier Upper Jurassic strata.

The equivalents of the upper part of the Montejunto formation, and the Abadia formation, can be traced southwards towards Lisbon (where they were penetrated by the Monsanto well), and southwestwards towards Sintra (Fig. 3). In the latter region they are brought to the surface by a small diapir-like granitic intrusion (the Sintra granite) dated at 76–80 Ma (i.e., very late Cretaceous). The San Pedro formation is a sequence of thermally-metamorphozed marbles exposed around the granite, dated as Oxfordian (Mouterde *et al.*, 1971; Ramalho, 1971) and probably a lateral equivalent of the Montejunto formation. The overlying Ramalhão and Mem Martins formations are suggested to be slope deposits, with carbonate debris flows forming an important component of the Mem Martins formation.

Rapid subsidence and synsedimentary fault and halokinetic movements characteristic of megasequence 2 suggest a rifting episode that may have heralded a pre-Aptian phase of ocean opening to the southwest of the Basin (Wilson *et al.*, 1989; Mauffret *et al.*, 1989)

Berriasian–Lower Aptian

The generalized facies pattern of siliciclastics being replaced southwards by carbonates seen at the end of megasequence 2 continues into megasequence 3 (Fig. 2). The Farta Pão formation, which contains brackish faunal elements of Tithonian age at its top (Ramalho, 1971) is overlain, probably without a break, by a series of carbonate units described by Rey (1972) which are grouped here into the Cascais formation. Elsewhere in the basin where megasequences 2 and 3 are developed in dominantly

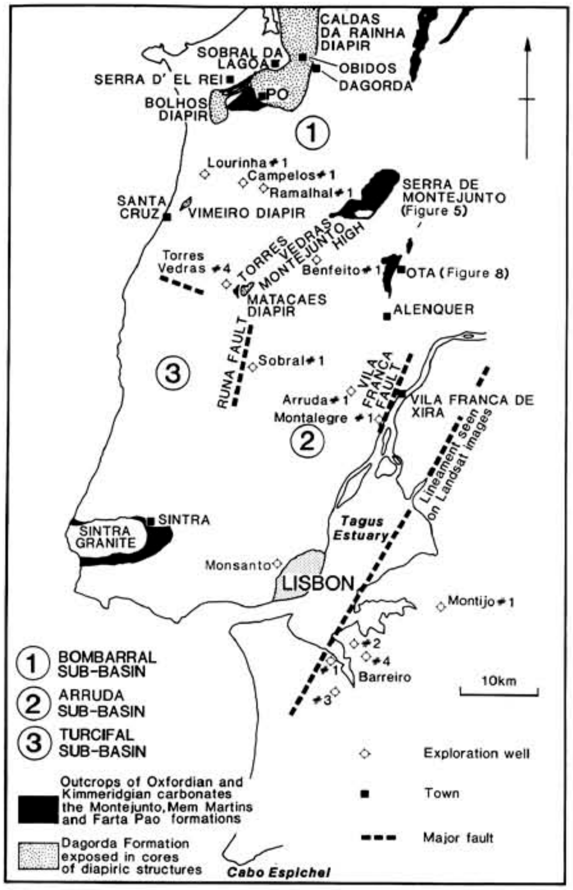

Fig. 3. Map of the southern part of the Lusitanian showing locations, exploration wells and structures mentioned in the paper.

siliciclastic facies, Rey (1972) suggested that Berriasian strata are missing, and so the siliciclastics of the Torres Vedras formation rest unconformably on older strata. In the Cercal area, Rey (1972) showed not only the Torres Vedras formation but also a later Aptian siliciclastic unit cutting across older strata, thus indicating continued tectonic activity along this part of the eastern margin of the Bombarral Sub-basin (Fig. 2).

Megasequence 3 is equivalent to the synrift sequences that preceded ocean opening drilled off the northwestern margin of Iberia (Sibuet & Ryan, 1979; Wilson *et al.*, 1989), but is much thinner and contains no deep-water sediments.

Structural setting

Seismic sections show the Brenha and Candeiros formations to be relatively constant in thickness over the southern half of the Lusitanian Basin, indicating little or no differential subsidence during the early and middle Jurassic. In contrast, thickness variations in the Cabacos, Montejunto and Abadia formations suggest major changes in Basin configuration in this area during the late Jurassic. Reactivation of NNE–SSW trending strike–slip faults in the Hercynian basement, along with the formation of diapiric structures resulted in the formation of three sub-basins (Fig. 3).

The Bombarral sub-basin developed as a withdrawal structure as salt migrated into the Vimeiro–Caldas da Rainha diapir line along its western margin. To the southeast the sub-basin is bounded by the Torres Vedras–Montejunto anticline (Fig. 2) which may be a fault-associated salt structure that lies on the southern limit of thick Dagorda evaporites (Wilson, 1988; Wilson *et al.*, 1989.)

The Arruda sub-basin is bounded on the east by the Vila Franca Fault. It is filled with > 2 km of arkoses of the Castanheira Member of the Abadia formation, and capped by the southward prograding slope silts of the top part of the formation. The northern margin of the sub-basin is formed by the Torres Vedras–Montejunto high, but its southern margin cannot be delineated, as it is obscured by the Cretaceous and younger rocks of the Tagus estuary.

The Turcifal sub-basin is bounded to the east by the Runa Fault zone, and to the north by an unnamed E–W trending fault. The nature of its Oxfordian–Kimmeridgian fill has yet to be determined by drilling.

In the southern-most part of the Lusitanian Basin, the tectonic setting of the Upper Jurassic sediments is more difficult to determine. To the southeast, the carbonate buildup at Barreiro occurs beneath a Neogene basin containing sediments up to 1 km thick. The Barreiro wells are situated immediately to the southeast of a major NNE–SSW lineament observed on Landsat images, the trend of which is coincident with the Lisbon canyon offshore. The lineament probably reflects a major basement fault. To the northwest of this lineament, the Monsanto borehole penetrated ≈ 1000 m of Abadia formation twice the thickness seen at Barreiro. The tectonic setting of the Upper Jurassic sediments brought to the surface around the late Cretaceous Sintra granite can only be inferred from sedimentological data discussed in a later section.

Buildup types and locations

The use of the term 'buildup' in this paper follows that of Wilson (1975) for 'locally formed... carbonate sediment which possesses topographic relief'. The term carries no inference about origins, geometry (i.e., ramp, shelf, etc.) or internal composition. We follow Tucker's (1985) definition of the terms 'platform', 'shelf' and 'ramp'. None of the carbonate depositional systems in Portugal are extensive enough to be termed platforms.

Figure 4 summarizes the age and principal facies characteristics of the Upper Jurassic carbonate sequences occurring within megasequence 2. Four types are recognized, which developed in distinct geographic regions within the basin.

Fault-controlled carbonate buildups

These are relatively thin (up to 500 m) shelves, contain lime-mud dominated facies with strong lateral variations, and contain distinct shelf-break facies. They are Upper Oxfordian to Upper Kimmeridgian in age (Montejunto formation and Ota limestones) developed only on the east side of the Lusitanian Basin (Fig. 4, columns 5–8).

Salt-controlled carbonate buildups

These are relatively thick (up to 1500 m) shelves, dominated by grainstones and packstones with little lateral facies variation and do not display a distinct shelf-break facies. They are largely of Upper Oxfordian–Lower Kimmeridgian (Montejunto formation) age and occur on the northwestern side of the basin (Fig. 4, columns 2 and 3).

Postrift passive basin fill sequence

This occurs on the southwest side of the Basin in strata exposed around the Sintra granite (Fig. 3; Fig. 4, column 2) and represents a prograding carbonate ramp system. Of Upper Kimmeridgian–Tithonian age (Mem Martins and Farta Pâo formations), it is dominated by carbonate mud facies with debris flow deposits common in the lower half of the sequence.

Limestone cap on prograding siliciclastics

This very thin (< 100 m) unit (the Amaral formation) occurs over much of the central and southern part of the basin. It caps the prograding slope deposits of the Abadia formation and is dominated by high-energy ooid grainstones (Fig. 4, columns 2–4, 6 & 9).

Nine carbonate facies associations are recognized within these sequences and are summarized in Table 1. The environmental interpretations of the facies associations are based on lithological and palaeontological data and the stratigraphical and spatial setting of individual sequences that are described in later sections. They are probably applicable to time-equivalent carbonates in other Atlantic settings.

FAULT-CONTROLLED BUILDUPS

These buildups are exposed on the northeast side of the basin at the Serra de Montejunto and at Ota, and were encountered to the south in the boreholes Montalegre #1 and Barriero #1–4.

The Serra de Montejunto

Setting

The buildup is bounded to the east by a WNW–ESE trending normal fault, which is parallel to an important basement structural trend affecting the Mesozoic development of the basin (Wilson *et al.*, 1989), from which the limestones of the Montejunto formation dip gently to the northwest (Fig. 5). The outcrop is terminated by a fault (the Pragança Fault) which passes northwards into a monoclinal flexure. Fluvial sandstones of the Lourinhã and Torres Vedras formations overstep the limestones on the northern side of the buildup, whereas the southern part of it is deformed by a large asymmetric anticline exposing Middle Jurassic carbonates in its core.

Age

Lime mudstones exposed to the southwest of the Montejunto anticline (Fig. 5) have yielded ammonites indicating the Bifurcatus to Planula Zones of the Upper Oxfordian (Mouterde *et al.*, 1971). The underlying Cabaços formation is considered to be middle Oxfordian in age (Ribeiro *et al.*, 1979), and the overlying Tojeira member has yielded ammonites

Table 1. Characteristics, interpretation and distribution of Upper Jurassic carbonate facies association of the Lusitanian Basin

Facies associations	Description	Principal biota	Environmental interpretation
1 Ammonitic lime mudstone	Dark clay-rich mudstones, associated with shales, small-scale slumps and carbonate turbidites	Ammonites, belemites, *Zoophycos*	Periplatform and basinal oozes
2 Limestone breccias	Oligomictic, matrix and clast supported breccias, generally with a matrix of calcareous shales	Rare or absent	Debris flows with resedimented carbonates
3 Thrombolitic bindstones	0·5–1·5 m thick, framework of thrombolitic or micritic crusts with stromatactis-like cavities and unbound wackestones	Hexactinellid and lithistid sponges, *Thartharella*, encrusting foraminifera	Deep-water/low light intensity biohermal mounds
4 *Tubiphytes* wackestones	Dark, fine-grained bioclastic wackestones, commonly with oncolites	Thin-shelled bivalves, corals. Tubiphytes	Lower-energy deposition, largely below wave-base and in shallower but sheltered locations
5 Reefal limestones	Wide variety of types including framestones, bindstones and bafflestones, often associated with reefal debris	Diverse: corals, stromatoporids *Solenopora*, chaetetids, nerineids bivalves, lithophagid bivalves, encrusting algae, encrusting foraminifera	High–moderate energy, fully marine sediments
6 Nerineid wackestones and packstones	Varied, highly fossiliferous limestones showing considerable variation on both a cm and dm scale	Diverse: nerineids, corals, bivalves, forams and dasycladaceans	Shallow marine, normal salinity lagoonal sediments; lithological variation caused principally by winnowing
7 Intraclastic and bioclastic packstones and grainstones	Many clasts with thin oolitic coats, oncolite-rich horizons common	Diverse: *Solenopora*, corals, stromatoporoids, diceratids, nerineids, foraminifera and thick-walled dasycladaceans	Moderate–high energy, fully-marine sediments
8 Lime mudstones and wackestones	Dense micritic limestones containing disseminated bioclasts and small micritic intraclasts	Restricted, low diversity: bivalves, nerineids (including *Ptygmatis*), dasycladaceans, miliolid and cyclinind foraminifera	Subtidal lagoonal deposits with some levels representing restricted conditions Shelf interiors
9 Fenestral limestones	Mudstones, wackestones and packstones, commonly oncolitic, frequently showing 'Lofer-like cycles', occasionally associated with soil horizons and omission surfaces	*In situ* Megalodontids (?*Pachyrismella*); nerineids *Ptygmatis*)	Shallow-subtidal, intertidal and supratidal sediments

M: Montejunto.
O: Ota.
B: Barriero.

Table 1. (*Cont.*)

Montejunto formations (east side of Basin)	Montejunto formations (northwest side of Basin)	Mem Martins & Farta Pão formations (southwest side of basin)	Amaral formations (central basinal area)
			Absent
	Deeper parts and basinward of the buildups and capping drowned buildups	Lower parts of the Mem Martins formation (up to 350 m on Fig. 18)	Absent
			Absent
M: thick sequences basinward of the shelf edge. O: lower reef-front and sheltered areas within the reef B: lower part of buildup	Bulk of the lower part of the buildup	Uppermost part of the Mem Martins formation (380–420 m on Fig. 18)	Absent
M: small coraliferous framestone knolls in front of the shelf break; small coral–chaetetid patch reefs within the shelf interior. O: fairly continuous framestone and bafflestone reefs at the shelf break, with coral bafflestones within the shelf interior B: towards top of buildup above association 4 and below the deep-water cap (associations 1–3)	Small coral–stromatoporid–chaetetid framestones most common in the intraclast grainstones (association 7)	Small bindstones & bafflestones of varying composition throughout the upper part of the Mem Martins formation (420–440 m on Fig. 18)	Coral bindstones and bafflestones just basinward of shelf break, and in lagoonal settings
Shelf interiors	Thin sequences associated with association 7, becoming more common towards the salt structures	Uppermost part of the Mem Martins formation (420–440 m on Fig. 18)	Inter-biostrome areas in lagoons
M: thin, discontinuous sequences at the shelf break O: behind and interfingering with reef (association 5), and thin cap to buildup B: with association 5	Thin and widespread sequence forming the upper half of the buildup	Absent	Fringing biostromal structure: cross-bedded ooid grainstones overly biostromes: deposited at shelf break
Shelf interiors	Absent	Farta Pão formation	Absent
Shelf interiors	Absent	Absent	Absent

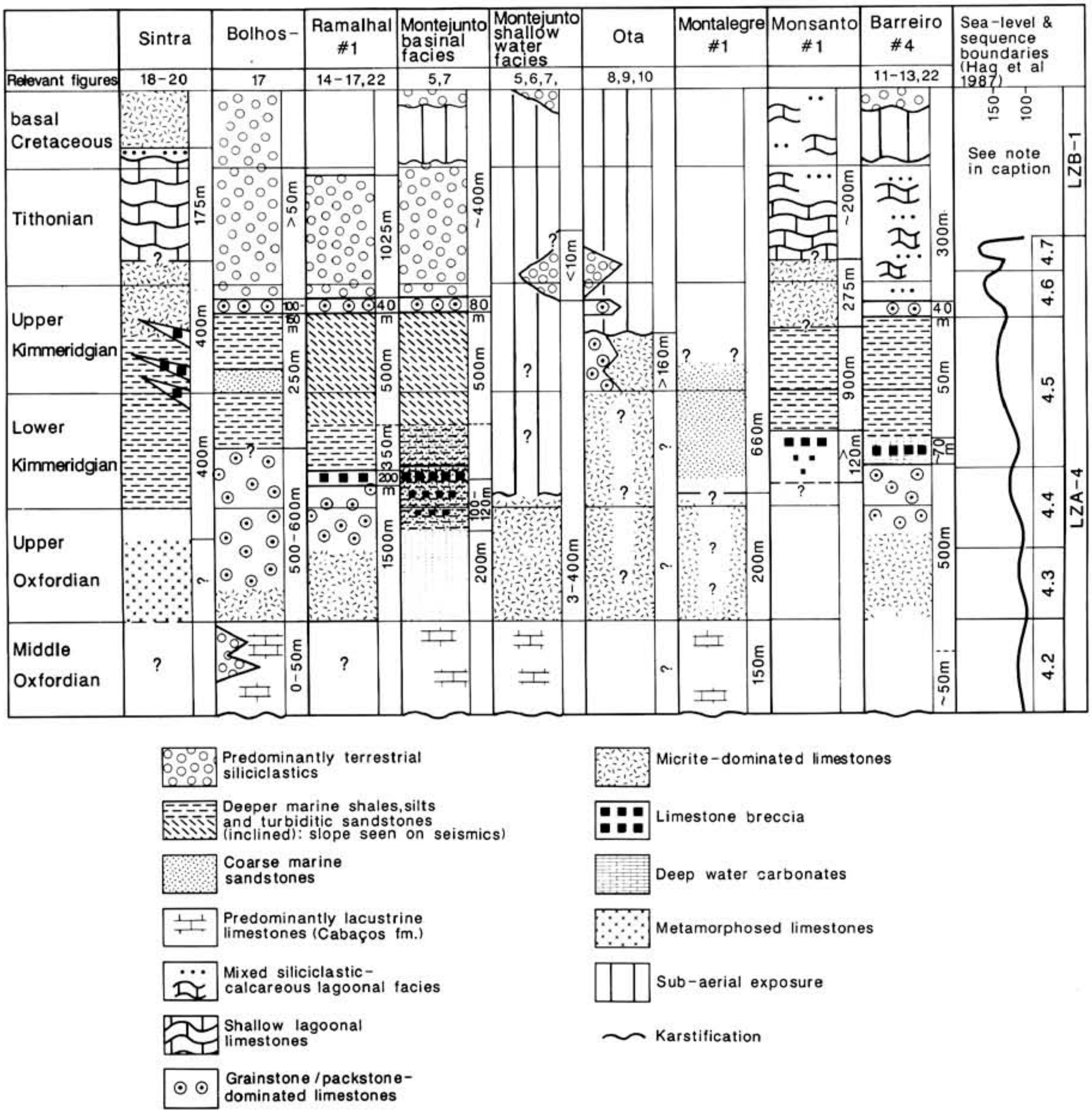

Fig. 4. Summary chart showing the stratigraphic distribution of the Upper Jurassic carbonate formations of the Lusitanian Basin. The correlation between the sea-level curve and sequence boundaries of Haq *et al.* (1987) with the Portuguese sequences cannot be made precisely due to lack of good biostratigraphic control. It is particularly difficult to identify the Oxfordian–Kimmeridgian boundary in shallow-water carbonate sequences. No attempt is made to show LZB-1 cycles, as precise dating of the Tithonian successions is not possible.

(Atrops & Marques, 1986) and foraminifera (Stam, 1985) indicating a topmost Upper Oxfordian to Lower Kimmeridgian age.

The dating of the shallow-water shelf carbonates of the Montejunto formation exposed to the north of the Montejunto anticline is less certain. They are conventionally placed entirely within the Oxfordian (Zbyszewski *et al.*, 1966) and are believed to be underlain by the Middle Oxfordian Cabaços formation. However, characteristic assemblages of

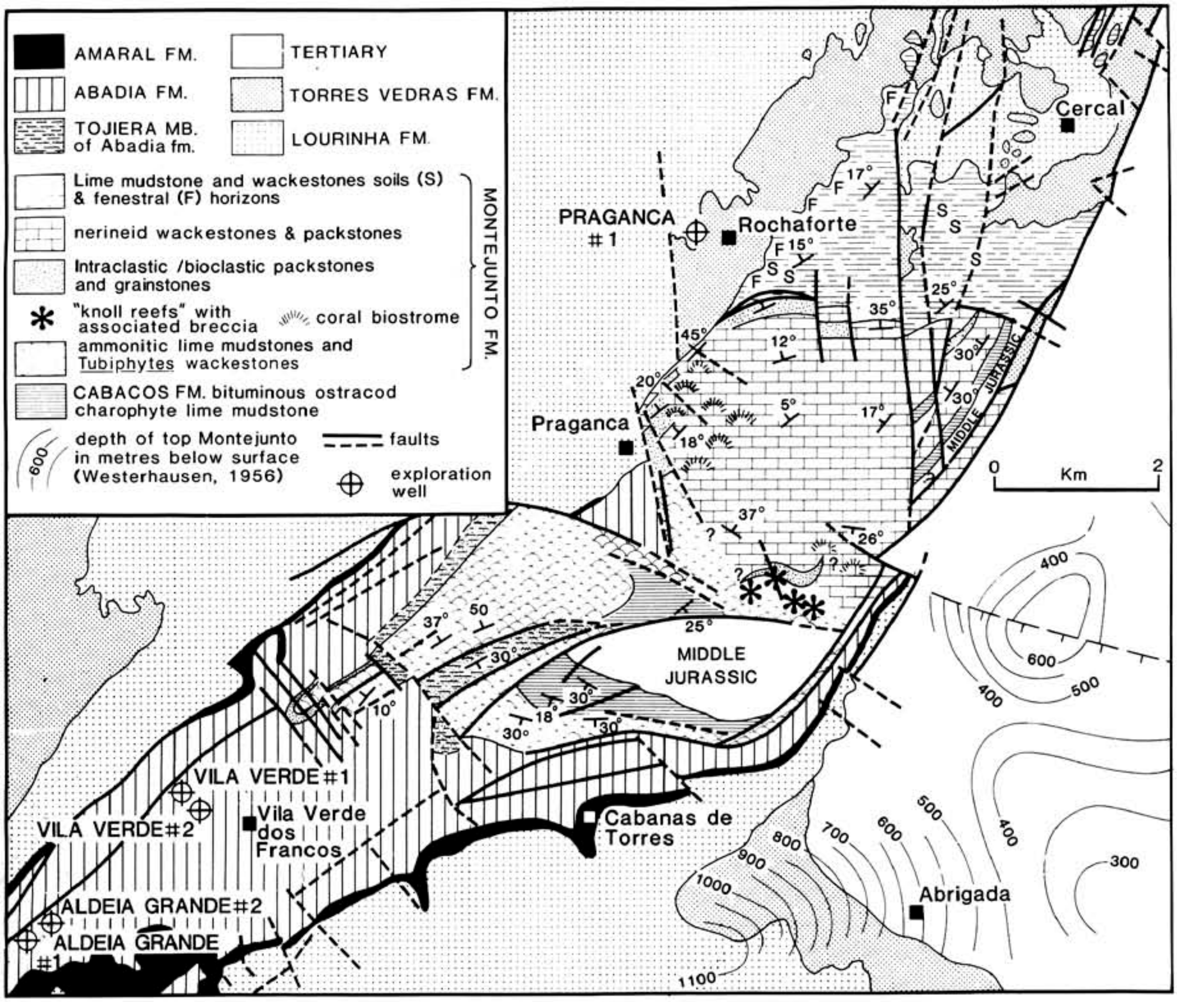

Fig. 5. Geological map of the area around the Serra de Montejunto showing distribution of carbonate facies associations in the Montejunto formation. Post-Montejunto outcrops are taken from Zbyszewski *et al.* (1966)

large diceratid rudists (*Diceras* and *Epidiceras*) found within them strongly suggest, but do not prove, an age no older than Lower Kimmeridgian for some of the limestones (P.W. Skelton, pers. comm.). The apparent absence of diagnostic micro-fossils such as *Campbelliella striata* and *Clypeina jurassica* suggest that Upper Kimmeridgian limestones are probably not present. Therefore, it is probable that although much of the shallower-water shelf carbonates are coeval with the ammonitic lime mudstones situated to the southwest, some may be of Lower, or even middle Kimmeridgian age (Guéry, 1984, suggested an age range up to middle Kimmeridgian).

Description and interpretation

Figure 6 is a schematic SW–NE cross-section across the Montejunto buildup summarizing the lateral facies changes mapped in the area, and incorporating our interpretation of its formation.

Periplatform and basinal facies are represented by ≈ 200 m of ammonitic lime mudstones exposed to the west and southwest of the Serra de Montejunto (Ruget-Perrot, 1961). Turbiditic packstones and wackestones, small-scale slump horizons and trace fossils (including *Zoophycos*) occur within the mudstones. To the southwest of Montejunto, the ammonitic lime mudstones are overlain by allochthonous oolitic packstones and grainstones.

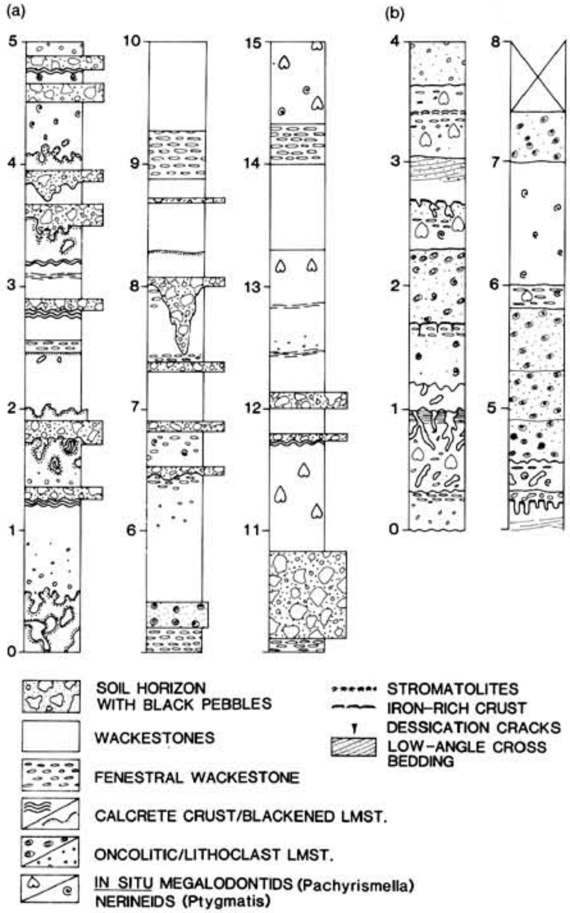

Fig. 6. Sample logs of sequences within the lime mudstone and wackestone facies (association 8) of the Montejunto buildup near Rocharforte (for location, see Fig. 5). (a) Soil-rich sequence; (b) peritidal 'loferitic' sequence. Scale on side of logs is in metres.

The Tojeira member overlies the ammonitic lime mudstones, but it is never found above the shallow-water shelf facies of the Montejunto formation to the northeast. Limestone breccias and shales are the principal lithologies of this member. A well-developed thrombolite boundstone is also exposed within its lower part, which incorporated angular pink feldspars and other basement fragments during its growth, indicating that basement was exposed nearby during this time. Basement clasts, along with contemporaneously-karstified limestones also occur within the breccias, and become more common in the upper parts of the Tojeira.

To the north of the Montejunto anticline, towards the inferred shelf-edge, the ammonitic lime mudstones pass into a thick sequence of wackestones and *Tubiphytes*-wackestones which were probably deposited on a low-angle slope. A number of small, well-developed coral framestone knolls occurs within the wackestones and are associated with redeposited beds of reef breccia. The dominance of micrite within this facies, and its basinward location, suggest deposition below normal wave-base, with the reef breccias deposited as storm deposits.

Thin, discontinuous sequences of oolitic and bioclastic grainstones are taken to mark the shelf-break (Fig. 5). Grainstones also occur farther to the northeast, where, such as at Rochaforte, they are particularly fossiliferous, containing heads of corals, stromatoporoids and *Solenopora*.

The shelf interior is largely composed of the nerineid wackestone facies (association 6). These limestones contain a wide range of fossils and show considerable lithological variation. Nerineids are concentrated in some horizons, as are heads of the chaetitid *Ptychochaetetes*, which in places combine with corals to form small patch-reef framestones and bindstones. Close to the shelf-edge grainstone shoals, a coral biostrome composed of abundant massive coral heads and phaceloid coral bushes occurs.

The nerineid wackestones pass abruptly northwards into lime mudstones and wackestones (association 8). Though there are some levels within the mudstones exhibiting a normal marine biota the majority of limestones contain few megafossils (largely nerineids when present) though some contain foraminifera and dasycladaceans indicating a very shallow, restricted environment.

Fenestral wackestones occur in the upper part of the mudstones around the northwestern margin of Montejunto (Fig. 5) and are formed of crudely-developed lofer-like cycles (Fig. 6). Supratidal conditions are marked by omission surfaces and rare stromatolite and soil horizons. The fenestral limestones are associated with a thick sequence of black pebble soil horizons exposed at Rochaforte (Fig. 6), which suggests that the area was frequently emergent.

The Montejunto buildup probably formed as an aggradational carbonate shelf (*sensu* Read, 1982). Both the shelf break and the boundary between facies associations 6 and 8 trend NW–SE, which is parallel to an important secondary element in the tectonic evolution of the Lusitanian Basin. The shelf break is marked by relatively minor thinning of the

Montejunto formation, in contrast to the dramatic thinning of the underlying Cabacos formation (Fig. 7). This, together with the fact that the Montejunto formation (in both its shallow- and deep-water developments) does not contain any limestone breccias suggestive of an abrupt shelf-edge, suggest that the slope break was located over a gentle tectonic flexure (Fig. 7).

However, it seems that this flexure did develop into a fault scarp at the end of the late Oxfordian and in early Kimmeridgian times, shedding limestone breccias basinward to form the Tojeira member, while shallow-water carbonate sedimentation probably continued over the shelf. The steep dips and monoclinal flexures between the facies blocks shown in Fig. 5 are probably related to Tertiary inversion tectonics.

Away from the Serra de Montejunto, the Praganca #1 well penetrated 500 m into the buildup, but did not reach the underlying Cabaços formation. Other exploratory wells to the southwest show that the basinal ammonitic lime mudstones are only ≈ 200 m thick; this southwestward thinning trend is also shown by the Cabaços formation.

Ota

Setting

The Ota buildup is situated ≈ 5 km S–SE of the Montejunto buildup (see Fig. 3), though the structural relationship between the two is obscured by the Lourinhã and Torres Vedras formations. The exposed part of the Ota buildup is some 6 km long, 2 km wide and up to 160 m thick (Fig. 8), with a tectonic dip a few degrees to the east. It is bounded on its western side by a N–S trending fault and is presumed to extend eastwards under a cover of Tertiary sediments. In places the Lourinhã formation rests unconformably on the karstified surface of the buildup.

As Ota is cut by deep quarries and natural valleys, lateral facies relationships are much better displayed than those at Montejunto. The presence of middle Oxfordian Cabaços formation pebbles within the Ota limestones indicates the uplift of a nearby region after the middle Oxfordian, but before the late Kimmeridgian. It is possible that the fault-bounded block of Cabaços formation situated to the northeast

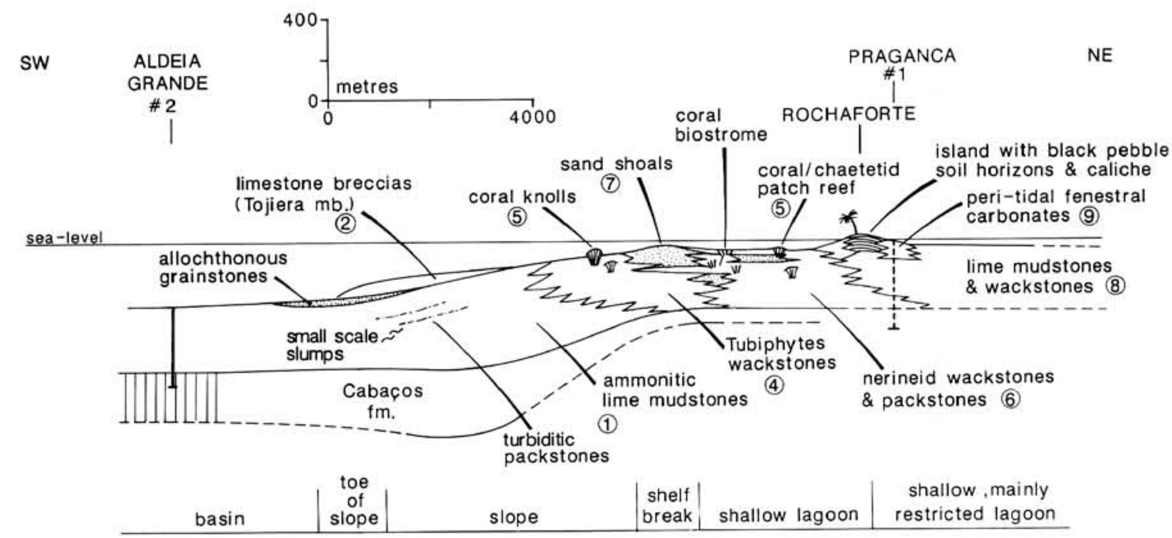

Fig. 7. Interpretative cross-section across the Montejunto buildup showing distribution of the facies associations described in Table 1.

of the Ota buildup (Fig. 8) was such an uplifted region.

Age

The association of the dasyclads *Clypeina jurassica*, and *Campbellina striata*, together with the foraminifera *Labyrinthina mirabalis* and *Alveosepta jaccardi* is typical of the Upper Kimmeridgian of Portugal (Ramalho, 1971). As the Amaral formation partly drapes the Ota limestones, and also occurs as an internal fill to palaeokarst within it, it is suggested that the buildup was deposited contemporaneously with the top part of the Abadia formation. The fault-bounded block of Cabaços formation to the northeast of Monte Redondo (Fig. 8) indicates that marine sedimentation did not occur prior to the late Oxfordian. A 250 m deep uncored water well drilled in the Ota limestone apparently did not reach the base of the unit (Manuppella & Balacó Moreira, 1984), so it is possible that the unexposed base of the buildup may be Lower Kimmeridgian or even Upper Oxfordian in age.

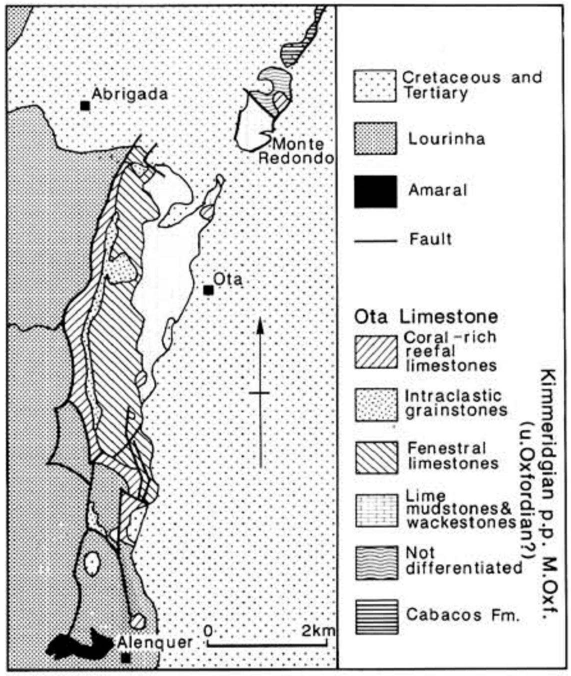

Fig. 8. Geological map of the area around Ota. From Leinfelder (1987).

Description and interpretation

Facies zonation indicative of an aggradational shelf carbonate buildup is clearly shown in Fig. 10. A narrow high-energy reefal barrier zone occurs on its western margin, behind which are situated back-reef sands, tidal limestones and lagoonal, low-energy lime mudstones and wackestones. The reefal belt exhibits a high proportion of coral framestones and algal-stabilized debris, together with algal bindstones and intraclastic–bioclastic grainstones (Fig. 9a). The interfingering of these sediment types suggests the development of a reefal spur-and-groove system (Fig. 9b).

Leeward, back-reef sands (association 7) are differentiated into bimodally-sorted sand flat intraclastic grainstones, partly exhibiting beachrock cements and poorly-sorted lagoonal grapestone facies. Tidal flat limestones are characterized by shallowing-upwards sequences, mostly composed of bioturbated lime mudstones and wackestones with an upward increasing number of irregular birdseyes, which grade into thin sheets of laminoid fenestral limestones (association 9). The presence of oncolitic channel lag deposits indicates the development of a discontinuous tidal flat zone crossed by tidal channels.

The lagoonal sediments are chiefly composed of restricted lime mud–wackestone facies (association 8) with local enrichment of skeletal or inorganic particles due to winnowing. Local mud-crack horizons and early diagenetic freshwater influence may indicate the development of shallow, stabilized linear mud banks as in the modern Florida Bay (*cf.* Enos & Perkins, 1979).

A prominent black pebble horizon related to intra-late Kimmeridgian subaerial exposure (Leinfelder, 1987; see Fig. 9) allows accurate facies correlation. It is clear that the facies pattern did not shift laterally (at least throughout the exposed part of the unit), despite local intraformational subaerial exposure and possible eustatic and tectonic oscillations. This may be explained by the existence of a bypass escarpment margin, preventing progradational reef growth despite its high productivity (Fig. 10). The position of this palaeoescarpment coincided with the present-day fault on the western limit of the reefal zone (Fig. 8). On seismic sections, this fault can be seen to have been active during the Kimmeridgian (Leinfelder & Wilson, 1989).

The Ota Limestone is probably located on a very narrow uplifted basement high and apparently represents the major part of a fairly small, isolated

Bahamian-like carbonate bank, which, during the Kimmeridgian, had no direct connection with similar, though older buildups to the north (Montejunto) and south (Leinfelder & Wilson, 1989). During the later Upper Kimmeridgian, the Ota block stopped subsiding, and intraclast and ooid grainstones spread over the structure and filled karst features. From the early Tithonian to at least the early Cretaceous, the block was subjected to subaerial exposure (Leinfelder, 1985).

The Barreiro buildup

Setting

First recognized as a stratigraphic anomaly on seismic sections, the Barreiro buildup occurs just to the south of the Tagus estuary (Fig. 3). In it the normal reflection character of the Upper Jurassic, comprising moderate amplitude, moderately continuous flat-lying reflectors is replaced by a lensoid anomalous zone of discontinuous to chaotic reflectors, with relatively high-amplitude dipping reflectors with a short lateral extent at its margins (Fig. 11). Seismic reflections beneath the anomaly are obscured, so that a clear picture of its structural setting cannot be gained. However, as the Barreiro anomaly is one of several seismic anomalies aligned along a line just to the south of and parallel to the major NNW–SSE trending lineament identified on Landsat images, it seems reasonable to suggest a crestal location on a titled-block dipping gently to the southeast.

Four petroleum exploration wells have been drilled at Barreiro (Figs 11c and 12). Barreiro #4 penetrated the main part of the seismic anomaly, and #2 and #1 were situated to the north and west of it respectively, but #3 was drilled close to another small anomaly to the southwest.

The location of the cores taken from the three wells that penetrated the Barreiro buildup is shown

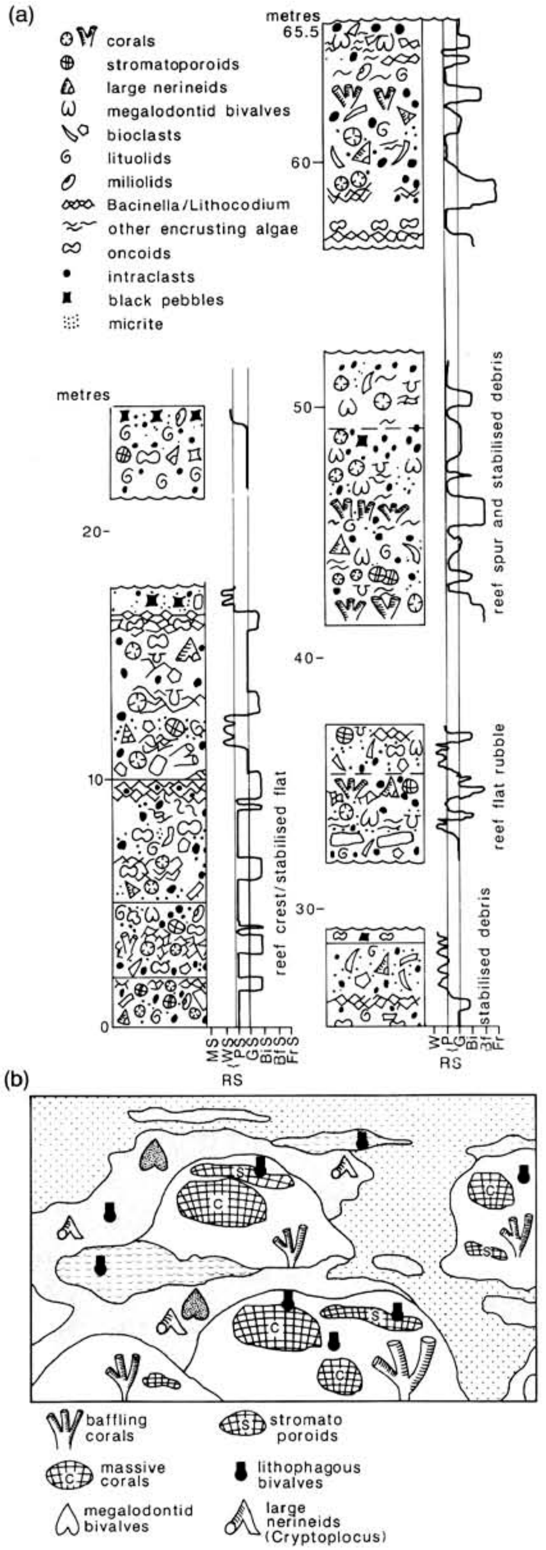

Fig. 9. Facies variation in the reefal zone in the Ota area. (a) Lithological log. Key: WS = wackestone; PS = packstone; GS = grainstone; RS = rudstone; BiS = bindstone; BfS = bafflestone; FrS = framestone. The relative abundances of lithologies within this sequence by volume are: packstones (including algal stabilized sediment) = 46%; bindstone + bafflestone + framestone = 25%; grainstone = 22%; wackestone = 7%. (b) Summary diagram illustrating the interfingering of facies types. A scale bar is not shown, as the variations shown may occur across widths ranging from 1 to 10 m.

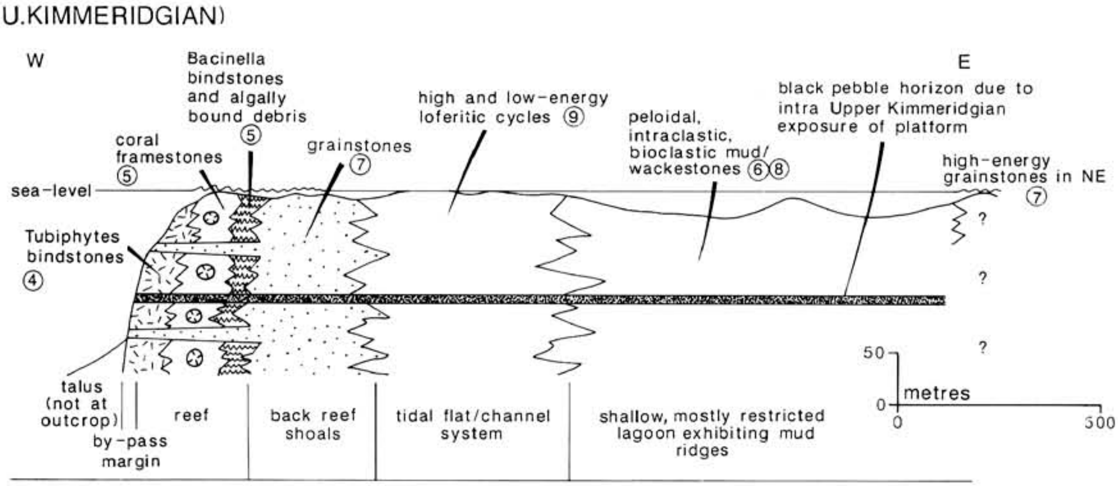

Fig. 10. Interpretative cross-section across the Ota buildup showing distribution of the facies associations described in Table 1.

in Fig. 12. Clearly, the data base is much less comprehensive than that for outcrops, but cores are available from both the central part of the seismic anomaly (#4) and its flanks (#1 and 2).

Age

On the basis of thin-section studies of algae and foraminifera, Ramalho (1971) concluded that the carbonate sequence beneath the Abadia formation in Barreiro #1-3 is Upper Oxfordian in age. However, the much thicker sequence encountered in Barreiro #4 may extend into the Kimmeridgian (E. Matos, pers. comm.). Ramalho's (1971) identification of the Amaral formation overlying the buildup places its upper age limit in the early part of the Upper Kimmeridgian.

Barreiro #4

The buildup in this well consists of three distinct units (Fig. 13). The lower unit consists largely of low-energy oncolitic wackestones (association 4) and rests directly on Middle Jurassic limestones, with the Cabaços formation apparently missing. The middle unit is composed dominantly of coral–stromatoporoid framestones and is overlain by an upper unit of deeper-water limestones and limestone breccias.

Bioclasts are common and varied in the lower wackestone facies, including fragments of stylinid and microsolenid corals, nerineid gastropods, brachiopods, inozoans, oysters and large cyclinid foraminifera. Small *in situ* heads of chaetetids and corals, some of which are oyster-encrusted, are also present.

The second unit, between 2358 and 2363 m, consists of a framework containing *in situ* heads of corals, microsolenid corals, stromatoporoids and ?*Solenopora* interbedded with light-coloured bioclastic nerineid wackestones, containing brachiopods, nerineids and foraminifera and small *in situ* microsolenids. The microsolenid corals, which form the main frame builder, are platey and are encrusted with a variety of organisms, chiefly thrombolitic crusts, with lesser numbers of inozoans, bryozoans and skeletal algae. Pervasive dolomitization of the lower parts of this core has destroyed its structure, though has greatly increased its porosity. The wackestones and packstones of the middle unit are less clay-rich than the wackestones of the lower unit, and may have been deposited in higher-energy, shallower-water conditions.

The transition between the shallow-water sediments of the buildup and the deeper-water carbonates of the upper unit that cap it is represented in core 2. *Tubiphytes* – wackestones and packstones occur at the base of the core, which, like the *Tubiphytes* – wackestones occurring at Montejunto, may have been deposited on slopes just basinward of the main buildup. A number of large angular limestone lithoclasts (largely consisting of association

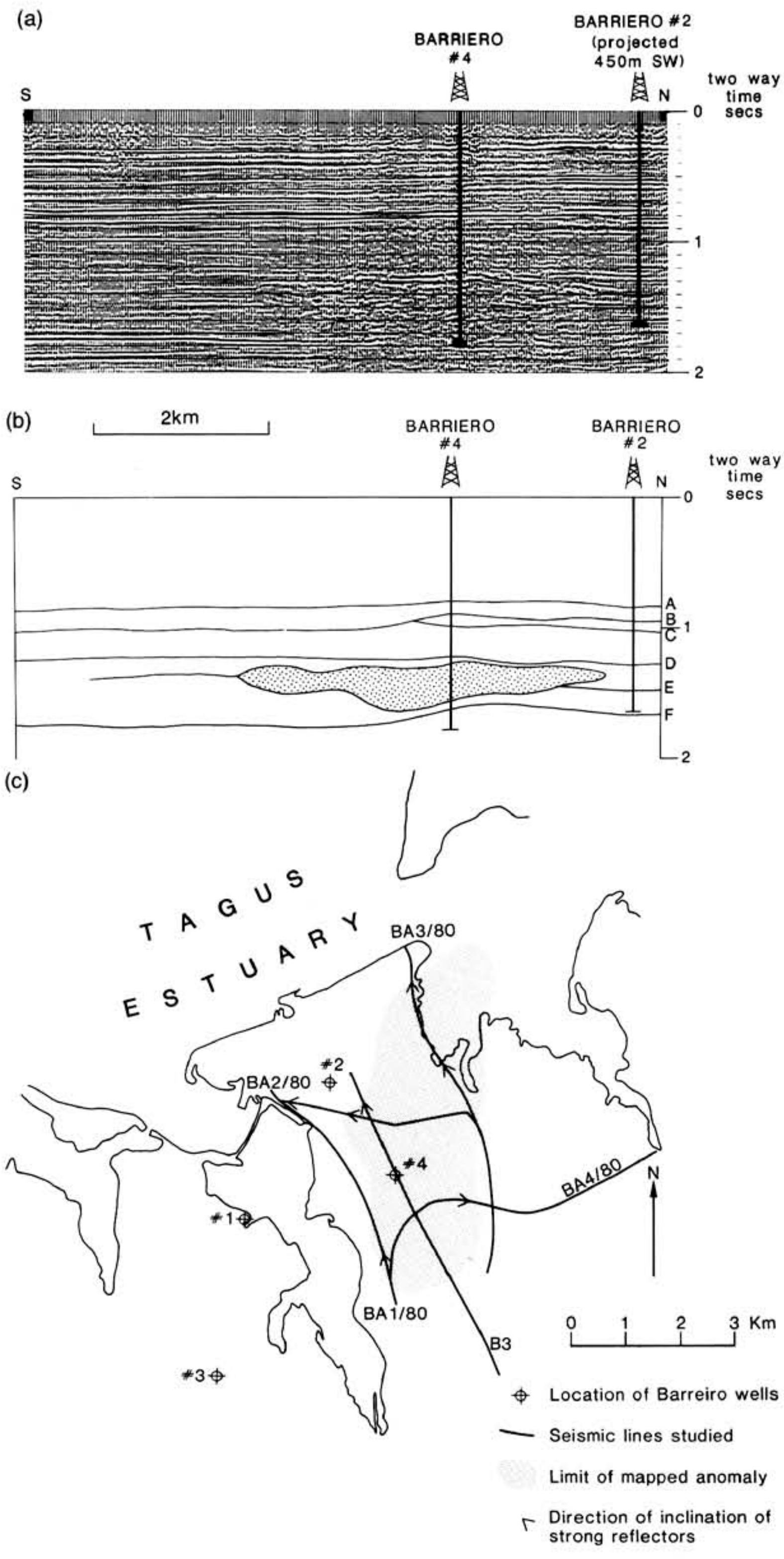

Fig. 11. The seismic anomaly produced by the Barreiro carbonate buildup. (a) Unintepreted migrated 24-fold vibroseis seismic line B3. (b) Interpretation of seismic line shown in (a) with anomaly shown as stippled area. Stratigraphic identification of reflectors is as follows: A = base Miocene; B = base Tertiary; C = top Portlandian; D = top Abadia formation; E = base Abadia formation; F = top Middle Jurassic. (c) Map of seismic anomaly showing positions of inclined reflectors at its margins and the location of the wells discussed in the text.

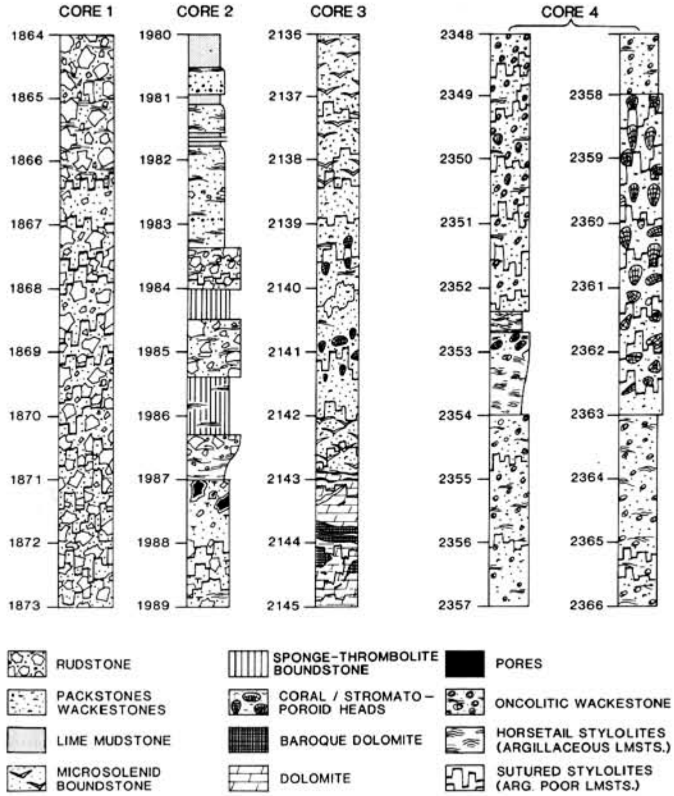

Fig. 12. Summary logs of cores taken from Barreiro #4. The positions of the cores within the buildup are shown in Fig. 13.

4) float within it, some of which were leached before their incorporation into the wackestones. The *Tubiphytes* – wackestones are overlain by a series of argillaceous limestone breccias and packstones, representing the deposits of debris and turbidity flows into deeper water, along with *in situ* thrombolitic bindstones.

Shales and allochthonous limestones form a 150 m thick cap above the buildup. These occur within core 1, which is composed entirely of limestone breccia formed of shallow-marine limestone clasts (largely fine-grained association 4, and some 6) set in a deeper-water mud matrix.

Barreiro #2

This well encountered half the thickness of Montejunto formation than that penetrated by Barreiro #4. All three units described from Barreiro #4 also occur within this well, suggesting some progradation over basinal facies. The initial argillaceous mound stage is represented by light, fine-grained bioclastic wackestones and lime mudstones containing numerous siliceous sponge spicules, associated with argillaceous breccia beds and massive diagenetic anhydrite. Only $\approx$ 50 m of the shallow-water carbonates occur in Barreiro #2 (core 7), and are formed of fossiliferous packstones and wackestones with *in situ* heads of corals. The packstones have moderate vuggy porosity with numerous oxidized oil shows. As in Barreiro #4, these are overlain by deeper-water shales, limestone breccia beds and thrombolitic bindstones.

Barreiro #1

Situated in a more basinal location than Barreiro #2, this well contains carbonates similar to the Cabaços formation at Montejunto. These consist of oil-impregnated thin-bedded ostracod–charophyte mudstones with numerous thin packstones and wackestones (cores 8–12). The overlying Montejunto limestones are more basinal than those in Barreiro #2 and #4. Dark, argillaceous wackestones (core 6) are followed by light, fossiliferous wackestones with good vuggy porosity (cores 3–4),

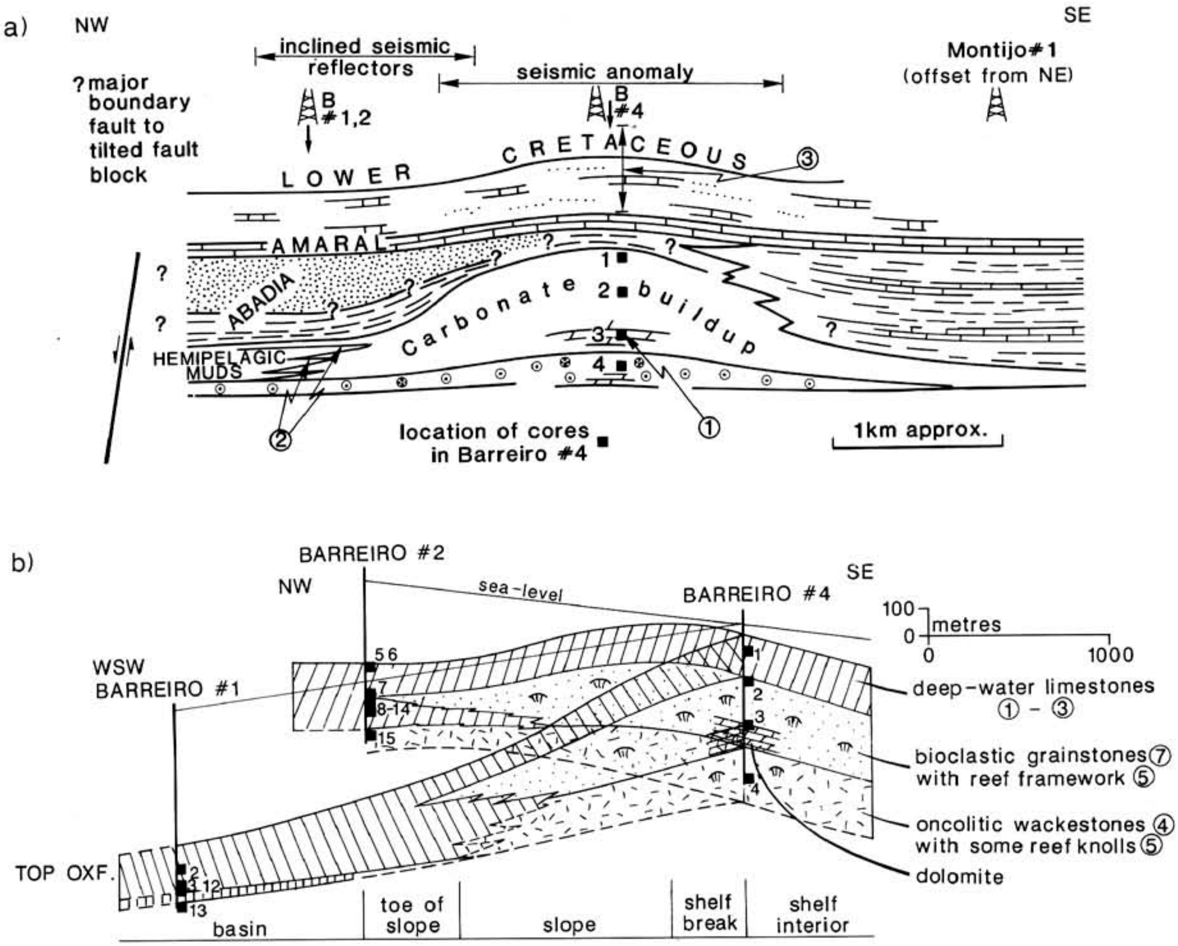

Fig. 13. Interpretative cross-sections of the Barreiro buildup. (a) Sketch section showing the relationship of the buildup to other stratigraphic units, and the location of cores in Barreiro #4. The circled numbers refer to features relevant to petroleum exploration as follows: (1) dolomitized porous zone within buildup; (2) dead oil shows in porosity within limestone breccias; (3) tar sands within the Upper Jurassic and Lower Cretaceous that accumulated in a trap formed by compactional drape over the buildup. (b) Interpretative cross-sections across the buildup showing position of cores within Barreiro #1, #2 and #4 and the distribution of facies associations described in Table 1.

which are overlain by argillaceous wackestones with limestone lithoclasts (core 2).

Barreiro #3

Barreiro #3 is located to the southwest of the main buildup, and reveals a very different sequence to those encountered in the other wells. Here the limestones are much thinner (just over 160 m thick) and composed largely of limestone breccias. In the lower part, the clasts are set in a matrix of light and interbedded bioclastic wackestones, possibly deposited under relatively shallow-water conditions. The breccia beds become more argillaceous up the sequence, and are interbedded with argillaceous and pyritic ammonitic lime mudstones, suggesting an increase in depth of deposition. As no major faults are revealed on seismic sections, a fault scarp talus origin for the Barreiro #3 sequence seems unlikely. However, the well is located very close to another seismic anomaly (not shown in Fig. 11, but see Fig. 21) and so the sequence could be a talus slope derived from a nearby buildup.

Discussion

Core data from Barreiro #4 indicates that the seismic anomaly shown in Fig. 11 is composed of a shallowing-up sequence consisting principally of facies associations 4, 5 and 7, which is capped by a deep-water sequence of associations 1, 2 and 3. In the more basinal areas to the west and northwest of the anomaly, Barreiro #1 and 2 also show a shallowing trend overlain by a deep-water cap, but the deeper-water facies associations 1, 2 and 3 predominate throughout the sequence (Fig. 12). The inclined reflectors at the margin of the anomaly suggest slight progradation to the west and northwest – a conclusion consistent with the shallowing trends seen in the wells. The deep-water limestones and breccias that cap the Barreiro buildup suggest that shallow-water carbonate sedimentation was terminated by drowning and the partial break-up of the buildup. Breccias of equivalent age encountered in Monsanto #1, 15 km across the Tagus estuary in Lisbon, may have been derived from the Barreiro buildup.

Speculation concerning the nature of the carbonate facies to the east of the Barreiro buildup can only be based on data available from Montijo #1 and outcrops at Cabo Espichel (for locations, see Fig. 3). At both locations, mudstones and wackestones of facies association 8 and 9 occur interdigitated with siliciclastic fluvial sands.

Compactional drape of Tithonian and Lower Cretaceous siliciclastic sands over the Barreiro buildup formed a trap in which an oil column > 200 m high accumulated, but was later oxidized to produce tar-impregnated sands (Fig. 12).

SALT-CONTROLLED BUILDUPS

Setting and age

A large buildup developed on the southeast side of the Caldas da Rainha – Vimeiro salt structure, which extends over an area of ≈ 200 km^2. It has been brought to the surface around the salt structure, and was penetrated by the Lourinhã, Campelos and Ramalhal wells (see Fig. 3 for locations). The wells show that the buildup thickens eastwards into the Bombarral Sub-basin, which was subsiding due to salt withdrawal. Ramalhal #1, which did not reach the Cabaços Formation, showed the buildup reached thicknesses of at least 1500 m, but at outcrop it is only a few hundred metres thick.

Dating of the Ramalhal – Serra d'el Rei buildup is uncertain. The presence of the Abadia formation over the buildup in the subsurface means that it is certainly Oxfordian in age, though no detailed faunal and floral information is available to state its upper age limit with precision, which may extend into the Kimmeridgian. At outcrop, Abadia-equivalent clastics are extremely thin and carbonate sedimentation more probably continued into the Kimmeridgian.

Seismic features

Figure 14 shows two seismic lines through the buildup near Ramalhal #1. Both sections show that the top is characterized by high amplitude mounded reflectors, whereas the lower part does not show such strong reflectors. In Figs 14a & b, mounded reflectors also show a progradational pattern. The positive relief on the apparent slope into the basin is of the order of 200 m, and beyond this on both Figs 14a & c the thinner zone of parallel high amplitude reflectors may be caused by deep-water ammonitic lime mudstones of the Montejunto formation and the overlying Tojeira member. This interpretation has not been substantiated by drilling.

Core data

Ramalhal #1

The 1500 m sequence penetrated by Ramalhal #1 represents the thickest development of the Montejunto formation in the Basin. As at Barreiro, the Ramalhal buildup shows a three-fold division consisting of a generally shallowing-upwards sequence from relatively fine-grained limestones (facies association 4, core 1), passing into more fossiliferous packstones and grainstones (association 5 and 7), which in turn are capped by deeper-water limestones (Fig. 15).

Biohermal limestones occur within the lower part of the buildup and these consist of heads of microsolenid corals, stromatoporoids and some *?Solenopora* in a fine-grained wackestone matrix. Numerous types of encrusters are present, including thrombolitic crusts, skeletal algae, stromatoporoids and bryozoa. The biohermal facies shows little vuggy porosity, but is cut by numerous small fractures. The upper part of the shallow-water buildup sequence (represented by core 7 starting at 2057 m, to core 18 down to 2460 m) consists of higher-energy fossi-

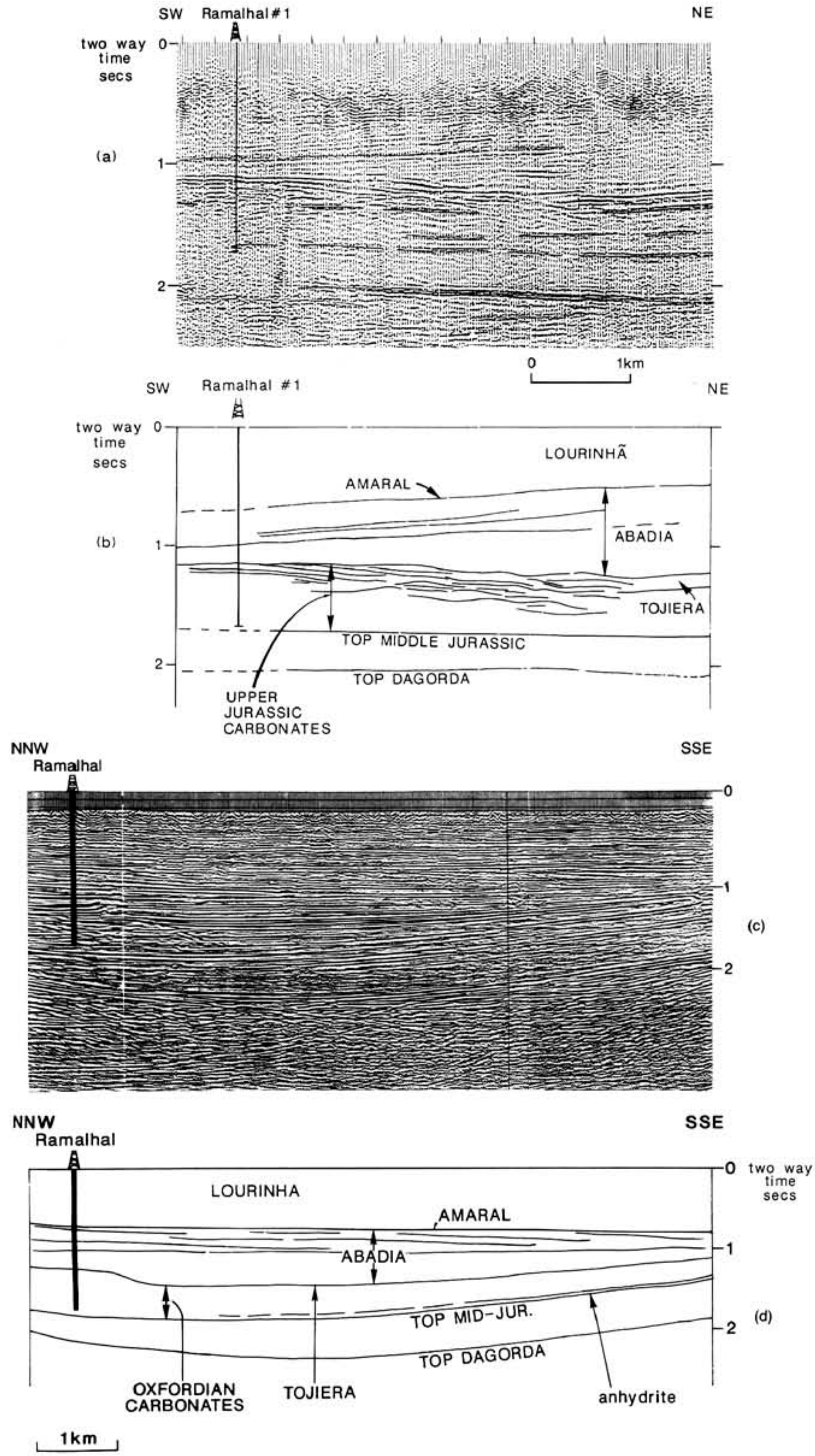

Fig. 14. Seismic sections across the Ramalhal part of the salt structure related buildup on the northwest side of the basin. (a) Unmigrated 24-fold dynamite line. Note that some interpretative lines were drawn on this section prior to its receipt by the authors. (b) Interpretation of line shown in (a) showing mounded clinoforms at the top of the Upper Jurassic carbonate section. (c) Migrated 48-fold vibroseis line. (d) Interpretation of line shown in (c).

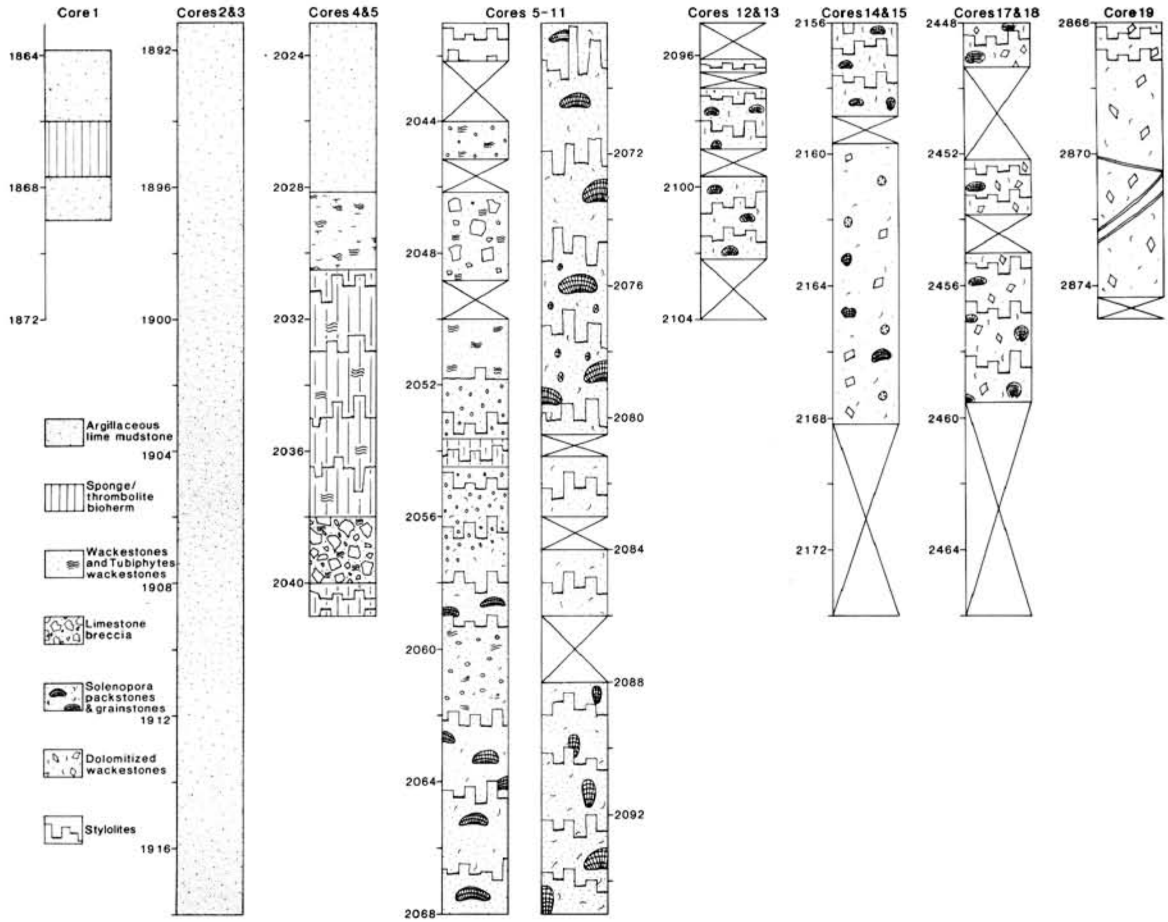

Fig. 15. Summary logs of cores taken from Ramalhal #1.

liferous *Solenopora* grainstones, packstones and wackestones, ≈ 400 m thick, containing heads of corals, stromatoporoids and *Solenopora*, and some *in situ* specimens of *Trichites*. A wide variety of clasts is contained within the packstones, many with thin oolitic coats, and the sediment shows good vuggy porosity, some of which is partially filled with baroque dolomite. The deeper-water limestones which cap the buildup consist of pyritic ammonitic lime mudstone, intercalated with matrix-rich limestone breccias and some minor thrombolitic bioherms (Fig. 15).

Campelos #1

The Cabaços formation is 400 m thick, and consists of lacustrine ostracod–charophyte mudstones intercalated with feldspathic sandstones. The Montejunto formation is significantly thinner, at ≈ 600 m, than in Ramalhal #1. Though no extensive coring was undertaken in this well, the three-fold division of the buildup can be recognized. The lower 400 m of the overlying Montejunto formation consists predominantly of lower-energy wackestones, above which occur 120–150 m of porous *Solenopora* grainstones. Deeper-water shales and limestones cap the buildup and can be recognized as a distinctive zone on electric logs by an increase in caliper and spontaneous potential and surprisingly, considering its clay content, a decrease of gamma-ray (Fig. 16).

Lourinha #1

A cored interval in the Cabaços formation consists

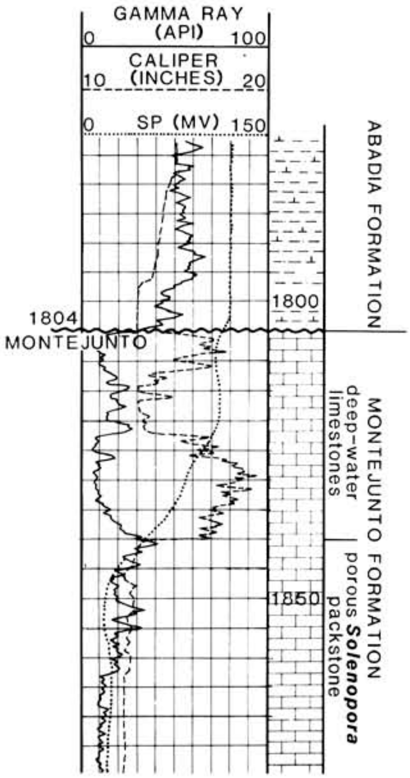

Fig. 16. Log signature of the top of the salt structure related buildup obtained from Campelos #1 showing the deeper-water limestone cap.

of feldspathic sandstones. These also contain angular evaporite clasts, possibly derived from the rising Bolhos diapir to the northwest. The three-fold division of the buildup cannot be recognized in this well, where the overlying marine carbonates consist of a thin sequence of fossiliferous packstones containing *Solenopora*, as well as corals and stromatoporoids, which are overlain by fine-grained, darker wackestones containing gastropods, serpulids, large cyclinid foraminifera, dasycladaceans and *Cayeuxia*, as well as *in situ* stick-like corals and stromatoporoids. The Abadia formation is not present in this well, so it seems possible that carbonate deposition continued near the crest of the salt high during the early Kimmeridgian, whilst siliciclastic sedimentation occurred farther into the Bombarral Sub-basin.

Outcrop data

The northwestward continuation of the Ramalhal buildup is exposed at the surface at several locations along the Vimeiro–Caldas diapiric structure and may extend in age into the Upper Kimmeridgian (Guéry, 1984). At these outcrops, Upper Jurassic carbonates show considerable variations in thickness, due to contemporaneous diapiric movement. At Vimeiro (Fig. 2), ≈ 300 m of limestone are exposed, consisting chiefly of oncolitic wackestones and oolitic packstones, with some minor amounts of *Solenopora* packstones and framestones. To the north, at Sobral de Lagoa and Dagorda, no more than 150 m occur associated with a thick Upper Jurassic karst fill in the underlying Middle Jurassic limestones (Ellis *et al.*, 1987). This may be the site of a diapir which reached the surface during the Jurassic (Fig. 3).

Between the Bolhos diapir and Pó, to the southeast of the town of Serra d'el Rei (Fig. 3), the Montejunto formation is 500–600 m thick, with a thin development of the Abadia formation sandwiched between the Oxfordian carbonates and 150 m of limestones of Upper Kimmeridgian age that are probably lateral equivalents of the Amaral formation. In the Serra d'el Rei area, the Cabaços appears to be only locally developed and, as in Lourinha #1, consists of intercalated ostracod–charophyte lime mudstones and arkosic sandstones. The lower part of the Montejunto formation, as at Ramalhal, is micrite-dominated incorporating a richly fossiliferous and varied sequence of rocks similar to the nerineid wackestone facies (association 6) at Montejunto. These are overlain by thick sequences of bioclastic, oolitic and oncolitic packstones and grainstones with abundant corals, stromatoporoids and *Solenopora*. The corals and stromatoporoids locally form framestones up to 4 m thick within the grainstones. The limestones at Serra d'el Rei show no evidence of drowning, and it is probable that shallow-water carbonate sedimentation continued into the Kimmeridgian.

Summary

Figure 17 shows an interpretative cross-section linking the subsurface and outcrop sequences of the Ramalhal–Serra d'el Rei buildup described above. The coarsening-up trend from wackestones to grainstones is common to nearly all the sequences studied, but the deep-water cap appears to be confined to basinal locations (Campelos #1, Ramalhal #1). In contrast to the Montejunto and Ota buildups, a well-defined reef zone or shelf-break facies did not

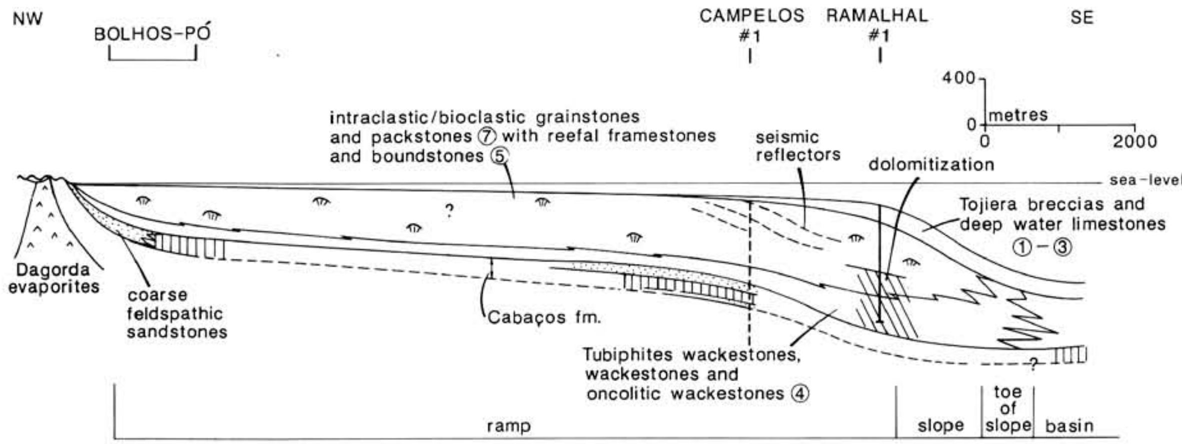

Fig. 17. Interpretative cross-section across the Oxfordian–Kimmeridgian salt structure related buildup on the northwest side of the basin, showing the distribution of the facies associations described in Table 1.

develop, and this may have prevented the development of a distinct lateral facies zonation. The buildup appears to have developed initially on a ramp produced as the Vimeiro–Caldas da Rainha structure rose to produce a broad salt pillow. The development of mounded, slightly progradational seismic reflectors at the top of the buildup, and the increase in slope angle in distal locations suggest that it was beginning to develop a shelf profile before it was drowned towards the end of the Oxfordian.

POSTRIFT PASSIVE BASIN FILL SEQUENCE

Setting and age

Dramatically increased subsidence rates associated with a rifting event in the Kimmeridgian (Wilson, 1979, 1988; Wilson *et al.*, 1989) halted carbonate sedimentation throughout much of the basin, though shallow-water carbonate sedimentation continued on palaeohighs into the Middle Kimmeridgian. This event was accompanied by the drowning and partial break-up of the older Montejunto formation buildups (of which the major examples have already been described) and was followed by the influx of Abadia clastics.

The southern part of the basin, however, remained starved of coarse clastics throughout the remainder of the Jurassic. The Monsanto borehole (Fig. 3) shows the basin filled with shales which are capped by a shallowing-upwards limestone sequence. To the west, near Sintra, a carbonate–shale slope deposit prograded into the newly deepened basin. These Upper Jurassic carbonates are now exposed around the diapir-like late Cretaceous Sintra granite.

The sequence exposed on the coast at Praia Abano is $>$ 1000 m thick and ranges in age from Upper Oxfordian to Berriasian. It is divided into four lithostratigraphic units (see Fig. 2), the top three of which are shown on the summary log of Fig. 18. The lowermost Upper Oxfordian San Pedro formation consists of thermally-metamorphozed limestones in which characteristic lithofacies types cannot be discerned but its implied age and purity imply an equivalence to shallow-water Montejunto limestones.

On the basis of studies of foraminifera and algae, Ramalho (1971) assigned the following ages to the formations above the San Pedro:

Ramalhão formation:
Lower to Middle Kimmeridgian
Mem Martins formation:
Middle Kimmeridgian–Tithonian
Fartã Pão formation:
Tithonian–lowermost Berriasian

The sequence was studied in detail by Ellis (1984).

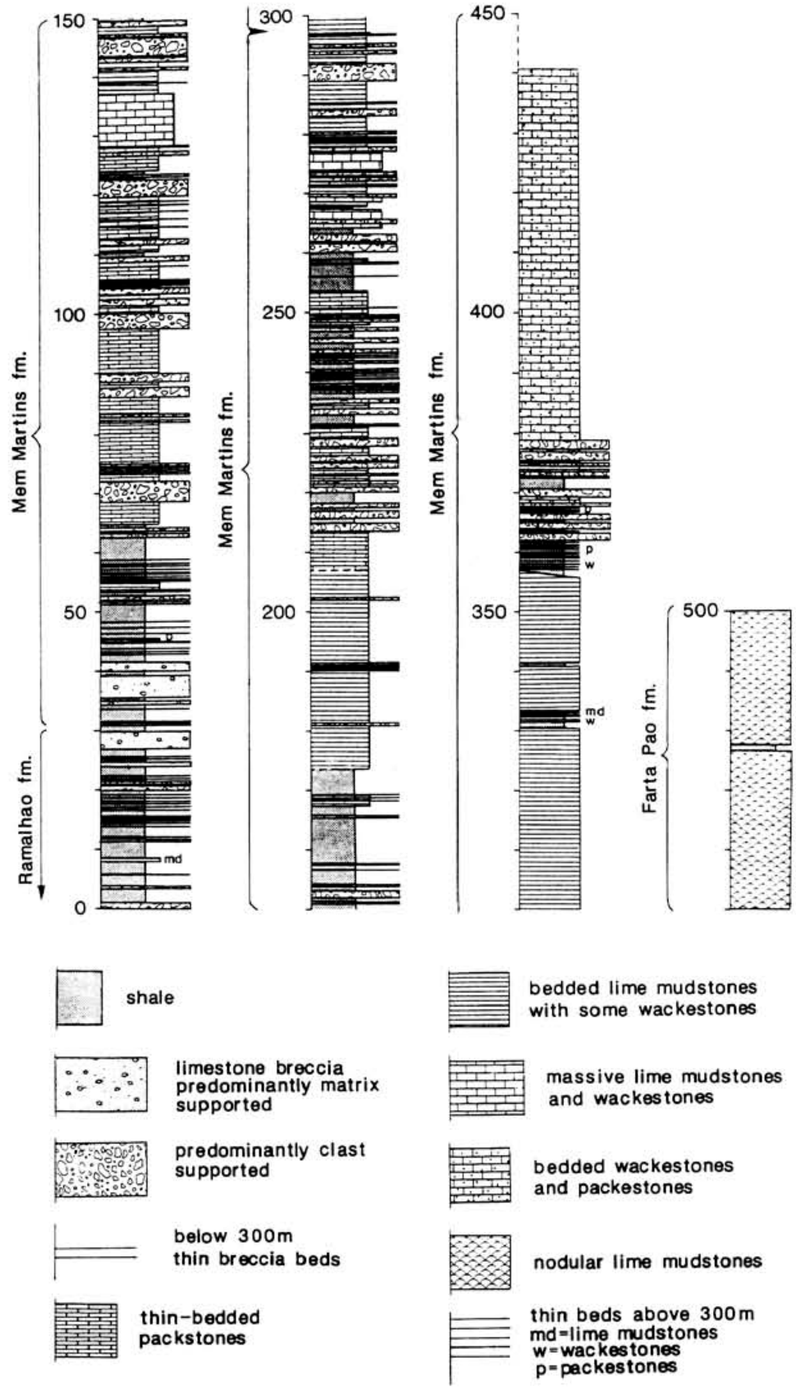

Fig. 18. Summary log of Kimmeridgian–Tithonian Sequence exposed north of Praia do Abano, on the coast southwest of Sintra.

The Ramalhão formation

This formation is dominated by shales (thermally metamorphozed to slates), but resedimented carbonates occur at the base as thin breccia beds and turbiditic wackestones. The formation is ≈ 400 m thick.

The Mem Martins formation

The Mem Martins formation is formed of a mixed carbonate–shale sequence, which passes upwards into pure limestones (Fig. 18). The base of this formation is marked by the first appearance of thick limestone breccias containing large allochthonous blocks of limestone (Ramalho, pers. comm.). Ranging from 0.2 m to over 4 m in thickness, the limestone breccias are composed of angular limestone lithoclasts largely composed of marine wackestones (facies association 4), as well as some transported corals and stromatoporoids, arranged chaotically within a matrix of calcareous shale. They were deposited as sheet or lobate debris flows (Ellis, 1984). None of the clasts show conclusive evidence of contemporaneous karstification. Thin-bedded packstones and grainstones occur in association with the breccias and were deposited as thin-bedded debris or turbidity flows. The background sediments consist of shales passing up into ammonitic lime mudstones (175–207 m, 280–355 m in Fig. 18), similar to Read's (1980, 1982) deep-water ribbon carbonates. Ellis (1984) concluded that the lack of sedimentary boudinage structures and other slope-related structures in the breccia-dominated part of the Mem Martins formation indicate that it was deposited on a slope inclined at less than one degree. The lack of breccias in the inland exposures to the east suggests that their disappearance was caused by a change in inclination at the toe of slope (Fig. 19a & 20). Tool marks at the base of one debris flow, and flute marks at the bases of carbonate turbidites suggest that the source area lay to the northwest.

The presence of abundant clasts of previously lithified limestone member is similar to that found in the Tojeira member at Montejunto and the deep-water caps of both the Barreiro and Ramalhal build-ups. The age of the lithified limestones is not known but is probably virtually contemporaneous with the background sediments. As lithified reefal debris is not a significant component of the breccias, a source area consisting of a reef bypass margin must be ruled out, and a fault scarp origin favoured as depicted in Fig. 19a. Transported corals and stromatoporoids and other bioclasts within the breccias, however, indicate that small patch-reefs were growing on the lithified limestones in the source area.

The top part of the Mem Martins formation (above 297 m in Fig. 18) does not contain Tojeira-like limestone breccias. Ammonitic lime mudstones continue to 355 m, and they contain thrombolitic bindstones and algal microsolenid bindstones to the east of the coastal sequences. An erosional surface above the ammonitic lime mudstones on the coast is overlain by shales and allochthonous packstones and wackestones and coraliferous rubble beds which have a limited lateral extent. These are overlain by fossiliferous *Tubiphytes* wackestones (association 4) with phaceloid coral bushes which pass up into nerineid wackestones and packstones (association 6), containing coral–chaetitid framestone patch-reefs and coral biostromes.

The top part of the Mem Martins formation is interpreted as a prograding carbonate ramp, across which the faunal diversity of bioherms increased from thrombolitic bindstones, through algal–microsolenid bindstones to coral–chaetitid framestones up the ramp into shallower waters. Small slump scars and debris flows also occurred (Fig. 19b).

The Farta Pão formation

Nodular lime mudstones containing a restricted biota of cyclinid foraminifera *Anchispirocyclina lusitanica*, miliolid foraminifera and dasyclads (*Salpingoporella annulata, Campbelliella striata*) (facies association 8) are the main constituent of this formation. The top of the formation contains condensed horizons, minor sandstones and oyster-encrusted firmgrounds (Ellis, 1984).

The restricted lagoonal environment represented by the Farta Pão formations marks an abrupt change in conditions from the fully marine Mem Martins formation and heralds the platform conditions of the Berriasian.

Summary

The Ramalhão and lower part of the Mem Martins formations are lateral equivalents of the Abadia formation, which prograded southwards during a relative sea-level stillstand. In the Sintra area, the deep-water basin was progressively and passively filled by shales and debris flows originating from a postulated fault scarp to the northwest (Figs 19 & 20). Once the basin had almost filled, a carbonate ramp system developed represented by the upper part of the Mem Martins formation (Fig. 20). A similar pattern of sedimentation occurs 25 km to the east beneath Lisbon, where the Monsanto well revealed a shallowing-up carbonate sequence with lithologies similar to the upper part of the Mem

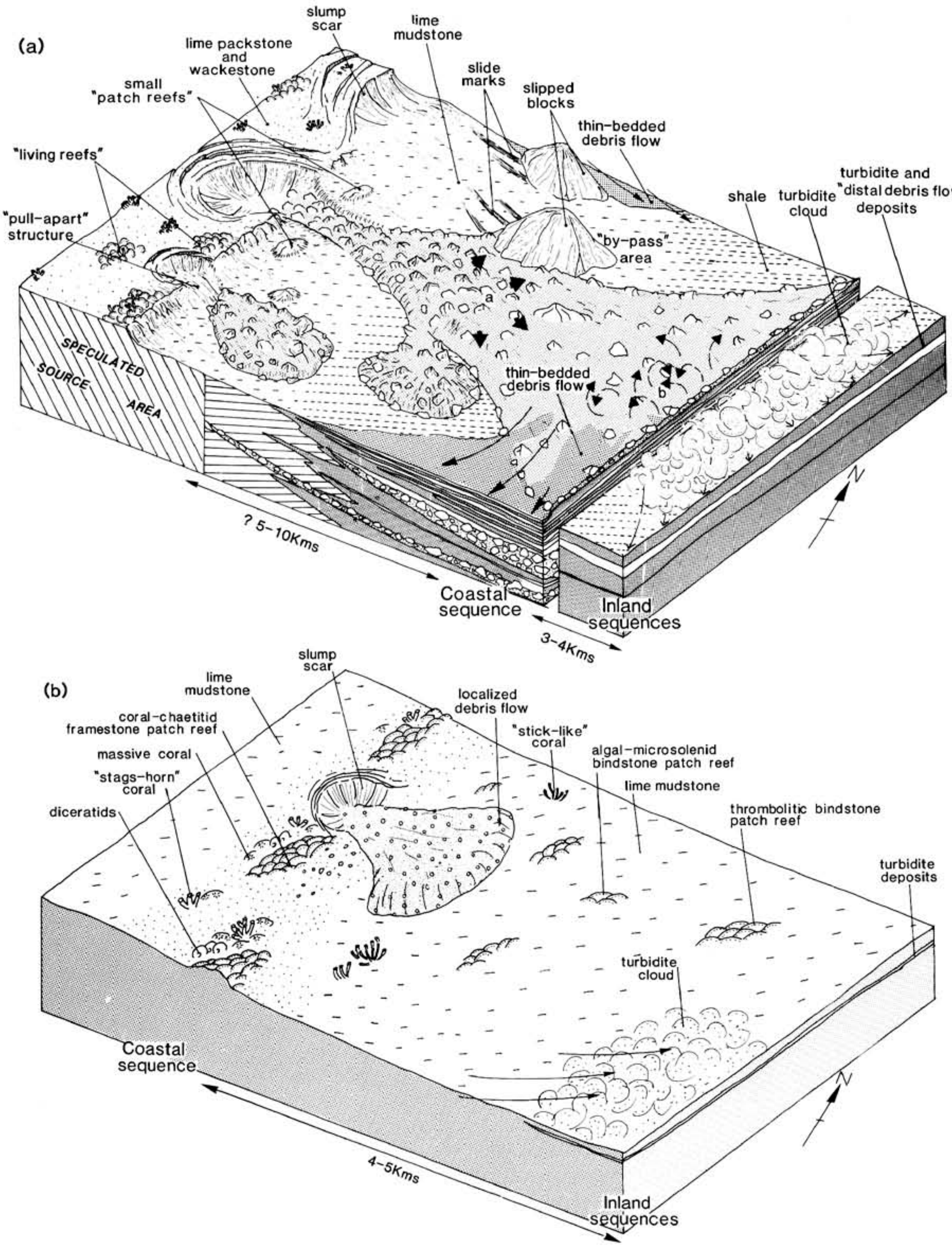

Fig. 19. Depositional models for the Kimmeridgian–Tithonian Sequences in the Sintra area (from Ellis, 1984). (a) Model for the breccia-dominated lower part of the Mem Martins formation. (b) Model for the upper part of the Mem Martins formation.

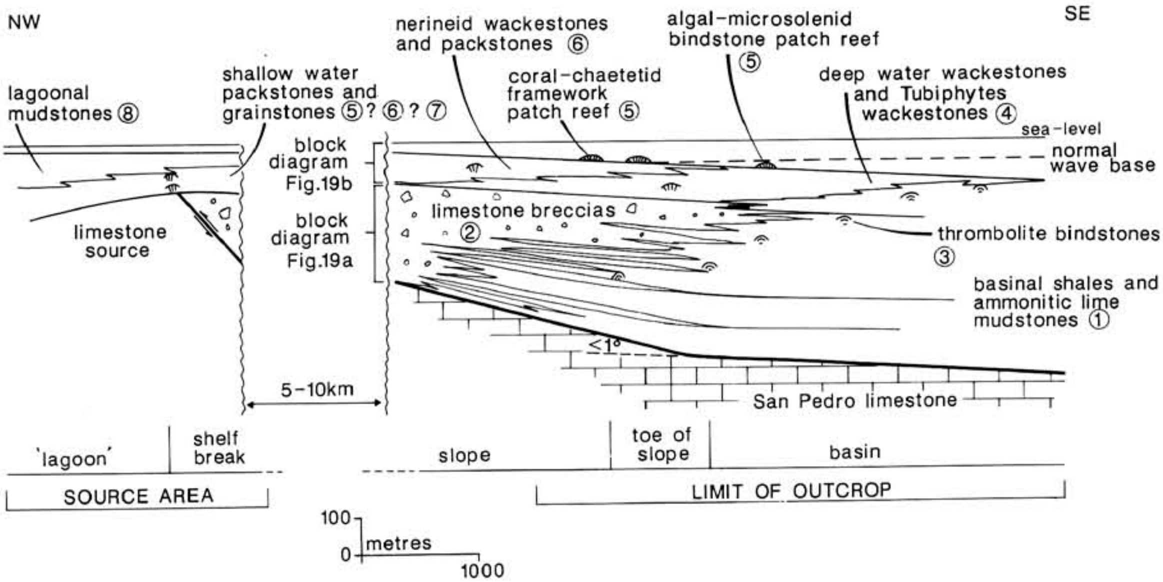

Fig. 20. Interpretative cross-section of the Kimmeridgian–Berriasian buildup on the southwest side of the basin, showing the distribution of facies associations described in Table 1.

Martins and Farta Pão formation overlying 900 m of Abadia marls.

LIMESTONE CAP ON PROGRADING SILICICLASTICS

Setting and age

The Amaral formation forms a thin ($\approx$60 m) limestone cap to the southward prograding slope marls and silts of the Abadia formation. It extends over an area of $> 1000\,km^2$ from the southern part of the Bombarral Sub-basin into the Arruda Sub-basin (Wilson, 1988, fig. 7) and is seen on seismic sections in the Turcifal Sub-basin.

The top part of the Abadia formation contains ammonites characteristic of the *tenuilobatum* and *pseudomutabalis* Zones which, together with the occurrence in the Amaral formation of the foram *Kurnubia palastiniensis* and the dasyclad *Clypeina jurassica* clearly indicates an Upper Kimmeridgian age for the latter formation (Dölher in Leinfelder, 1986).

Description and interpretation

The Amaral formation represents a carbonate sheet sand and exhibits fewer facies associations than the other buildups described in this paper (Table 1). High-energy grainstones and bioherms (associations 5 and 7) dominate, but lower energy fossiliferous wackestones (association 6) occur in lagoonal areas.

In the centre of the Arruda Sub-basin, the basal 30 m of the Amaral formation consists of coral bindstones forming individual structures up to 10 m thick. These contain a diverse biota of baffling and massive corals and stromatoporoids, with molluscs, echinoids and encrusting algae and forams. This reefal facies grades vertically and laterally into coral-rich bioclastic oncolitic packstones and grainstones, with minor nerineid packstones and bioturbated bioclastic wackestones. Significant amounts of ooids also occur in these sediments.

Around the Torres Vedras–Montejunto high, and in the Campelos and Ramalhal wells, the Amaral consists predominantly of ooid grainstones up to 30 m thick. This facies also occurs above the lower biostromal unit in the centre of the Arruda subbasin. At outcrop, the grainstones are cross-bedded, with sets up to 10 m thick. The amount of detrital quartz-forming ooid nuclei increases upwards, and siliciclastic sandstones and oyster patch-reefs up to 2 m thick are intercalated with the grainstones towards the top of the sequence.

In the Torres Vedras–Montejunto area, the ooid grainstones of the Amaral formation were interpreted by Ellwood (1987) as an ooid bar system that formed at the shelf break of the southern prograding Abadia formation slope system. To the south, in the Arruda region, the coral biostromes appear to have developed slightly downslope from the shelf break ooid sands.

POSSIBLE CONTROLS ON CARBONATE DEVELOPMENT IN PORTUGAL

Recapitulation

Four carbonate sequence types occur in the Upper Jurassic of the Lusitanian Basin; the geographical distribution of three of them is shown in Fig. 21, and their stratigraphical relationships in Fig. 4.

1 On the east side of the basin, faults exerted a significant influence on carbonate facies distribution, resulting in the development of carbonate buildups with shelf geometries during the Oxfordian – Kimmeridgian. These developed distinct lateral facies zonations, and in the case of the Montejunto and Ota buildups were aggradational. Carbonate muds form a significant proportion of the structures as they were protected by a distinct shelf-break facies. The buildups are relatively thin over fault blocks (200–500 m, Figs 7, 10 & 13) indicating relatively low subsidence rates.

2 On the northwest side of the basin, a thick (up to 1500 m) Oxfordian–Kimmeridgian coarsening-up grainstone-dominated buildup formed on the flank of a rising salt pillow structure. No distinct shelf-break facies or significant lateral facies zonation developed. The top of the buildup shows progradational features and the development of a shelf-like profile on seismic sections (Fig. 17).

3 Following the Kimmeridgian rifting event a thick (≈1000 m) Kimmeridgian–Tithonian Sequence of shales, debris flows and low- to moderate-energy wackestones and packstones developed in the southwest of the basin. This sequence, which lacks high-energy grainstones, developed as a prograding ramp deposit and is interpreted as a passive basin fill

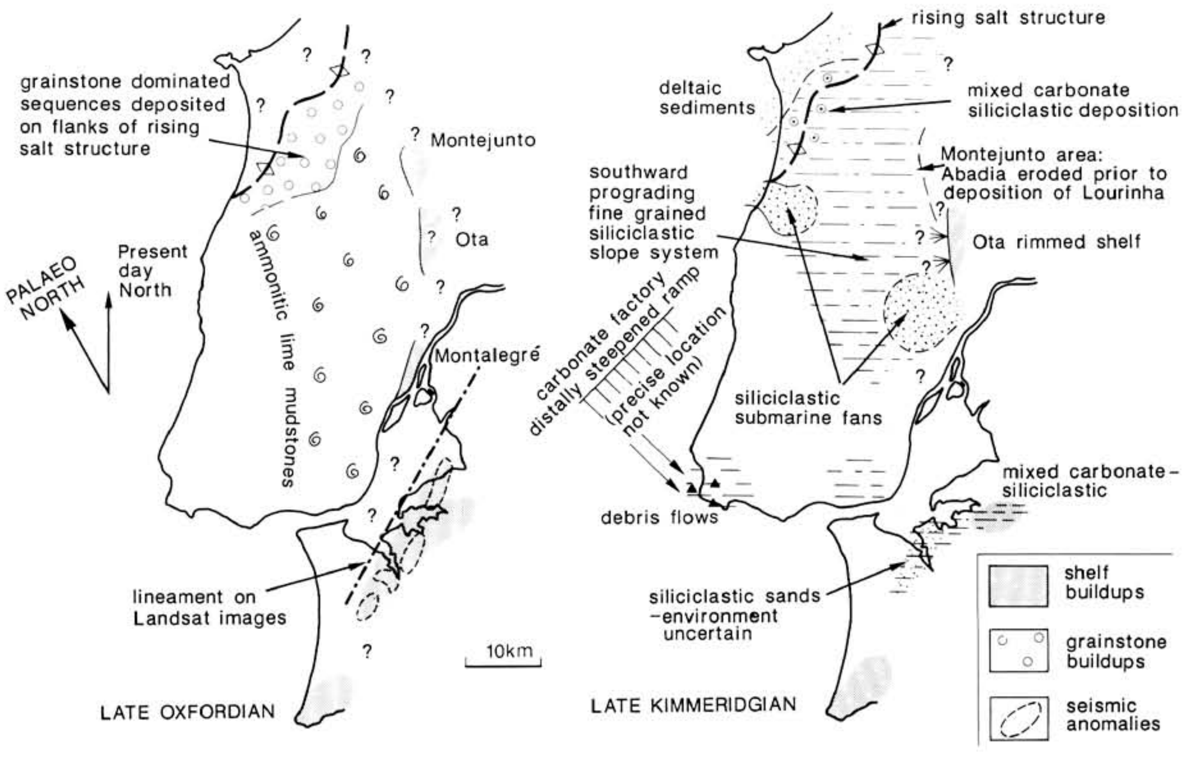

Fig. 21. Sketch maps showing the occurence of carbonate buildups in the southern part of the Lusitanian Basin during the late Oxfordian and late Kimmeridgian.

in a siliciclastic starved part of the basin (Fig. 20).
4 A thin (≈60 m) Upper Kimmeridgian coral biostrome and ooid grainstone developed as a sheet-like cap to the southward prograding slope marls and silts of the Abadia Formation.

The possible controls of the formation and demise of these buildups is now reviewed under the headings of palaeogeography, tectonic setting and sea-level changes.

Palaeogeography

As indicated at the beginning of the paper, during the Late Jurassic the Lusitanian Basin opened southwestwards on to the newly opened southern North Atlantic (see Fig. 1). Therefore the eastern and northern parts of the Basin were likely to have experienced the highest wave energies, as waves approaching from the southwest would have had the opportunity to develop over the longest fetch, indeed along the whole 4–5000 km length of the North Atlantic as it then existed. Thus it seems probable that the southwest margin of the present-day basin, which during the Upper Jurassic faced southeast (see Fig. 20) was the most sheltered, thus explaining the development of the lowest energy carbonate sequence in the Sintra area.

Tectonic setting

The differences between the nature of buildups on the eastern and northwestern margins of the basin during the Oxfordian–Kimmeridgian are clearly related to their tectonic settings. The grainstone-dominated buildups to the northwest developed on the flanks of a rising salt structure, whereas those on the east were bounded on their basinward sides by flexures or faults. For this reason, the eastern buildups, such as Montejunto and Ota, developed good lateral facies zonation patterns, which were unable to migrate laterally because tectonically-controlled shelf break prevented basinward progradation. The subsidence histories of the two settings account for the difference in thickness of the two buildup types (Fig. 22). It is probable that both regions experienced comparable tectonic subsidence during the Upper Jurassic, but in the Ramalhal area this was augmented by salt withdrawal. This effectively added Triassic–Hettangian tectonic subsidence to that occurring during the late Jurassic. Clearly, carbonate sedimentation at Ramalhal was able to keep up with a subsidence rate of some 75 mm yr^{-1} (at least 1500 m of compacted carbonate accumulated during the late Oxfordian timespan of 2 Myr).

Sea-level changes

The eustatic sea-level curve of Haq *et al.* (1987) is plotted on the summary diagram of buildup development presented in Fig. 4. Lack of precision concerning the ages of parts of the Upper Jurassic sections in Portugal means that caution must be exercised in correlating the Haq curve and its associated sequence boundaries with depositional events in the Lusitanian Basin. An additional problem is that during the latest Oxfordian and early Kimmeridgian, parts of the Lusitanian Basin experienced extremely rapid rates of tectonic subsidence which could have obscured effects produced by eustatic sea-level changes (Wilson *et al.*, 1989).

The most significant change of relative sea-level during the late Jurassic in Portugal was the 700 m rise followed by a relative stillstand that permitted the Abadia slope system to prograde southwards and the Mem Martins formation to form as a passive fill. This highstand may correlate with cycles LZA-4.5 of Haq *et al.* (Fig. 4), yet the lower sequence boundary on seismic sections (Fig. 14) appears to be at the base of the Tojeira member, the base of which is situated in the Upper Oxfordian, and so would correlate better with cycle LZA-4.4. Resolution of this problem must await more detailed biostratigraphical studies. It is tempting to suggest that the drowning of buildups and the appearance of resedimented carbonate breccias was synchronous throughout most of the basin and was caused by a combination of latest Oxfordian and earliest Kimmeridgian eustatic and tectonic effects. Throughout much of the Basin, this event was followed by the southwards progradation of siliciclastics of the Abadia formation, but shallow-water carbonate sedimentation continued on salt- and fault-controlled highs.

AN ATLANTIC PERSPECTIVE

The purpose of the final section of the paper is to examine the nature of the carbonate buildups comprising the 'Mesozoic reef trend' beneath the Atlantic continental shelf of North America in the light of conclusions made in Portugal. Despite the very different sizes of the two regions, far more is known

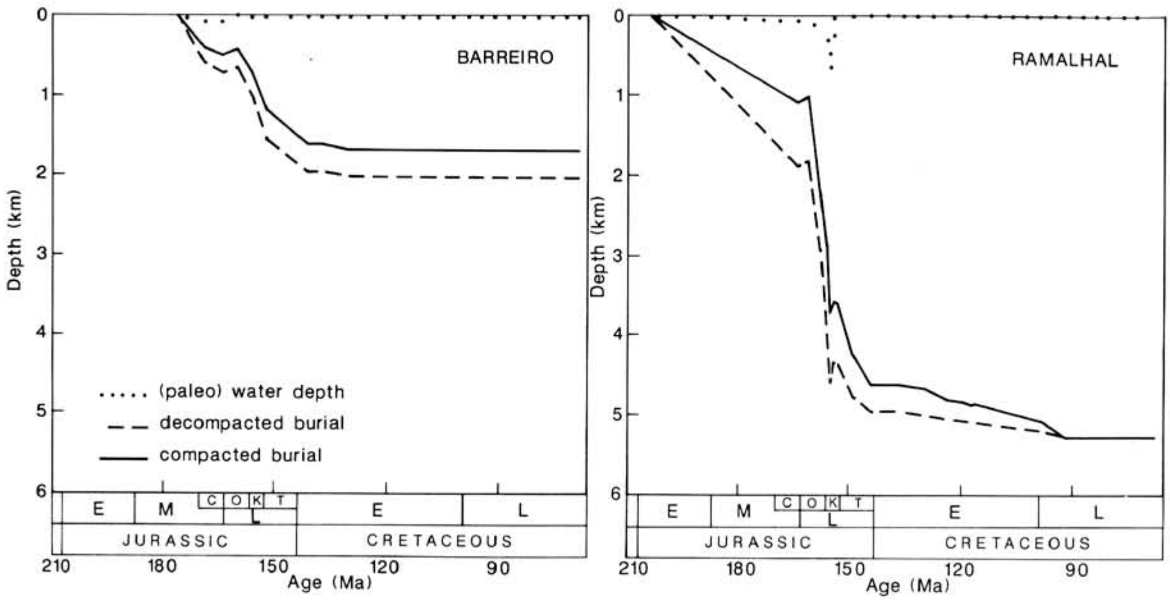

Fig. 22. Burial histories for the Barreiro and Ramalhal areas. That for Barreiro was computed from well data from Barreiro #1, but the well data for Ramalhal was augmented using seismic data below the Upper Jurassic down to the top-Dagorda level, and above the Lourinhã formation using thicknesses from nearby measured sections. Palaeowater depths were estimated from sedimentological and palaeoecological studies.

about the lithological content and lateral facies variation of the Portuguese buildups.

Buildup geometries and settings

A number of carbonate buildups from the North American Atlantic margin have similar cross-sectional geometries and settings to those in Portugal. Fault-controlled shelves analogous to Montejunto and Ota, for example, were identified from the Grand Banks Le Have platform by Jansa (1981). The carbonate ramp of the Mem Martins formation displays similar lithofacies and cross-sectional geometry to sequences cored by Petro-Canada Shell Penobscot L-30 on the Scotian Shelf (Eliuk, 1981; Ellis, 1984: although breccias were not recorded from this Canadian example), while the Amaral Formation has a similar stratigraphic setting to the 'O' marker carbonate of the Grand Banks (Jansa, 1981), for both units overly prograding slope sediments. The majority of the eastern North American Upper Jurassic buildups and those taken to represent the main 'reef trend' (Schlee & Grow, 1982), were located over a rapidly subsiding continental margin and facing the newly-opening ocean. Though this represents a very different setting from

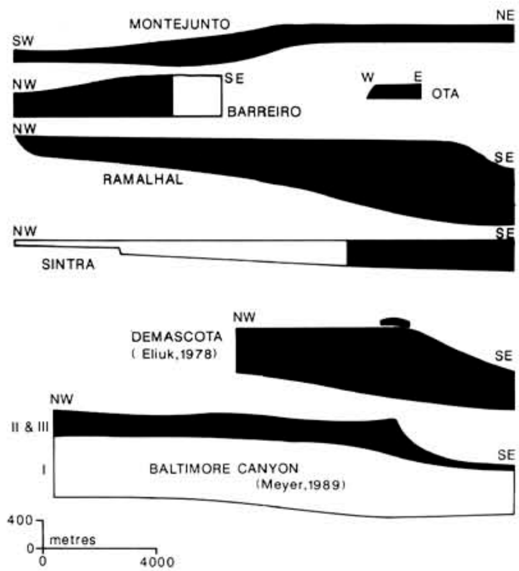

Fig. 23. Comparative cross-sectional geometries of Portuguese and North American buildups discussed in the text. The white areas in the Portuguese examples represent speculative extensions of the buildings not seen at outcrop or penetrated by wells. The white area in the Baltimore Canyon example comprises siliciclastic sediments to the north west, which pass basinwards into carbonates and then into presumed slope deposits.

the Portuguese buildups, they developed comparable thicknesses and geometries to the salt-influenced Ramalhal buildup.

Meyer (1989) recorded three stages in the development of North American Atlantic margin carbonate buildups. The first of these (Stage I) consists of prograding carbonate clinoforms which developed into aggradational carbonate shelves (Stage II). A thin cap of deeper-water carbonates records a drowning event (Stage III). Explanations for the two main styles of buildup growth (Meyer's Stages I and II) vary widely from author to author. Meyer suggested that buildups receiving siliciclastic sediments from the hinterland prograde (Stage I), while those that do not, aggrade (Stage II). Mattick (1982), however, takes exactly the opposite view! Erlich *et al.* (1987), in contrast, postulated a eustatic control, whereby rapid shelf-margin progradation was caused by a sudden short-lived sea-level fall, whereas aggradation was caused by a rapid rise.

Both aggradational and progradational shelves occur within the Upper Jurassic of the Lusitanian Basin as well as a number of examples of drowned buildups, equivalent to Meyer's Stage III and containing similar facies (Ellis *et al.*, 1985). Clastic input played no significant part in the development of these Portuguese buildups, though this does not rule it out as a factor influencing either the position or geometry of the American buildups. In Portugal, aggradational and progradational buildup types developed during the same period of relative sea-level rise. The two buildup geometries in the Lusitanian Basin are linked to local tectonic conditions, rather than differing eustatic sea-level changes.

Facies variation

The nature of the shelf-edge along the North American Atlantic margin has been described as largely reefal, similar to modern reefs (Schlee & Grow, 1982), reefal only in aggradational phases (Mattick, 1982; Erlich *et al.*, 1987; Meyer, 1989), or as a carbonate bank system in which 'oolitic shoals were present near the edge, and skeletal, peloidal wackestones and biomicrites were deposited in the inner part of the platform', where 'coral–stromatoporoid and sponge bioherms were only rare constituents' (Jansa, 1981).

The Nova Scotian shelf has yielded the greatest amount of lithofacies data based on core samples. Eliuk (1978, 1979, 1981) described shelf-break sediments in this region to consist largely of non-skeletal oncolitic grainstones and packstones, with some well-developed coral–stromatoporoid reefs, such as those cored in Shell Demascota G-32 (Fig. 24). Like the Barreiro and Ramalhal buildups from Portugal, this sequence shows a general shallowing-upwards trend, capped by deeper water facies following a drowning event. Eliuk (1978), Jansa *et al.* (1983) and Ellis (1984) agreed that the cored intervals within this well exhibit a true reefal framework, but there was less agreement about the significance of the shallow-water facies in cores 2 and 3.

Deeper-water thrombolitic boundstones, containing the characteristic microfossil *Thartharella*, form much of the lowest core in Demascota. Eliuk envisaged that this passed up into a persistent coral-dominated reefal structure, analogous to modern shelf-edge reefs, building up from the deep-water bioherms into a semi-exposed reef-flat environment. He considered that the presence of red algae (*Solenopora*) also gave a 'modern aspect' to the reef. However, on the basis of electric log data, Jansa *et al.* (1983) and Ellis (1984) suggested that the reefal intervals represented by cores 2 and 3 (Fig. 24) were no more than 15–20 m thick (consisting of coral–chaetitid framestone), and bounded above and below by wackestones and shales. They compared them to Wilson's (1979) 'knoll reefs', which formed in quiet-water conditions at or just below, wave base.

A modern, reef-flat analogy for the Demascota buildup is challenged by two other observations. Firstly, *Solenopora* identified by Eliuk (1978) and likened to red algae in modern reef flats, was re-identified as the milleporid *Milleporidium remesi* by Ellis (1984), who also remarked at the conspicuous lack of binding and encrusting algae within the framework. In Portugal, *Solenopora* only occurs as individual heads within grainstones and packstones and is extremely rare in knoll-reef frameworks. Secondly, the breccias within Demascota core 2 which were considered by Jansa *et al.* (1983) to be reef-flat debris, were interpreted by Ellis (1984) as a diagenetic breccia.

Recent Shell–Amoco–Sun wells drilled in the Baltimore Canyon Trough area also indicate a grainstone and packstone-dominated shelf edge (Erlich *et al.*, 1987) similar to those of the salt-controlled buildup in Portugal. Cores from an eastward prograding clinoform interval penetrated by 0337 Civet (equivalent to Meyer's Stage II buildup) show a similar shallowing-upwards sequence (Fig. 24), from deeper-water wackestones to coral–stromatoporoid

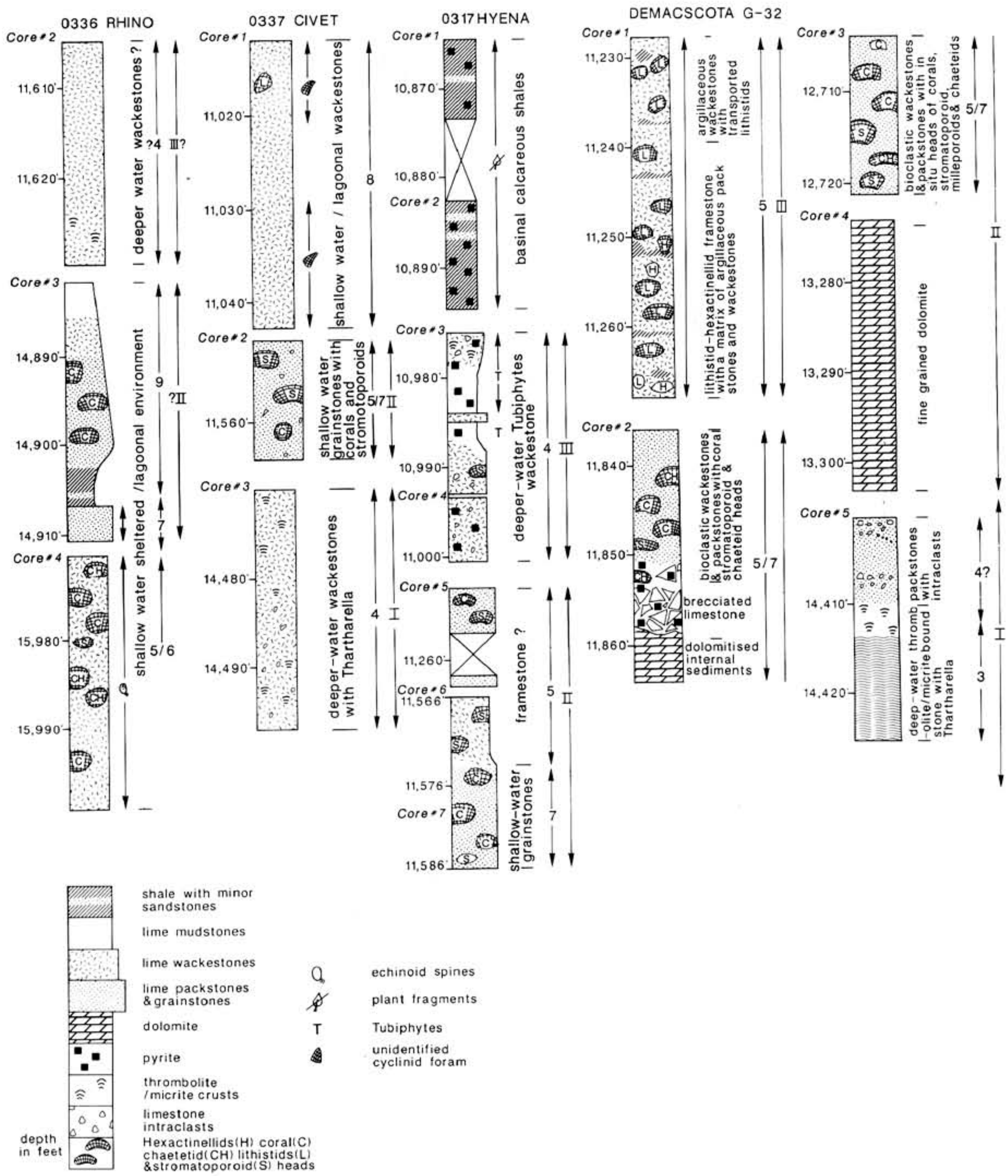

Fig. 24. Summary logs of cores taken in wells drilled into the Upper Jurassic buildups on the North American margin of the North Atlantic. The numbers 1–9 refer to facies associations described in Table 1, and I–III indicate Meyer's (1989) stages of building development.

grainstones. The grainstones exhibit no framestone structure and, in this case, do not have a deeper-water cap. A more argillaceous lagoonal facies (similar to that probably occurring southeast of Barreiro) occurs shelfward from the Civet well in 0336 Rhino (Fig. 24). Only one well was drilled into an aggrading reefal structure (equivalent to Meyer's Stage II). This yielded coral–stromotoporoid grainstones, with a possible true high-energy framestone interval (cores 5 and 6, Fig. 24) and was capped with slightly deeper-water *Tubiphytes* wackestones.

Though core data from the American buildups are sparse, they tend to support Jansa's (1981) idea of a largely grainstone-dominated carbonate shelf edge, with significant shelf-break reefal structures being a relatively rare component. Comparison with the Portuguese buildups supports this conclusion for reefal frameworks are not an important influence on sedimentation, other than the Ota Reef, which was an unusual structure being strongly influenced by a shallow basement fault. In the larger buildup developments of the American seaboard, shelf-break reefs, when they are present, may largely be of the 'knoll-reef' type envisaged for the Demascota buildup. Jansa (1981) suggested that many of the steep carbonate platform edges known from the area might have formed by early submarine lithification and may not be reefal in origin.

The general lack of well-developed coral–stromatoporoid reefs within the high-energy environments of the North Atlantic basin during the Jurassic is surprising in view of James's (1984) conclusion that this was a period of significant reefal growth. It appears that at least in the Atlantic Basin, corals and stromatoporoids were not able to outpace other types of carbonate sedimentation to produce major reef structures. Except where carbonate deposition was strongly controlled by faulting (such as Ota), the evidence available suggests that corals and stromatoporoids were only able to construct smaller-scale knoll-reefs in lower, energy environments such as those in the Portuguese Montejunto buildup and the Canadian Demascota example. Scott (1984) envisaged a similar habitat for coral–stromatoporoid bioherms in the Lower Cretaceous of North America, leaving higher-energy environments free for colonization by rudists.

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