THIRD-ORDER SEQUENCES IN AN UPPER JURASSIC RIFT-RELATED SECOND-ORDER SEQUENCE, CENTRAL LUSITANIAN BASIN, PORTUGAL

REINHOLD R. LEINFELDER

Institut für Paläontologie und Historische Geologie, Ludwig Maximilians Universität, Richard Wagner Strasse 10, D-80333 München, Germany.
E-mail: r.leinfelder@lrz.uni-muenchen.de

AND

R. CHRIS L. WILSON

Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, United Kingdom, MK7 6AA.
E-mail: R.C.L.Wilson@open.ac.uk

ABSTRACT: A Middle Oxfordian to Tithonian transgressive/regressive 2nd-order sequence is recognized over most of the Lusitanian Basin of Portugal. This paper describes the nature of this sequence and its constituent 3rd-order sequences in the Arruda subbasin situated 30 km north of Lisbon. Lack of good outcrops precludes the identification of 3rd-order sequences in the transgressive part of the 2nd-order sequence, but they are easily identified in the regressive part in four different tectonic settings.

The transgressive part of the 2nd-order sequence is related to rift movements that created the subbasin. During rift initiation, carbonate depositional systems dominated. These were drowned during the rift climax phase when footwall uplift caused local erosion and karstification, and the influx of coarse siliciclastic sediments near active faults. 2nd-order maximum flooding occurred during the Late Oxfordian *bimammatum* zone at which time the subbasin was relatively starved of sediment and was a deep depression.

Third-order sequences deposited during the immediate postrift phase (i.e., at the beginning of the 2nd-order regression) are aggradational lowstand arkosic submarine fan deposits. As accommodation was reduced by sedimentation, localized transgressive to highstand reefal carbonates formed on the shallow proximal part of the fan. The late postrift phase was heralded by progradational sequences consisting of lowstand fine-grained slope deposits capped by transgressive/highstand coral boundstones and oolites. These filled the basin virtually to sea level, so that succeeding 3rd-order sequences lacking lowstands developed in shallow, low-energy carbonate and siliciclastic fluvial facies.

Limited biostratigraphic control suggests that the 11 3rd-order sequences may be co-eval with those recognized elsewhere in Europe. If this is correct, the ages of these European sequences suggest that the rift climax event in the Arruda subbasin lasted only 1–2 my, and that subsidence rates approached 2m/ky in the center of the subbasin.

INTRODUCTION

The Middle Oxfordian to Tithonian succession of the central part of the Lusitanian Basin contains several mixed siliciclastic-carbonate associations. These accumulated during extremely rapid rift-related basement subsidence and subsequent slow regional subsidence. This paper shows how the sequence stratigraphic approach provided new perspectives concerning the subsidence history and origin of the complex facies mosaic of one subbasin.

The Arruda subbasin, situated 35 km north of Lisbon, is a half-graben about 20 km wide that developed during the Late Oxfordian/earliest early Kimmeridgian Age (Figs. 1, 2). It was filled by four major depositional systems (Fig. 3): (1) carbonate buildups and associated deep-water sediments (Ellis et al., 1990; Leinfelder, 1994), (2) coarse-grained siliciclastic submarine fan (Leinfelder and Wilson, 1989), (3) southward prograding fine-grained siliciclastic slope capped by carbonates (Ellwood, 1987; Wilson, 1989; Leinfelder and Wilson, 1989; Nose, 1995), and (4) coastal plain and shelf (Leinfelder, 1986, 1987a). The distribution of these systems in space and time was largely controlled by changes in accommodation space caused by tectonism and sediment infilling, resulting in a 2nd-order transgressive/regressive sequence. Third-order sequences are recognized within the 2nd-order sequence in different tectonic settings in the subbasin.

The first section of the paper summarizes the tectonic setting and stratigraphic framework of the Arruda subbasin, after which (in the second section) the nature of the Late Jurassic transgressive/regressive 2nd-order sequence that fills it is discussed. The seismic and sedimentologic features of the rift initiation, rift climax, immediate postrift and late postrift phases of the subbasin's development are documented. The third section of the paper describes the nature of 3rd-order sequences

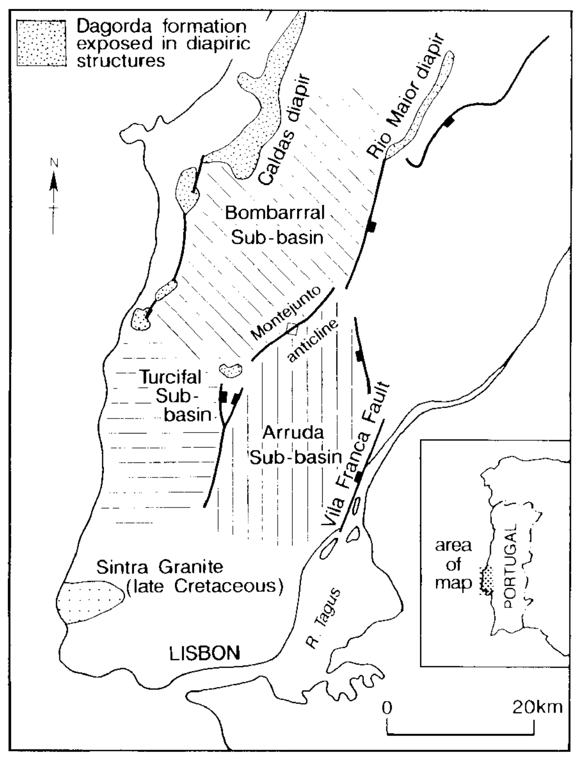

FIG. 1.—Sketch map of the central part of the Lusitanian Basin showing the location of Late Jurassic subbasins. Note that faults north of the Montejunto anticline are reversed due to Miocene inversion.

Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, SEPM Special Publication No. 60

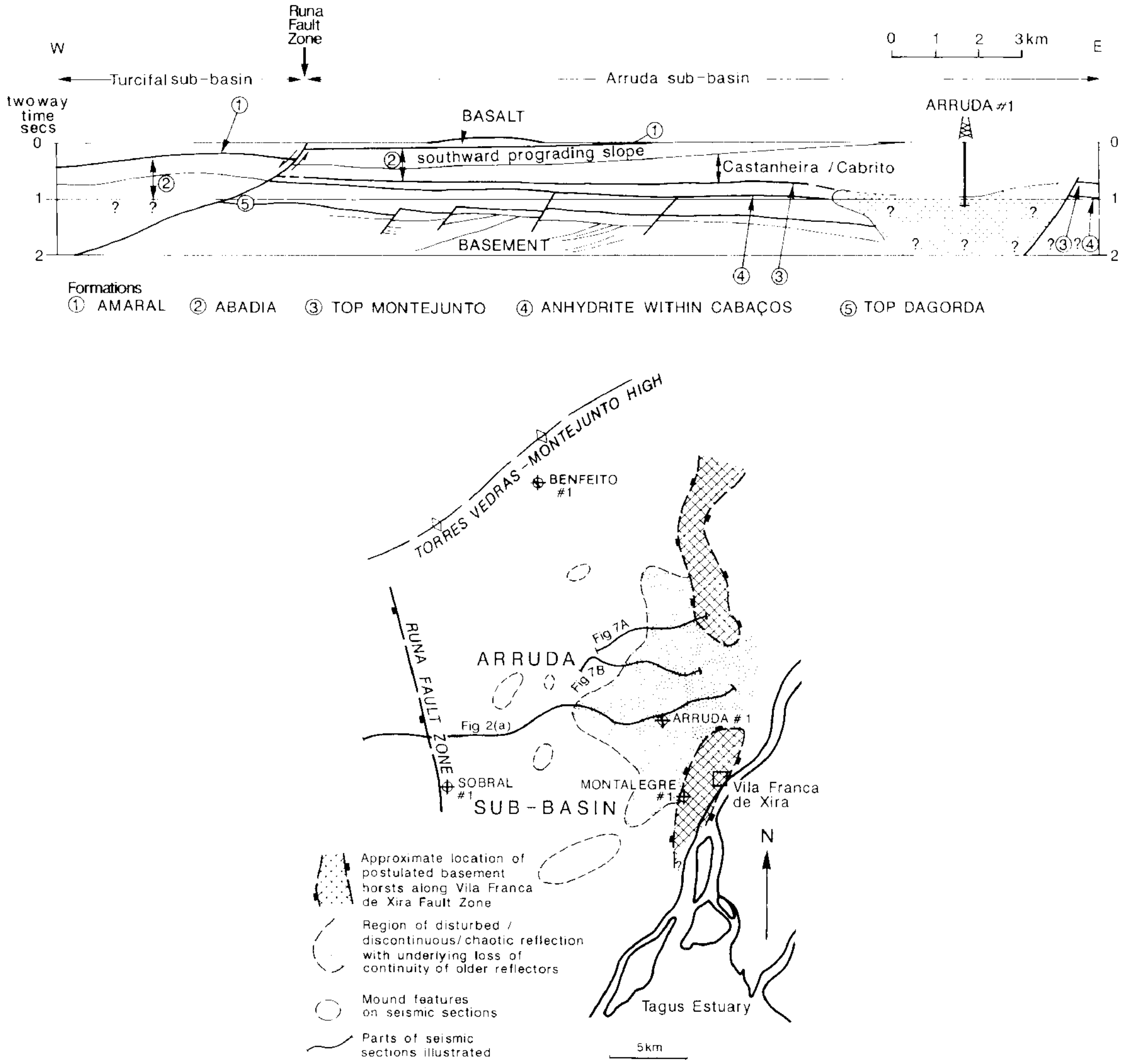

FIG. 2.—The structure of the Arruda subbasin. (A) Interpretation of west-east seismic line showing the half graben geometry of the Arruda subbasin. For ages of reflectors, see Fig. 5. (B) Sketch map showing the location of seismic line (A) and those shown in Fig. 7. The tectonic structures bordering the subbasin and the location of the Castanheira member submarine fan system described by Leinfelder and Wilson (1989) is also shown.

that occur in the regressive part of the 2nd-order sequence in four distinct tectonic settings within the subbasin. In light of the probable correlation between the 3rd-order sequences in the four tectonic settings, the final section of the paper discusses the timing of rifting and possible correlation with sequences recognized elsewhere in Europe.

GEOLOGICAL FRAMEWORK

Tectonic Setting

Three subbasins occur in the central part of the Lusitanian Basin to the north of Lisbon (Fig. 1). They began to develop during the mid-Oxfordian and probably ceased to exist as separate subbasins by the end of the Late Jurassic Epoch. Wilson et al. (1989) suggested that the transtensional rifting episode that created them was the precursor to Late Jurassic ocean spreading in the Tagus Abyssal Plain to the west.

The half-graben structure of the Arruda subbasin is known largely from seismic data (Fig. 2A). It is separated from the Bombarral subbasin by a saddle formed by the Torres Vedras-Montejunto anticline. This anticline (Fig. 2B) was initiated during the Late Jurassic as a salt pillow structure that was further deformed by Miocene transpressional movements (Wilson et al., 1989). The west side of the subbasin is bounded by the Runa fault zone, the northern sector of which consists of a graben in which Upper Cretaceous sediments and volcanics are preserved (Fig. 4). On seismic lines, this zone is seen to be underlain by a major westward-dipping normal fault that forms the eastern margin of the Turcifal subbasin. A piercement diapir occurs at the north end of the fault zone. The eastern margin of the subbasin is a complex zone consisting of two horsts separated by a probable transfer zone. Miocene inversion produced a broad low-amplitude domal structure (the Arruda anticline, the crest of which is situated in the area around Arruda #1) above the thick fill of Upper Jurassic sediments. The location of the southern limit of the subbasin is unknown, because no seismic data have been shot in this area.

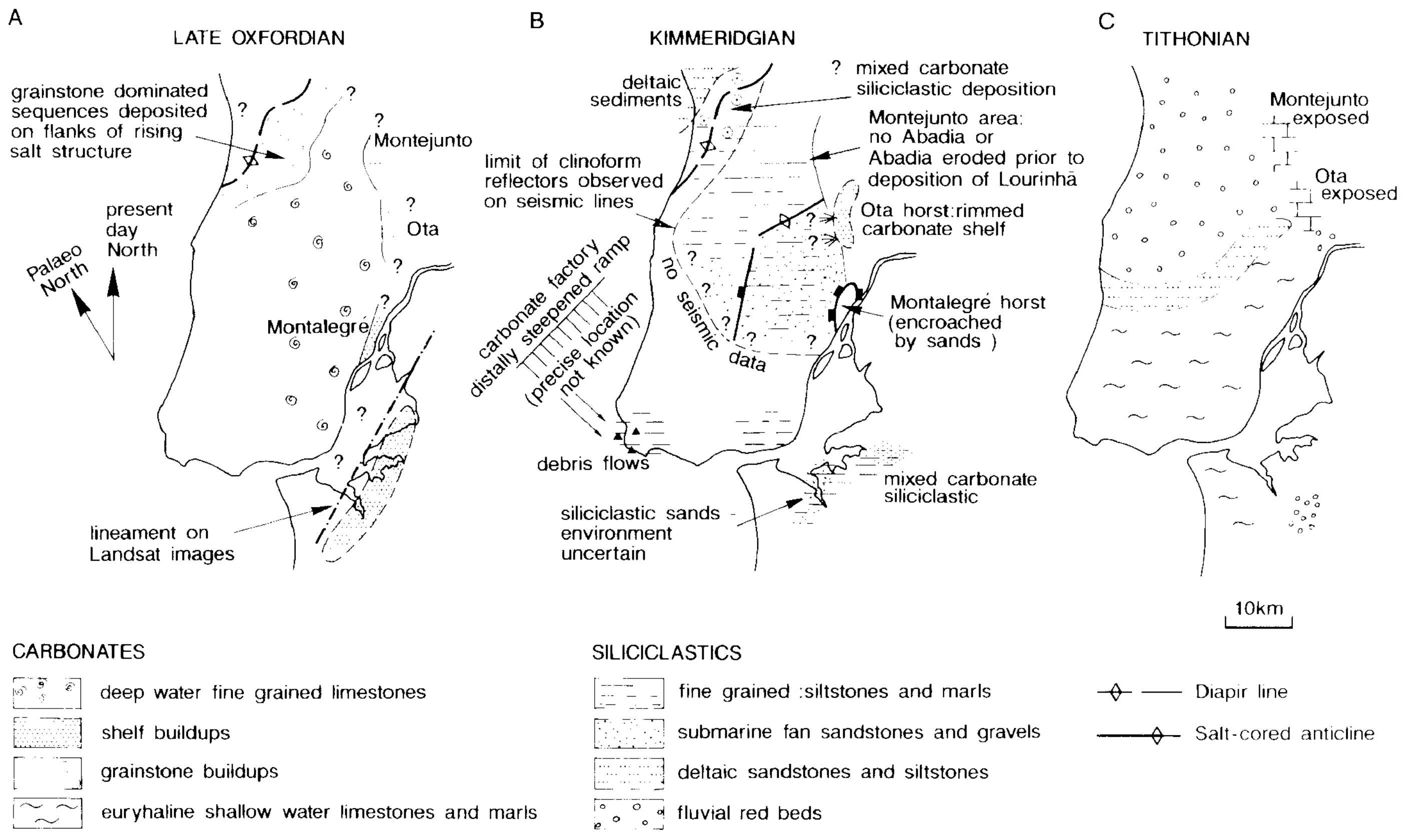

FIG. 3. The distribution in time and space of the four major depositional systems that filled the Late Jurassic subbasins of the central part of the Lusitanian Basin (modified from Ellis et al., 1990; Leinfelder, 1987a). (A) Late Oxfordian (Montejunto formation): shallow-water carbonate buildups formed on structural highs (salt pillows to northwest, and fault-related on east side of the basin) (B) Kimmeridgian: siliciclastic sedimentation dominated, with a submarine fan system building westwards from a gap in the hangingwall of the eastern boundary fault system of the Arruda subbasin (Castanheira member of the Abadia formation). The area of clinoform reflectors was formed by a southward prograding siliciclastic slope system (un-named top part of Abadia formation) overlain by shallow water shelf carbonates (Amaral formation). In the western part of the Arruda subbasin, fan and slope deposition were contemporaneous. The Ota carbonate buildup is contemporaneous with the top of the fan and the prograding slope. (C) Tithonian: fluvial sediments sourced from the north (Lourinhã formation) interfinger to the south with shelf carbonate and marls (Farta Pão formation).

Stratigraphy

Wilson et al. (1989) recognized four megasequences in the Mesozoic succession of the Lusitanian Basin and linked them as follows to events in the opening of the Atlantic:

4	Late Aptian Campanian	Ocean spreading around west and north Iberian margins.
3	Valanginian—Early Aptian	Rifting around north and northwest Iberia
2	Middle Oxfordian—Early Berriasian	Rifting, and ocean spreading beneath the Tagus abyssal plain.
1	Triassic—Callovian	Triassic rifting and later thermal subsidence, but no ocean opening.

Figure 5 shows the lithostratigraphic units within the second and part of the third megasequence that are discussed in this paper. During the Triassic and earliest Jurassic periods, movements along Hercynian basement faults produced basins that were filled with red siliciclastics (Silves formation*) and evaporites (Dagorda formation). The latter are relatively thin in the study area but, to the north beneath the Bombarral subbasin, were thick enough to be mobilized to produce salt structures (Fig. 1). The Triassic and Hettangian sediments accumulated in grabens and half-grabens, but the younger Lower and Middle Jurassic sediments (Brenha and Candeeiros formations) blanketed the entire Lusitanian Basin and exhibit simple facies geometries indicative of a westerly inclined carbonate ramp system.

The early part of the second megasequence is characterized by extremely high apparent basement subsidence rates (Wilson et al., 1989) and (apart from the basal Cabaços formation) major lateral changes in facies (Figs. 3A,B). Its base is marked by a basin-wide hiatus spanning latest Callovian to Early Oxfordian time. The rest of the second megasequence is described in the next section of the paper. Megasequence 3 shows a relatively simple facies distribution, with dominantly fluvial siliciclastics of the Torres Vedras formation interfingering southwards and westwards with the marine carbonates of the Cascais formation (Fig. 5).

2ND-ORDER SEQUENCE

Introduction

After a brief review of the Upper Jurassic stratigraphy of the Arruda subbasin, the evidence for its tectonic and sedimentary

*The Term 'formation' is not shown with a capital 'f' in this text, as the stratigraphic scheme shown in Figure 5 is informal.

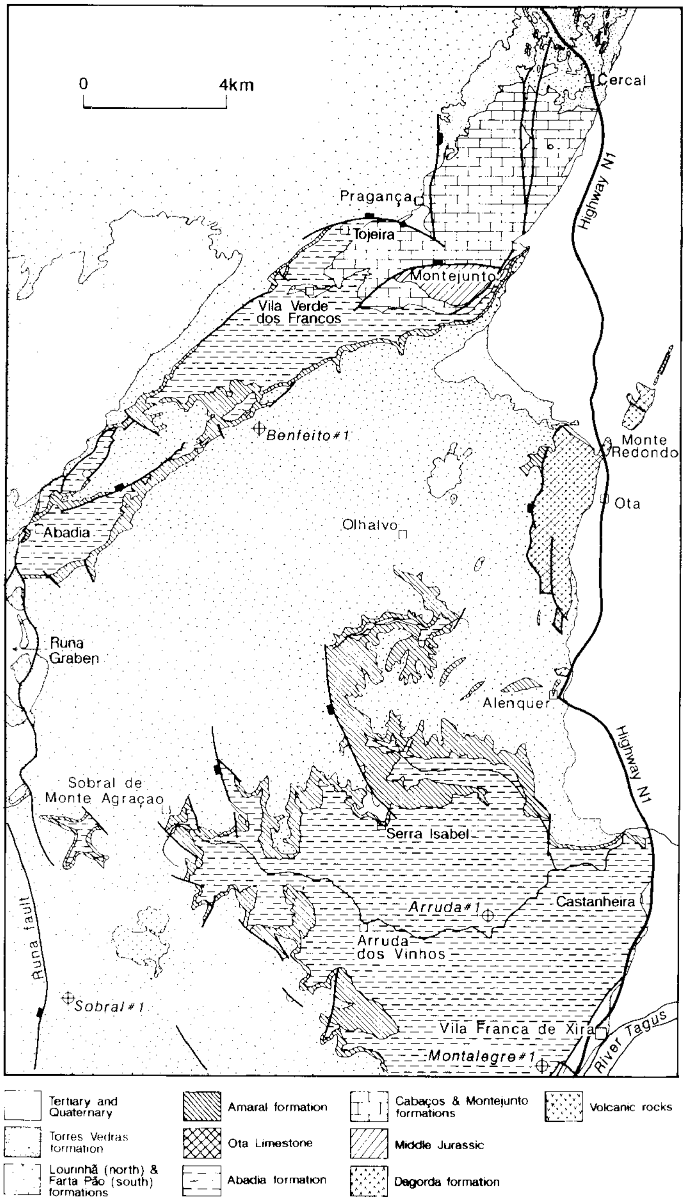

FIG. 4.—Geological map of the Arruda subbasin showing the localities and boreholes referred to in the text.

history is described in detail, and interpreted in terms of tectonic systems tracts defined by Prosser (1993). The former part of this section of the paper provides a brief summary of the late, Jurassic tectono-sedimentary history of the subbasin. Figure 6 shows the relationships between the lithostratigraphic units that comprise the transgressive/regressive upper Jurassic sedimentary fill of the Arruda subbasin.

In many places in the Lusitanian Basin, the top of the Middle Jurassic succession is marked by karstification, rubification and caliche formation (Felber et al., 1982; Leinfelder, 1983; Ruget Perrot, 1961; Wright and Wilson, 1987). The period of exposure indicated by these features is linked to the presumed hiatus extending from the topmost part of the Callovian to the top of the Lower Oxfordian. This hiatus, the increased subsidence rates during the Oxfordian and early Kimmeridgian Stages compared with those during the Early and Middle Jurassic Epochs, and the change from shelf carbonates at the top of the Middle Jurassic formation to lacustrine/marginal marine carbonates of the Cabaços formation, all indicate a significant change in the tectonic framework of the Lusitanian Basin (Wilson et al., 1989).

Lacustrine and marginal marine carbonates of the Cabaços formation were deposited over the entire Lusitanian Basin during early Middle Oxfordian time. Thickness variations of this formation and the overlying marine carbonates of the Montejunto formation show that differential subsidence resulted in the formation of separate subbasins. Rapid deepening occurred over much of the Arruda subbasin during the deposition of the Montejunto formation, except along its eastern margin where shallow water carbonate buildups formed (Fig. 3A).

There was a sudden influx of siliciclastic material all over the Lusitanian Basin during the Late Oxfordian *bimammatum* zone. In the Montejunto area on the northwest flank of the Arruda subbasin, this change occurs at the boundary between the Montejunto formation and the Tojeira member of the Abadia formation. Foraminiferal evidence suggests that the greatest water depths occurred during deposition of the Tojeira member (Stam, 1985), suggesting that the 2nd-order maximum flooding event occurred during the *bimammatum* zone.

The bulk of the sedimentary fill of the Arruda subbasin consists of the Castanheira member, which reaches a thickness of over 2 km beneath Arruda dos Vinhos. The lateral equivalent of this unit in the Montejunto area is the Mirante member, which is only about 50 m thick. Both members consist of arkosic sandstones and gravels.

The uppermost unnamed member of the Abadia formation consists of siliclastic mudstones, shales and siltstones with subsidiary sandstones. On seismic sections, it corresponds to a clinoform reflection package (Wilson, 1989; Leinfelder and Wilson et al., 1989) indicating southward progradation of a slope

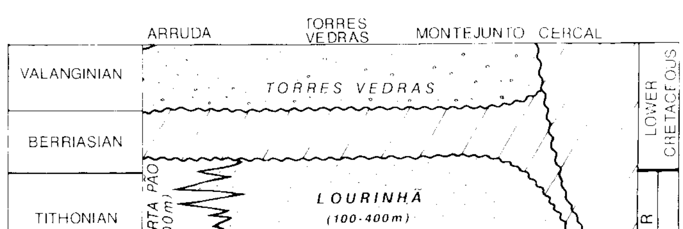

FIG. 5.—Upper Triassic, Jurassic and lowermost Cretaceous stratigraphic summary chart of the Arruda subbasin. The lithostratigraphic nomenclature is informal; formations are shown in capitals and members in lower case. R indicates main rifting episodes.

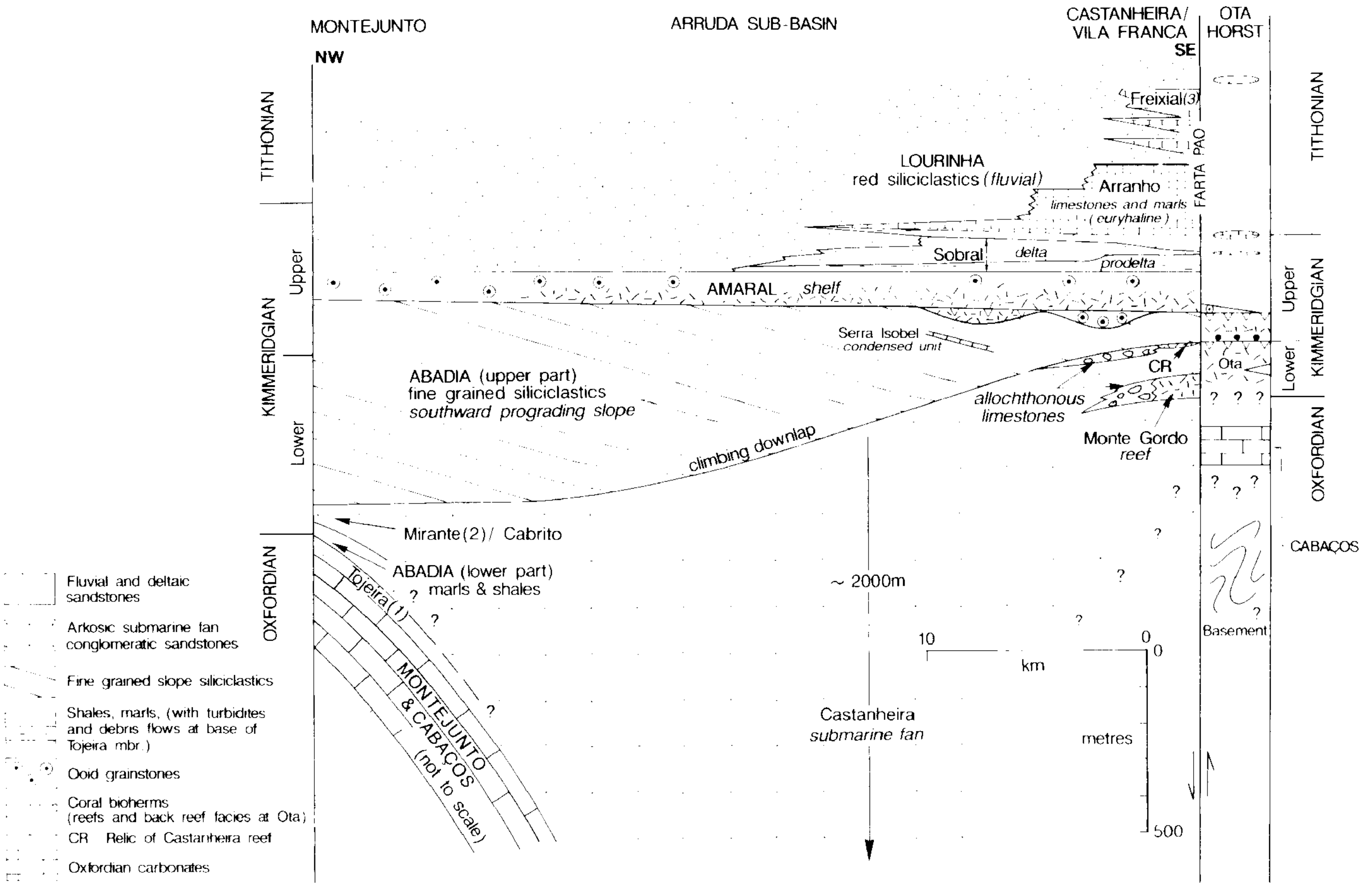

FIG. 6. Lithostratigraphic cross section showing the nature of the 2nd-order transgressive-regressive sedimentary fill of the Arruda subbasin. The nomenclature is informal: formations are shown in capitals, and members in lower case. Text in italics indicates depositional environment. (1): marls with siliciclastic and carbonate turbidites and debris flows with allochthonous shallow water karstified limestone blocks (~80 m); (2): sandstones and conglomerates with limestone clasts (10–30 m) in north-south channel ~3.5 km wide; (3): euryhaline limestones and marls; CR: relic of Castanheira reef.

system. Along the north and western flanks of the Arruda subbasin, this unit is about 550 m thick, but thins south-eastwards to about 60 m near Castanheira. The Abadia formation is capped by shallow-water shelf carbonates of the Amaral formation.

The progradation of the Abadia-Amaral slope/shelf system was the last episode of dominant marine deposition, after which a mixed fluvio-deltaic shelf system (Lourinhã and Farta Pão formations) prograded southwards (Fig. 3C).

Tectonic Systems Tracts

Prosser (1993) described how seismic reflection configurations and facies characteristics of rift basin fills are related to tectonic rather than eustatic controls. She described such linked depositional systems as tectonic systems tracts and recognized four types: rift initiation, rift climax, immediate postrift and late postrift. Highlighting the potential for subsidence to outpace sedimentation to cause transgression and a reduction of sediment influx, she suggested that many workers have probably over-estimated the amount of truly synrift sediments present in basins. She argued that because the size of drainage basins "is critical in determining the rate of sediment input, it is probable that during early rifting, preexisting large drainage basins will be fragmented, resulting in low sediment input." Only when rifting ceases will large drainage basins be established that are related to the recently developed fault-controlled topography, and the 'holes' left by rifting will be filled with coarse-grained sediments.

Our work indicates that the sedimentary fill of the Arruda subbasin exhibits many of the characteristic features described for rift basins by Prosser (1993), allowing for the following characteristics that are not encompassed by her model. (1) carbonates formed the first phase of the basin fill, (2) the growth of the salt pillow beneath the present-day Torres Vedras-Montejunto anticline caused reflector convergence onto this structure, and (3) there is no evidence for the derivation of sediments from the hanging wall of the Arruda half-graben.

As will be shown in the final section of the paper, integrating the 3rd-order sequence stratigraphy with Prosser's (1993) tectonic systems tract model suggests that the period of rifting was relatively short (1–2 my) in the Arruda subbasin.

Rift Initiation

During rift initiation, movements on basin boundary faults result in "a depression in the crust's surface" (Prosser, 1993) but no significant fault scarps. Continued movement will result in wedge-shaped seismic packages. In the Lusitanian Basin, such movements resulted in a radical reorganization of the distribution of carbonate depositional systems, from a prerift westward-dipping ramp to buildups forming over fault or diapirically controlled highs during rift initiation.

On seismic sections across the Arruda subbasin, the Oxfordian carbonates thicken towards the southeast and east due to movement along the eastern boundary fault complex, and the growth of a salt pillow beneath the present day Montejunto-Torres Vedras anticline. Such thickening is characteristic of the rift initiation and rift climax phases of Prosser (1993). However, as the sedimentary record shows no evidence of either significant subaerial exposure or the erosion of the thick argillaceous and carbonate-rich Lower and Middle Jurassic formations, the carbonate deposition is interpreted to represent rift initiation rather than rift climax.

Ellis et al. (1990) and Leinfelder (1994) recognized several types of buildups in the Lusitanian Basin, based on their facies characteristics and tectonic setting. 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 lesser amounts of packstones, grainstones and boundstones. In the Arruda subbasin, buildups of this type occur along its eastern margin from Montejunto in the north (late Oxfordian, possibly extending into the early Kimmeridgian), to the south at Ota (Kimmeridgian) and in the subsurface in Montalegre #1 (late Oxfordian). In the western Montejunto area, basinal deep-water lateral equivalents are exposed and were encountered in Benfeito #1 and Sobral #1 (for locations of these boreholes, see Figs. 2B, 4), and they are presumed to extend beneath the entire subbasin. There are no occurrences of the salt-controlled buildups described by Ellis et al. (1990) in the study area.

The lacustrine marginal marine Cabaços formation and deep-water part of the Montejunto formation show semi-continuous low-amplitude reflections that diverge towards the center of the Arruda subbasin. The strong double reflector at the base of this reflection package (Fig. 7) is caused by a mixed anhydrite/carbonate unit in the lower part of the predominantly lacustrine Cabaços formation. At the eastern margin of the subbasin, there is an area of chaotic reflections (Fig. 7A) that Leinfelder and Wilson (1989) interpreted as being caused by the massive coarse-grained facies in the proximal part of the Castanheira fan (Fig. 2B). On most seismic lines, the anhydrite and top Montejunto reflectors fade out into the chaotic zone (Fig. 7B), which suggests that seismic energy is dissipated by the overlying proximal fan facies of the Castanheira member of the Abadia formation.

After the episode of emergence that resulted in the late Callovian—early Oxfordian age hiatus, relative sea-level then rose sufficiently to produce the lacustrine and marginal marine conditions in which the Cabaços formation was deposited. Accommodation then increased rapidly so that hemipelagic carbonates of the Montejunto formation were deposited over most of the subbasin. However, in the northern part of the eastern boundary fault complex in the east of the Montejunto area, a carbonate buildup developed over the footwall (Ellis et al., 1990). It is probable that faults did not break through to the surface at this time (as no coarse carbonate slope deposits indicative of exposed scarps are present), but that fault-tip folds produced depositional profiles upon which shallow-water carbonate buildups could develop over the higher fold limb.

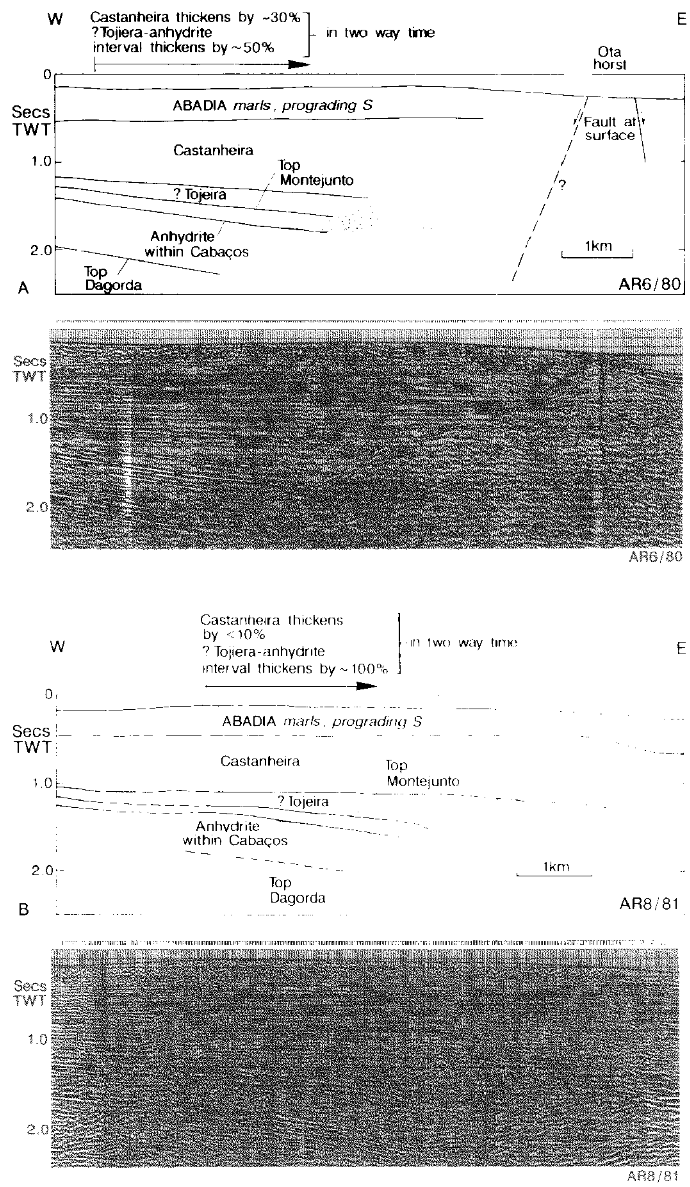

FIG. 7.—West-east seismic lines across the eastern margin of the Arruda subbasin, showing sediment thickening towards the eastern boundary fault complex. The percentage increases shown relate to two way time and not actual sediment thickness. The stippled areas are zones of chaotic reflectors interpreted by Leinfelder and Wilson (1989) as the proximal massive coarse-grained facies of the Castanheira submarine fan. For location of the two seismic lines, see Fig. 2B.

Rift Climax

During the rift climax phase, the maximum rate of fault displacement occurs, and "so sedimentation is likely to be outpaced by subsidence and differential relief will be created across the fault scarp" (Prosser, 1993). During this phase, basins are likely to be sediment-starved, as rates of subsidence are very high compared to erosion and new drainage systems have not become established.

In the Arruda subbasin, the sedimentological features of the Tojeira member indicate that it was deposited during the rift climax phase. It is only exposed in the Montejunto area, where it spans the upper part of the *bimammatum* zone and the *planula* zone of the late Oxfordian (Atrops and Marques, 1986, 1988). The member consists of an alternation of marls and thin (up to 50 cm) turbidites composed of arkosic and carbonate sand. Bedded micritic ammonite-bearing limestones similar to those of the Montejunto formation are present in places. Occasional debris flow units also occur, not only containing siliciclastic pebbles and sand, but also allochthonous shallow-water carbonate blocks up to house size, some of which exhibit karstification. The shedding of large blocks of karstified shallow-water carbonates suggests significant footwall uplift causing subaerial diagenesis and erosion. For the first time since Late Triassic time, coarse-grained Hercynian basement material appears in sediments, suggesting that it was exposed in nearby footwall blocks.

On seismic sections, the interval interpreted to be the lateral equivalent of the Tojeira member thickens significantly towards the eastern boundary fault zone (Fig. 7), which together with the observed sedimentological features described above, is consistent with the interpretation that it represents the rift climax systems tract.

Immediate Postrift

At the immediate postrift stage in rift basin development, differential subsidence across boundary faults ceases, but the basin continues to subside due to lithospheric cooling. Prosser (1993) suggested that this phase of basin development is characterized by a change from divergent to parallel reflections as fault-block tilting ceases and that this is accompanied by strong onlap updip on the hanging wall and possible downlap in the center of the basin.

Relatively continuous high-amplitude reflections showing convergence towards the western and northwestern margins of the Arruda subbasin characterize the arkosic sands and gravels of the Castanheira member. Some onlap is seen at the base of this reflector package on the southeastern flank of the Torres Vedras-Montejunto anticline. In the Arruda subbasin, seismic sections do not show a marked change from a divergent to nondivergent reflection package characteristic of the rift-climax to immediate postrift transition. However, there is a significant change in the degree of divergence (Fig. 7) that probably occurs (it has not been drilled) at or near the base of the arkosic sands of the Castanheira member. The divergent reflection pattern in the immediate postrift systems tract shown on Fig. 7 is interpreted as being due in part to the growth of a salt pillow beneath the present day Montejunto-Torres Vedras anticline and to thinning of sediments away from the source of the submarine fan across the probable transfer zone within the eastern boundary fault zone. Therefore, there is both a halokinetic and sedimentary overprint on the seismic character of the immediate postrift systems tract.

On the eastern margin of the Arruda subbasin, about 350 m of coarse arkosic sandstones and conglomerates of the top part of the Castanheira member are exposed. A total minimum thickness of 2200 m was proved by Arruda #1, which did not penetrate the base of the member. The sandstones contain pebbles and cobbles of granite, gneiss, slate, quartzite and vein quartz, and in places carbonate clasts occur. The massive structureless sediments sometimes contain large reefal blocks. Claystone boulders up to 8 m across also occur in which the original bedding is sometimes orientated vertically. These features indicate deposition by debris flows. In the finer facies, amalgamated channels occur, showing fining-upward trends; these suggest deposition from turbiditic flows. Fine-grained shaly intervals in the cores from Arruda #1 contain marine palynomorphs. Evidence from cores suggests an overall coarsening-upward trend. The ammonite *Ardescia pseudolictor*, found at outcrop near the top of the member, indicates a middle early Kimmeridgian age (middle part of *hypselocyclum* zone, Leinfelder, 1994).

On the basis of outcrop, borehole, and seismic data, Leinfelder and Wilson (1989) interpreted the Castanheira member as a submarine fan supplied with sediment through a gap in the eastern boundary fault complex (Fig. 2B). The zone of chaotic reflections on the eastern margin of the subbasin was interpreted by them to be caused by the proximal massive and coarse-grained part of the fan system.

Late Postrift

Prosser (1993) stated that the late postrift systems tract is the result of the continued peneplanation of topography caused by faulting and further filling of accommodation space formed by earlier tectonism. Parallel reflections are likely, though they may show some divergence towards the basin center due to compaction of previously deposited sediments. Erosion of fault block crests may result in the development of fining-up sequences, and eustatic sea-level changes are now more likely to control sediment input rates and change the amount of accommodation available.

The top part of the Castanheira member shows a fining-up trend, and contains two reefal intervals related to 3rd-order sequences (see below) that is identified as the basal late postrift systems tract. The uppermost unnamed part of the Abadia formation, the Ota limestone and Amaral, Lourinhã and Farta Pão formations, represent the remainder of this tract.

The Ota limestone cannot be distinguished on seismic sections, because a zone of chaotic reflections (typical of seismic data in many places in the Lusitanian Basin where thick carbonates occur at or near the surface) characterizes the horst zone. It is contemporaneous with the upper part of the Castanheira member and the prograding top part of the Abadia formation (Ellis et al., 1990; Leinfelder et al., 1988; Leinfelder and Wilson, 1989). It developed as a narrow reef-rimmed platform on a horst on the eastern margin of the Arruda subbasin (Leinfelder and Wilson, 1989; Leinfelder, 1992, 1994). The aggradational geometry of the platform and its facies zonation are the result of its growth on top of the a horst formed during earlier rifting. No reef talus or deeper-water sediments are exposed; they are presumed to have developed at the foot of the fault scarp and, if present, are now buried by, or interfinger with, the Castanheira and uppermost members of the Abadia formation. The Ota limestone represents the immediate postrift systems tract developed in a siliciclastic-starved setting above the footwall on the northern segment of the Arruda subbasin boundary fault system.

The southward-prograding clinoforms seen on seismic sections (Wilson, 1989; Leinfelder and Wilson, 1989) show clearly that the siltstones and marls comprising the uppermost unnamed member of the Abadia formation were deposited in a prograding slope setting. The presence of turbiditic sandstones, slump horizons, mud pebble breccia beds and resedimented ooid grainstones seen at outcrop are consistent with this interpretation. Occasional higher-amplitude reflections can be traced downdip into the continuous high-amplitude reflections of the underlying submarine fan deposits of the Castanheira member. The transition between the two seismic facies units occurs at successively higher reflections in the older package, so that as the clinoform unit thins southwards, it exhibits a kind of "climbing downlap" relationship with the underlying unit. This indicates that the submarine fan system (sourced from the east) continued to be deposited as the slope system prograded southwards.

Outcrop and well data show that the slope and shelf sediments extend over much of the central part of the Lusitanian Basin. In the Bombarral and Turcifal subbasins and along the northern and eastern margins of the Arruda subbasin, these sediments are about 550 m thick/ but thin to 60 m in the vicinity of Castanheira, due presumably to lateral replacement by the Castanheira member. Unlike the deposits of the first two depositional systems, they do not show significant thickness changes over major tectonic structures, except in the northern part of the eastern boundary fault complex, where they are replaced by the Ota limestone.

Throughout the southern part of the Lusitanian Basin the Amaral formation is recognizable on seismic sections as a strong reflection capping the clinoform reflection package at the top of the Abadia formation. It was deposited in a shallow high-energy shelf setting on top of the southward-prograding marls and siltstones. In the Arruda subbasin, the Amaral formation contains lenses of coral boundstones (some of which are thrombolitic) overlain by ooid grainstones (Leinfelder et al., 1993b; Nose, 1995). Patches of grainstones that occur above the karstified top of the Ota limestone are relics of the Amaral formation (Leinfelder, 1994). This is the earliest occurrence of a lithostratigraphic unit extending from the Arruda subbasin across onto the hangingwall of the boundary fault system. This indicates that the basin was "full" and beginning to overflow across its eastern margin and that the depositional profile was no longer related to topography produced during the rift climax phase. However, the effects of differential compaction across the fault resulted in the Ota block remaining slightly higher during the deposition of the Lourinhã and Farta Pão formations (Leinfelder, 1985).

The prograding slope and shelf system is overlain by mostly red siliciclastic fluvial deposits of the Lourinhã formation (Hill, 1989). Only at the base are deltaic sediments present (Sobral member) that are probably latest Kimmeridgian in age (Leinfelder, 1986), possibly extending into the earliest Tithonian (Manuppella, pers. comm. 1994). Immediately to the east of the Ota platform, freshwater oncoid horizons occur that formed in spring-fed streams and lakes (Leinfelder, 1985). The Arranhó member of the Farta Pão formation consists of limestones and marls with a rich fauna of euryhaline to partially brackish bivalves in the lower part and coral biostromes in its upper part. The Arranhó member occurs only in the southern part of the Arruda subbasin. The overlying Freixial member also consists of limestones, marls and sandstones with a euryhaline to brackish fauna (Leinfelder, 1986, 1987a).

The Lourinhã and Farta Pão formations are situated near the surface over most of the Arruda subbasin, so that their true seismic characters usually are not well recorded. Where clear reflection characteristics of the Lourinhã formation can be discerned, moderate to strong parallel discontinuous reflectors occur, consistent with the presence of fluvial or deltaic sand bodies of limited lateral extent.

The relatively simple facies relationships in the Lourinhã and Farta Pão formations, with fluvial sediments being replaced southwards by marine limestones and marls, contrasts with the complexity of earlier facies distributions in the subbasin. This simple pattern, which extends across the Lusitanian Basin to the present-day coastline, indicates that by Tithonian time, depositional profiles were no longer linked to rift-related subsidence or topography.

Summary of Tectono-Sedimentary History

The transgressive/regressive 2nd-order sequence of the Arruda subbasin was produced by a combination of rapid rates of subsidence during the late Middle and Late Oxfordian rift initiation and rift climax episodes and the subsequent reduction of accommodation space by sedimentation.

The nature and location of the depositional systems that filled the subbasin were controlled by the topography produced during rifting and later erosion and burial as new drainage systems were established. During initial rifting, differential subsidence across faults was not sufficient to cause exposure above sea level, but it did result in the deposition of aggradational carbonate buildups along the eastern margin of the subbasin. Strong relief was produced during the rift climax, but only the crests of hanging walls were emergent or covered by shallow-marine water, after which the subbasin was a large depression waiting to be filled once new drainage systems had developed. During the immediate postrift phase, coarse-grained sediment was transported via a transfer zone in its eastern boundary fault zone by high-density turbidity flows. The final filling of the subbasin virtually to base-level was accomplished by a southward-prograding fine-grained slope-shelf system that in terms of Eliet and Gawthorpe's (1995) drainage domains, was axial. By middle late Kimmeridgian times, the accommodation space created during the rifting episode and later subsidence caused by sediment loading and/or lithospheric cooling had virtually been eliminated, and so the remainder of the subbasin fill was deposited in fluvial (axial) and shelf settings. The footwall and hangingwall drainage domains of Eliet and Gawthorpe (1995) were not developed, though their fifth, karst, domain probably developed over a small area associated with the Ota platform.

The rift initiation and climax phases of development of the Arruda subbasin represent the transgressive phase. Foraminiferal studies (Stam, 1985) suggest that deepest water conditions are represented by the Tojeira formation, in which case the 2nd-order maximum flooding surface occurs within the *bimammatum* zone.

The following episodes in the tectono-sedimentary history of the Arruda subbasin can be distinguished (see Table 1 for a summary of these).

Rift Initiation (Cabaços and Montejunto formations).—

Regional uplift resulted in the late Callovian-Early Oxfordian hiatus. Later fault movements in the basement produced flexures in the overlying Triassic-Middle Jurassic cover, which in places triggered salt migration. This lead to the development of subbasins and shallow-water carbonate buildups on the elevated parts of the flexures or salt highs. The change from the lacustrine carbonates and evaporites of the Cabaços formation to the shallow- and deep-water limestones of the Montejunto formation indicates a relative rise in sea level during Middle Oxfordian time.

Rift Climax (Tojeira member).—

During Late Oxfordian time, differential subsidence was accentuated, and fault scarps were formed. Hangingwall subsidence drowned older carbonate systems, and footwall uplift resulted in meteoric diagenesis and shedding of blocks of older carbonates into the basin. The sudden influx of basement-derived clastics into the area indicates significant fault-related topography to the east and northeast.

Immediate Postrift (Castanheira and Mirante members).—

Reflector divergence towards the footwall of the eastern boundary fault complex is probably not indicative of continued displacement but is due to the influx of sediment through a transfer zone between two fault segments along the eastern margin of the Arruda subbasin. Thus the initial "hole" produced during the rift-climax was only filled when a new drainage system was established that could transport basement-derived debris across presumed fault-related topography situated to the east and northeast. Large thickness variations (~ 50—2000 m) resulted from the infilling of fault-related topography.

Late Postrift (Top Castanheira and Uppermost Unnamed Member of Abadia formation, Amaral, Lourinhã and Farta Pão formations).—

There is little variation in the thickness of these units, as by now only the Ota platform remained as a significant high along the eastern boundary fault zone. This area was starved of siliciclastic sediments, and a reef-rimmed carbonate system developed over it at the same time as the fine-grained siliciclastic slope system prograded southwards. Rift-related topography was finally eliminated (apart from the effects of differential compaction) by the time the Amaral formation was deposited.

UPPER OXFORDIAN TO TITHONIAN 3RD-ORDER SEQUENCES

In this section, the 3rd-order sequence stratigraphic interpretation of successions developed in the regressive part of the 2nd-order sequence is discussed. The successions occur in four contrasting tectonic settings within the Arruda subbasin:

- Montejunto—Torres Vedras Anticline: salt pillow on northwest margin of the subbasin
- Arruda area: depocenter of the Arruda half-graben
- Castanheira—Vila Franca de Xira: transfer zone on eastern margin of the subbasin
- Ota carbonate platform: crestal position immediately to the east of the footwall of the northern part of the eastern boundary fault system

Biostratigraphic correlation of sequences in the four areas is combined to provide a 3rd-order sequence stratigraphic framework for the entire subbasin. This is used to add precision to the probable ages of the tectonic phases already described. We also describe the way in which the nature of 3rd-order sequences changed as the subbasin was progressively filled. The descriptions and interpretations are divided into sections dealing with the nature of sequence boundaries (SB) and lowstand (LST), transgressive (TST) and highstand (HST) depositional systems tracts. The constituent parts of the sequences are named according to their location (e.g. SB M1, LST M1, etc; M: Montejunto).

Montejunto—Torres Vedras Anticline

Superficially, the Oxfordian carbonate succession in this area appears to be one sequence (Fig. 8). A subaerial unconformity or hiatus occurs at the base and is overlain by lowstand lacus-

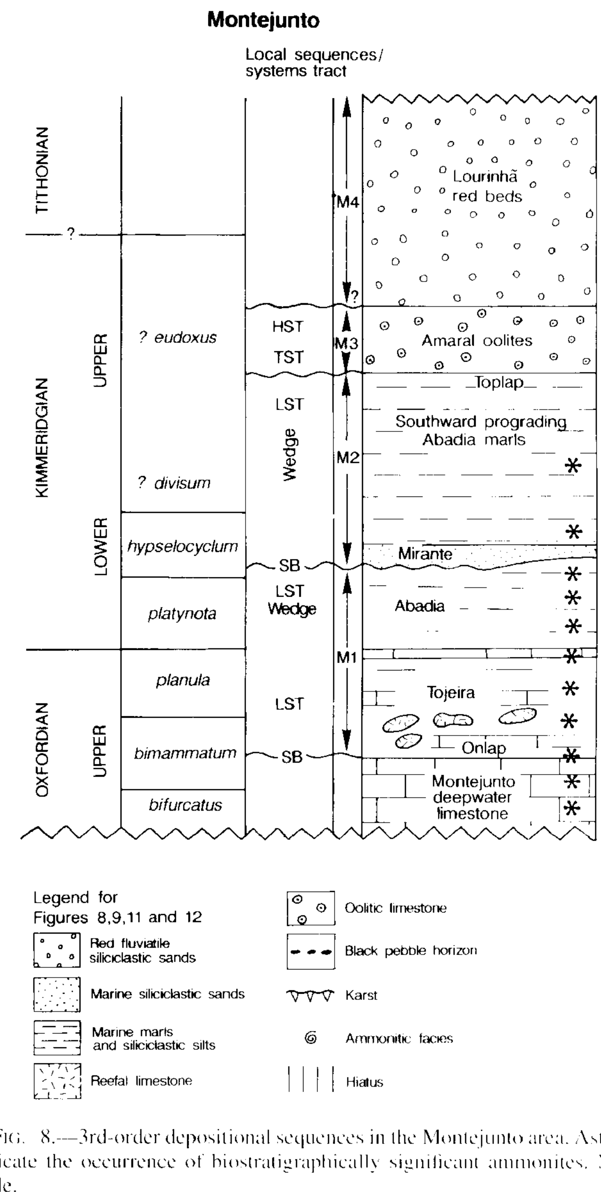

FIG. 8.—3rd-order depositional sequences in the Montejunto area. Asterisks indicate the occurrence of biostratigraphically significant ammonites. Not to scale.

trine and marginal marine deposits with evaporites of the Cabaços formation. Above this shelf and deeper water carbonates of the Montejunto formation suggest transgressive and highstand depositional systems. However, we believe that it is likely that several 3rd-order sequences are present in this succession, but poor outcrops and tectonic complications make it difficult to piece together an accurate lithological succession. Therefore the 3rd-order sequence interpretation presented here begins at the base of the Tojeira member.

Sequence M1.

SB M1.—As described earlier, the Tojeira member consists of shales and marls with siliciclastic and carbonate turbidites and debris flows containing allochthonous shallow-water limestones. The contact with the underlying deep-water carbonate facies of the Montejunto formation is erosional in places (Ellwood, 1987), which, together with the abrupt facies change across the boundary, indicates a sequence boundary.

LST M1.—On the northern side of the Montejunto massif, to the southeast of Pragança, the Tojeira member contains a basal carbonate rudstone package at least 20 m thick, which is composed of clasts and boulders derived from the Montejunto carbonate platform to the east. Some of the boulders were karstified prior to transport. The sediments grade upward into a marl succession with intercalated beds of allochthonous grainstones and packstones. To the south of Montejunto, these allochthonous intercalations are largely absent and are replaced by ammonite-bearing lime mudstones that we interpret as being a more distal facies deposited at a greater distance from fault scarps. In the Torres Vedras and Abadia areas, the lateral equivalent of the Tojeira member consists of marls similar to those that occur in the upper clinoform part of the Abadia formation.

Age of Sequence M1.—Ammonites from the Tojeira member indicate a Late Oxfordian age (late *bimammatum* to *planula* zone, Atrops and Marques, 1986, 1988).

Sequence M2.—

SB M2.—In the Montejunto area, Ellwood (1987) described sandstones and conglomerates (which he named the Mirante conglomerate member) abruptly overlying marls. This facies shift, and the local erosional base to the member, indicates the presence of a sequence boundary.

LST M2.—This system tract comprises the Mirante conglomerate member and the overlying succession of Abadia formation marls, which are over 500 m thick.

According to Ellwood (1987), the Mirante member ranges in thickness from about 20 m to 60 m. It contains clasts of quartzites, schists and granite up to 30 cm across, and limestone clasts over 1 m in diameter. The sand fraction contains abundant fresh feldspar crystals up to 0.5 cm long. The clast composition is very similar to that of the Castanheira member that reaches a thickness of over 2200 m in the deepest part of the Arruda subbasin, 25 km to the south. Ellwood (1987) suggested that the Mirante member was deposited in a north-south-oriented channel at least 3.5 km wide, through which sediment was transported southwards towards the depocenter around Arruda dos Vinhos, where the material met with coarse Castanheira fan siliciclastics derived from the east (as indicated by poorly developed clast imbrication and cross stratification).

The Mirante member is overlain by Abadia formation marls that display south-dipping clinoform reflectors on seismic sections. The marls contain occasional sharp-based sandstones less than 1 m thick. These show flute and groove casts and contain Bouma sequences t_{abc} and t_{ac} or only parallel lamination or current ripple cross stratification. Rare paraconglomerate intervals occur, containing large limestone boulders showing boundstone lithologies similar to those present in the overlying Amaral formation, 20 km to the south (see below), but which do not occur in this formation in the Montejunto area.

As discussed below, we believe that no transgressive or highstand deposits are preserved in Sequence M2.

Age of Sequence M2.—Atrops and Marques (1986) reported *platynota* zone and lowermost *hypselocyclum* zone ammonites from the marls above the Tojeira member, indicating that Sequence M2 commences in the latter zone. Mouterde et al. (1972) assigned the marls above the Mirante member to the *divisum* zone, but in the Montejunto area it is not possible to constrain the age of the top of the Abadia marls.

Sequence M3.—

SB M3.—The sequence boundary is identified at the base of the Amaral formation. In the Montejunto area, this formation is only about 10 m thick, compared with thicknesses approaching 100 m around Torres Vedras and in the Arruda area. It consists of marls, sandstones and ooid grainstones, and they could be interpreted as a transgressive systems tract at the top of Sequence M2. However, viewed in a regional context, the absence of the coral-rich boundstone facies characteristic of the topmost HST and earliest TST above the LST Abadia marls in the Arruda area (see below) and the sharp contact between slope marls and ooid grainstone described by Ellwood (1987) suggests the presence of a sequence boundary. An alternative interpretation is that the Amaral represents a carbonate-dominated TST/HST of the underlying sequence (Leinfelder, 1993) overlying siliciclastic lowstand sediments (Mirante member and overlying LST M2 marls).

TST M3.—Based on Ellwood's (1987) description of the Amaral formation in the Montejunto area, we interpret it as a TST deposit. A 1-m-thick sharp-based ooid grainstone with low-angle truncation surfaces marks the base of the formation where it is best exposed on the south side of the Montejunto anticline at Portela de Sol, some 3 km east of Vila Verde dos Francos. The remainder of the formation consists of five coarsening-up 1.0 to 3.5-m-thick parasequences. These contain marls interbedded with fine-grained sandstones that show an upward increase in thickness. The intervals are capped by a sandstone and/or a fine to medium ooid grainstone. Ellwood suggested that the sharp base of the Amaral formation indicates that the wave-base was shallow (<5 m) and/or that there was a rapid change of slope at the shelf edge. This would explain the absence of hummocky, swaley and wave-ripple cross stratification. The sequence stratigraphic approach leads to an alternative interpretation: the expected wave-dominated shoreface transitional deposits between the top of the Abadia and the Amaral formations were eroded prior to deposition of the TST of Sequence M3 (i.e., during lowstand or as the transgression began). This interpretation also explains the absence of boundstone facies at the top of the Abadia formation that occur further south in the Arruda area and their occurrence as resedimented blocks in the LST (clinoform Abadia marls) of sequence M2 in the Montejunto area.

The nature of the contact between the Amaral and Lourinhã formations is not exposed in the Montejunto area. Therefore, it is not possible to identify the next sequence boundary, or to decide whether the fluvial sediments of the Lourinhã represent HST deposits of Sequence M3, or a younger sequence.

Age of Sequence M3.—The Amaral formation has so far yielded no biostratigraphically significant fossils, so its age can only be inferred from regional stratigraphic considerations. The youngest known ammonites found in the Abadia formation are indicative of the *divisum* and *acanthicum* zones (Ruget Perrot, 1961; Mouterde et al., 1972; Atrops and Marques, 1988). Younger ammonites giving a basal Tithonian age occur in the top part of the Sobral and the base of the Arranhó formations (cf. Ruget-Perrot 1961; Atrops and Marques 1986; Leinfelder et al., 1993a). Thus, it is probable that the Amaral formation in the Montejunto area represents the Late Kimmeridgian *eudoxus* zone.

The Arruda Area

In this area, the boundary between the Oxfordian and Kimmeridgian strata is not exposed. Subsurface data indicate that this area was the deepest part of the Arruda subbasin and is now filled with over 2200 m of arkosic sands and gravels of the Castanheira member (Leinfelder and Wilson, 1989). Above the Castenheira member there occur lithostratigraphic units broadly comparable to the clinoform Abadia marls (but only ~200 m thick in this area) and the Amaral and Lourinhã formations in the Montejunto area (Fig. 9). In addition, marine carbonates of the Farta Pão formation interfinger northwards with the Lourinhã formation.

Sequence A1.—

LST A1.—The base of Sequence A1 cannot be seen at outcrop. Arruda #1 showed that over 2200 m of arkosic sandstones and gravels of the Castanheira member lie beneath the top few tens of meters of it that are exposed at the surface. This member is interpreted as a LST fan. The overlying slope marls and siltstones of the top part of the Abadia formation floor much of the wide Arruda valley but are not well exposed. Occasional slump horizons, mud pebble layers and beds rich in lignite debris occur. The Abadia marls are interpreted as a prograding LST wedge.

TST and HST A1.—Within the Abadia marls, about 30–40 m below the Amaral formation, a distinctive condensed section is relatively well exposed at Serra Isabel (Fig. 10) to the north of Arruda dos Francos. It can be followed in an east-west direction along the strike of the prograding top Abadia slope system. This condensed interval is named the Serra Isabel unit and is up to 10 m thick. It consists of marly limestones with a rich benthic fauna often stained by iron hydroxides. Ammonite-rich beds are present, as are coral and crinoid meadows, and microbial thrombolite reefs up to 7 m thick that in places contain corals and siliceous sponges (Leinfelder et al., 1993a, b; Werner et al., 1994). Extremely low rates of background sedimentation are indicated by these features, particularly the microbial crusts. These low rates suggest rising relative sea level and the deposition of a TST. The occurrence of thrombolites lacking corals

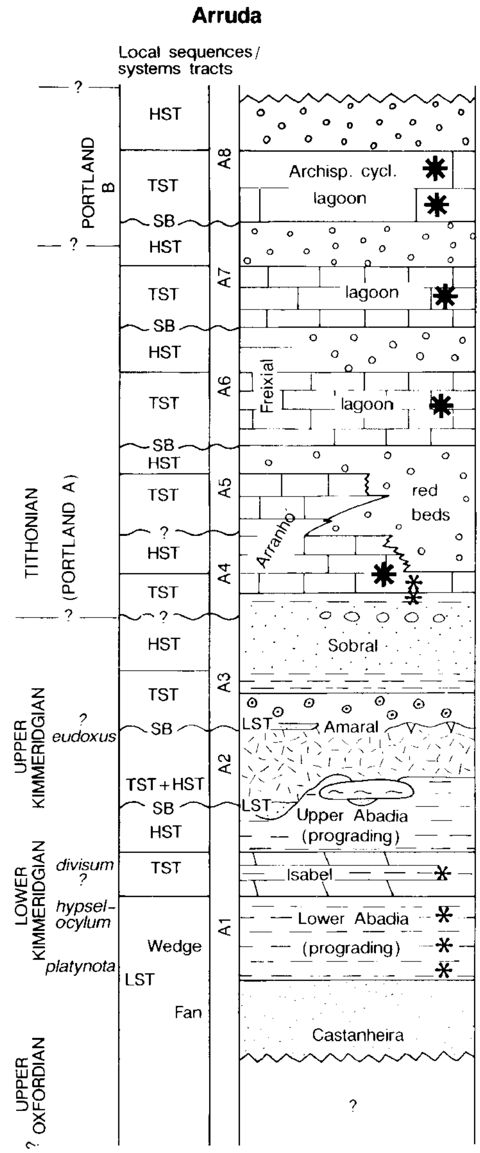

FIG. 9.—3rd-order depositional sequences in the Arruda dos Vinhos area. Asterisks indicate the occurrence of biostratigraphically significant ammonites (small asterisks) and microfossils (large asterisks). For key, see Fig. 8. Not to scale.

in a fairly shallow-water setting, the abundance of authigenic glauconite, and the presence of clusters of the dysaerobic benthic bivalve *Aulacomyella* indicate that sea-level rise was accompanied by oxygen depletion in shallow water (Leinfelder et al., 1993b). The Abadia marls above the Serra Isabel condensed unit contain some low-diversity coral meadows (Nose, 1995) and are interpreted as the highstand.

Age of Sequence A1.—Ammonites from the Serra Isabel unit indicate that the top of the sequence may span the top *hypselocyclum* to *divisum* zones (Leinfelder et al., 1993a, b).

Sequence A2.—

SB A2 and LST A2.—Near the top of the Abadia marls, the occurrence of a series of oolitic sandstone channels marks a facies shift indicative of a sequence boundary (Nose, 1995).

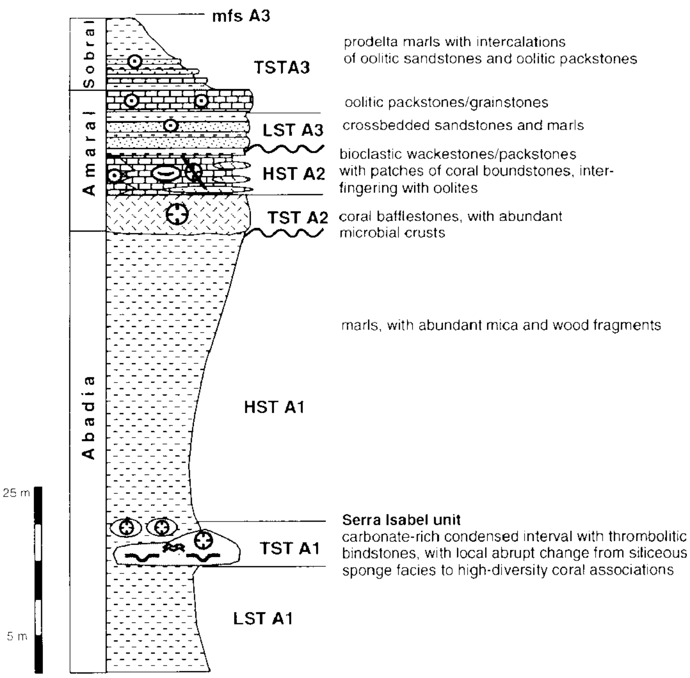

FIG. 10.—Log of succession exposed beneath Serra Isabel on the northern side of the Arruda valley (after Leinfelder et al., 1993a), with local rather than regional sequence stratigraphic interpretation shown (see text for discussion).

TST A2.—Coral thrombolite bioherms and pure thrombolitic bioherms occur within a marl succession immediately above the sandstone channels and grade into a discontinuous carbonate coral bioherm/biostrome level of the lower Amaral formation that is interpreted as a flooding surface. This lower biohermal level is overlain by bioclastic limestones and oolitic carbonates. This parasequence is in turn overlain by a second, more prominent and continuous parasequence occurring over much of the Arruda area. It is composed of mostly crust-rich, coral bioherms and biostromes, representing the maximum flooding event. Frequently, the lower coral level is not developed and the upper coral limestones of the Amaral formation are in sharp contact with the underlying Abadia marls. This probably represents a ravinement surface within the TST A2. Alternatively, Nose (1995) discussed the existence of an additional depositional sequence, based on the fact that erosional channels may also occur locally at the base of the upper coral limestones. However, the laterally discontinuous character of the lower coral limestones and the probable short duration of its deposition are arguments in favor of a parasequence interpretation. The upper coral limestones tend to become more bioclastic towards the top (Nose, 1995), which is interpreted as early highstand deposits of HST A2 (Fig. 10).

Sequence A3.—

SB A3.—Within the upper coral limestones, a discontinuous level exhibiting karst features is present. Sometimes this shows greenish clays containing exclusively calcitic fossils. The enrichment of calcitic fossils (brachiopods, crinoids, pectinid bivalves) and the disappearance of the normally dominant aragonitic elements (particularly corals) is interpreted to be due to early meteoric dissolution of aragonite along an intraformational groundwater table. The subaerial sequence boundary must occur above this level and is best placed at the transition between coral limestones and oolites, which becomes a more abrupt boundary above larger bioherms. The discontinuous pattern of dissolution features suggests the development of local freshwater lenses around islands representing exposed larger coral bioherms (Nose, 1995). LST A3 deposits encompass the green marls as well as oolitic sandstones and sandy oolites occasionally intercalated between the coral limestones of TST/HST A2 and superimposed oolites of TST A3 (Fig. 10).

TST A3.—The upper part of the Amaral formation was deposited in a very shallow subtidal to intertidal environment. It consists of cross-bedded ooid grainstones that occasionally contain oyster reefs, which are interpreted as the first flooding of the TST A3. There is a gradational boundary between the shelf carbonates of the upper Amaral formation and the deltaic Sobral member of the Lourinhã formation. The lower part of the Sobral member consists of *Gervillia*-rich prodelta marls (Leinfelder, 1986, 1987a), the top of which is interpreted as the maximum flooding surface of TST A3.

HST A3.—The middle part of the deltaic Sobral member shallows upwards, highlighting the advance of the deltaic system during this highstand that swamped the preceding prodelta environment.

Age of Sequence A3.—Ammonites from the top part of the Abadia formation imply that the Amaral formation may largely represent the top part of the *acanthicum* and the *eudoxus* zone of mid-late Kimmeridgian age (Nose 1995). Therefore, the major part of the Sobral member may represent the latest Kimmeridgian (*beckeri* zone), although an ammonite from the top part of the Sobral member indicates a basal Tithonian age (Manuppella, pers. comm. 1994).

Sequence A4.—

SB and TST A4.—In the southwestern part of the Sobral delta system, a bed of marine conglomerate rich in reworked caliche pebbles occurs in the top part. This is interpreted as a transgressive lag deposit overlying SB A4. Above the SB, the marine facies of the Sobral member deepens upward, passing from sandstones into widespread *Gervillia*-rich prodelta marls that are overlain by marine clayey carbonates marking the base of the Arranhó member of the Farta Pão formation. The low-energy, shallow-water carbonates are rich in bivalves and are strongly bioturbated. A thin tongue of these limestones extends northwards for a significant distance into the fluvial sediments of the Lourinhã formation (Leinfelder 1986, 1987a) and is interpreted as a maximum flooding surface.

HST A4.—The Arranhó member becomes more marly upwards and gradually retreats to the south with marginal marine and terrestrial siliciclastics of the Lourinhã formation prograding southwards. This interval is interpreted as HST A4.

Age of SB A4–5.—Based on microfossil assemblages, the entire Arranhó formation is early Tithonian in age (Leinfelder, 1986; Ramalho, 1981).

Sequence A5.—

A further southward retreat of the Arranhó member is taken to mark SB A5; the shallow-water carbonate sediments of the upper Arranhó and the tongue of the fluvial Lourinhã formation are interpreted as the TST and HST. There are insufficient field data to separate these two tracts.

Sequences A6–A8.—

The Freixial member of the upper Farta Pão formation (upper part of lower Tithonian to base of Cretaceous rocks, according to microfossil zonation) consists of carbonate-dominated marine to marginal marine intervals alternating with fluvial red beds of the Lourinhã formation (Leinfelder, 1986). The marine to brackish carbonates deposited in a shallow-ramp setting represent transgressive and, possibly, early highstand phases. As the exposures are not good enough to permit examination of the boundaries between the marine and terrestrial facies, it is not clear whether fluvial progradation occurred during lowstands or highstands. Since the transgressive marine sediments mostly exhibit very shallow-water characteristics, the latter interpretation is more likely. This conclusion is consistent with the fact that by this time the Arruda subbasin was virtually full of sediment so that a relative fall in sea level would result in no accommodation space being available and therefore no lowstand deposits would be preserved.

Castanheira—Vila Franca de Xira Area

In this area, arkosic sands and gravels of the Castanheira member are developed in a more proximal setting, close to the probable transfer zone in the eastern boundary fault complex through which the sediments were supplied (Fig. 2B). In addition, two reefal limestone intervals developed on siliciclastic-starved areas of the fan and shed large allochthonous blocks into adjacent areas (Fig. 11).

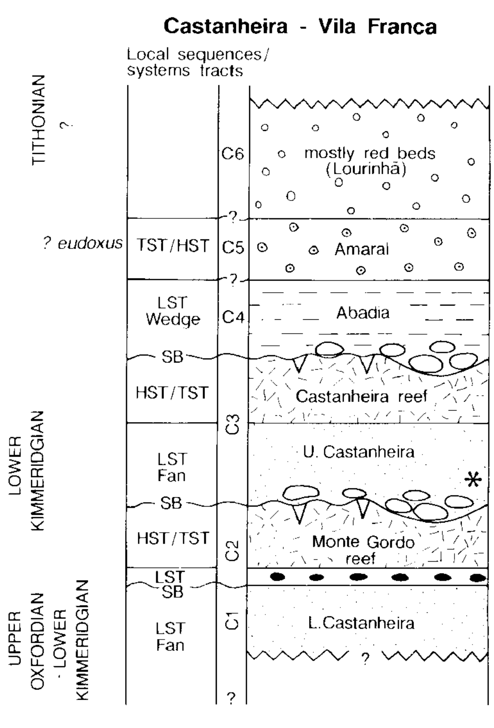

FIG. 11.—3rd-order depositional sequences in the Castanheira and Vila Franca de Xira areas. Asterisk indicates occurrence of ammonites indicative of the *hypselocyclum* zone; ovals within Sobral member indicate conglomeratic horizon. For key see Fig. 8. Not to scale.

Sequence C1.—

The base of this sequence must occur in the subsurface, but it was not penetrated by Arruda #1. It is probably identifiable on seismic sections at the top of the uppermost interval that shows significant divergence towards the eastern boundary fault zone (shown as equivalent to the Tojeira member on Fig. 7). The sedimentary characteristics of the Castanheira member described earlier indicate that only a LST occurs in Sequence C1.

Sequence C2.—

SB C2 and LST C2.—At Monte Gordo (a prominent hill above Vila Franca de Xira), the sequence boundary is interpreted to be the contact between the Castanheira arkoses of Sequence A1 and a rudstone to grainstone interval several meters thick at the base of the Monte Gordo limestone that contains many black pebbles. Interparticle crystal silt is very frequent in places and indicates repeated subaerial exposure during a lowstand.

TST and HST C2.—The grainstone to rudstone interval is overlain by the Monte Gordo limestone, which is about 60 m thick. At the base, there are several meters of grain-rich coral limestones dominated by microsolenids. The lime mud content then increases upwards, and siliceous sponges, indicative of deeper settings, become fairly abundant (Leinfelder et al., 1993a). This deepening trend is reversed towards the top of the Monte Gordo limestone, where coral bafflestones dominate and siliceous sponges disappear (Leinfelder, 1994). The deepening-up part of the succession is interpreted as the TST, and the shallowing-up part as the HST.

Sequence C3.—

SB C3.—This sequence is characterized by a paleokarst surface at the top of the Monte Gordo limestone.

LST C3.—Parautochthonous to allochthonous limestone boulders embedded in arkosic sands and conglomerates occur above and on the flanks of the Monte Gordo reef relic. Block formation was caused by karstification during SB C3 together with tectonically or gravitationally induced collapse. Both the allochthonous blocks and the reef relic are overlain by coarse-grained siliciclastic sediments containing reworked reef pebbles and poorly preserved ammonites that represent the remaining part of LST C3. Further north, about 1 km west of Castanheira, an interval of allochthonous reef boulders can be correlated with those associated with the Monte Gordo reef. This indicates a time of more extensive reef growth within the Castanheira fan (Leinfelder, 1994) during the TST and HST of the preceding sequence. In the Castanheira area, the boulder level is overlain by about 150 m of Castanheira fan conglomerates.

TST and HST C3.—In the Castanheira area the siliciclastic sediments above the lower boulder level are capped by a 3 m thick reefal limestone. This is probably a relic of a once-thicker reefal interval. The limestone consists of coral bafflestones, most of which are in life position, and framestones with a fairly high diversity of corals (Leinfelder, 1994). A similar autochthonous reef relic occurs about 1 km to the south at the same level. The boundary between the limestone and the underlying conglomerates is transitional: the grain size and amount of terrigeneous material decreases upwards as the carbonate content increases. This trend is consistent with the interpretation that the carbonate interval represents a TST/HST, with relative sea-level rise progressively reducing the influx of siliciclastic material.

Sequence C4.—

SB & LST C4.—The Castanheira reef limestone contains karstic cavities filled with siliciclastic material, indicating that a subaerial exposure surface developed on top of the former reef surface; this is SB C4. A significant period of karstification is indicated by the existence of an adjacent field of huge parautochthonous to allochthonous reefal boulder blocks that were karstified prior to transport. Most of the blocks occur close to the two occurrences of the Castanheira reef limestone, and their lithology is identical. Block formation probably was caused by the collapse of tower karsts at the beginning of LST C4 times.

To the east of Castanheira, the Abadia marls onlap the Castanheira formation. The base of the marls contains carbonate debris flows with large allochthonous blocks of karstified reefal limestone. The marls exhibit a more proximal character compared with the Arruda or Montejunto areas, for they are rich in plant debris and contain occasional allochthonous charophyte gyrogonites (Manuppella, pers. commun., 1994). These deposits and the boulder fields associated with the Castanheira reef relic and are interpreted as a lowstand fan, with the overlying marl succession representing a prograding lowstand wedge.

Sequence C5.—

SB C5.—As in other locations in the Arruda subbasin, the abrupt change from slope deposits of the Abadia marls to shelf carbonates of the Amaral formation is a significant shift from deeper to shallower conditions and may be interpreted as a sequence boundary, above which lowstand deposits are missing (cf. the Montejunto area). The Amaral carbonates clearly represent TST deposits, since carbonate formation in a setting with a high siliciclastic influx requires this input to be shut off by a transgression.

TST and HST C5.—Unlike the Amaral formation in the Arruda area, exposures of this formation north of Castanheira show no reefal facies. There it consists entirely of ooid grainstones that contain a significant amount of siliciclastic detritus, both as nuclei to the ooids and as small pebbles of vein quartz and basement material.

Sequence C6.—

As in the Montejunto area, the red beds of the Lourinhã formation lie above the Amaral formation; a sequence boundary is interpreted to occur between them. However, without reference to the interpretations made in the Montejunto, Arruda and Ota areas, local interpretation in the Castanheira challenges this interpretation. Lack of exposure of SB C5 and CB 6 in the area leaves open the possibility that the Amaral formation represents TST C4, overlying LST C4, with the Lourinha red beds interpreted as HST C4 (Leinfelder, 1993). However, the regional context together with the presence of reworked pebbles of Amaral limestones at the base of the Lourinhã formation supports the position of sequences C5 and C6 shown on Fig. 11.

Age of Sequences C1 to C6. —

Biostratigraphic indicators are extremely rare in the Castanheira-Vila Franca area. The ammonite *Ardescia pseudolictor* was found at the top of the Castanheira member, indicating a mid-early Kimmeridgian age (middle part of the *hypselocyclum* zone) for Sequence C3.

Ota Carbonate Platform

The succession shown in Figure 12 was deposited on a narrow reef-rimmed aggradational platform (Leinfelder, 1992, 1994). This developed above the footwall of the eastern boundary fault complex of the Arruda subbasin at approximately the same time as the slope/shelf system of the top Abadia formation prograded across the subbasin (Fig. 12) (Leinfelder et al., 1988; Leinfelder and Wilson, 1989).

Sequence O1.—

The base of the Ota limestone is not exposed. Therefore, that part of the buildup occurring below a wedge-shaped unit of black pebble conglomerate (see Sequence O2) cannot be interpreted in sequence stratigraphic terms.

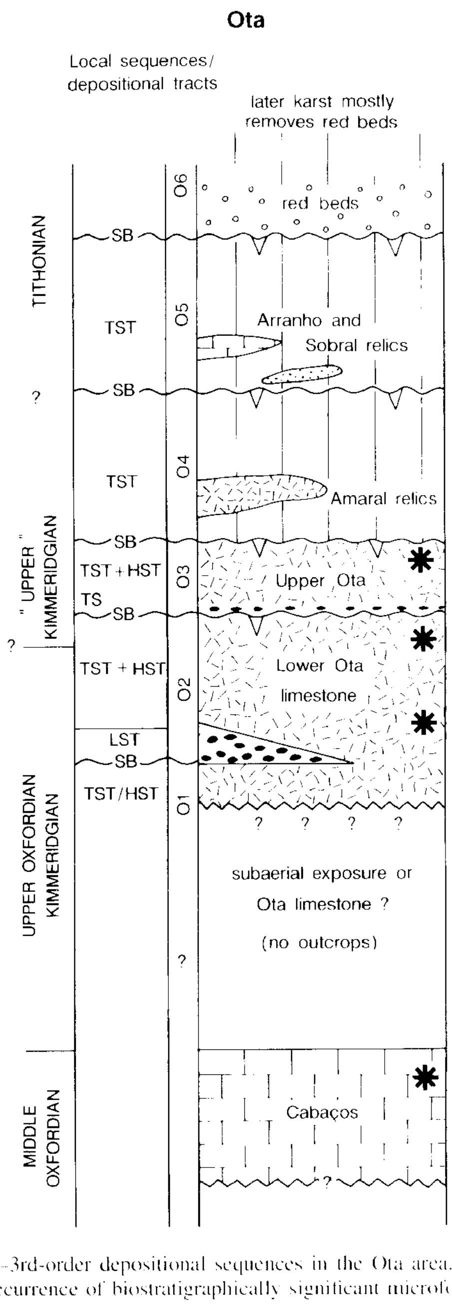

FIG. 12.—3rd-order depositional sequences in the Ota area. Asterisks indicate the occurrence of biostratigraphically significant microfossils. For key see Fig. 8. Not to scale.

Sequence O2.—

SB and LST O2.—A wedge shaped unit of black pebble conglomerate with an erosional base marks the SB and a locally developed LST. Over a distance of 1 km it thins from 4–5 m at the eastern margin of the Ota platform to only 20 cm towards the platform interior. Many of the clasts are reworked dasyclad and charophyte limestones of the Middle Oxfordian Cabaços formation. The conglomerates consist of poorly rounded to angular clasts set in a micritic groundmass. They were deposited as debris flows forming a small lowstand alluvial fan that developed away from a narrow, subaerially exposed area at the eastern margin of the platform (Leinfelder, 1987b, 1994). The wedge shape of the deposit and lack of oncoidal encrustation of pebbles clearly precludes interpretation of these deposits as a transgressive lag.

TST and HST O2.—Platform carbonates sandwiched between the wedge of black pebble conglomerate and a higher black pebble horizon represent TST and HST O2. The strongly aggradational nature of the Ota buildup shows that it was able to keep up with a relative sealevel rise during TST O2. Aggradation continued during the early part of HST O2, because progradation was prevented by the existence of a steep, tectonically induced bypass margin. This interpretation is consistent with the crust-rich, high-energy character of the Ota reef at the western platform margin (Leinfelder, 1992).

Sequence O3.—

SB O3 and TST O3.—The base of this sequence is marked by a 10 to 50-cm-thick lithoclastic and oncolitic black pebble horizon. This horizon occurs right across the platform and rests unconformably with an angular discordance (<5°) on older strata, indicating tectonic tilting. Occasionally, tilting is overprinted by subaerial erosion, resulting in an irregular erosional surface coated by caliche crusts (Leinfelder, 1987b). Elsewhere, the horizon is a marine hardground bored by lithophage bivalves (Leinfelder, 1994), representing an amalgamation of SB O3 and a transgressive surface at the base of TST O3. The oncolitic character of most of the horizon, with black pebbles serving as nuclei for oncoids, is typical of a basal TST lag deposit.

TST O3 and HST O3.—This sequence consists of aggradational platform carbonates similar to those of sequence O2.

Sequences O4–O6.—

The karstified top of Sequence O3 and the presence of relics of the Amaral formation and the Sobral and Arranhó members (Leinfelder et al., 1988; Leinfelder, 1994) suggests the presence of at least two sequence boundaries beneath the fluvial Lourinhã formation (the base of which is a third sequence boundary). It is probable that the younger lithostratigraphic units onlapped the Ota platform during transgressive phases, only to be almost totally removed during succeeding lowstands.

Discussion

Composite sequence stratigraphy of the Arruda subbasin.—

Although good biostratigraphic data are lacking in places, there is enough information available, in combination with using the Amaral formation as a marker horizon, to constrain the ages of the sequences identified at the four separate localities as shown in Fig. 13. Fig. 14 shows the composite sequence stratigraphy for the Upper Oxfordian and Kimmeridgian strata that was established by comparing the interpretations of the successions studied at four separate localities in the subbasin.

3rd-Order Sequence Stacking Patterns.—

Sequences 2–5 in the Arruda subbasin are dominated by lowstand deposits, consisting either of arkosic submarine fan sands and gravels derived from the east or southward-prograding fine-grained slope siliciclastics (Fig. 14). This dominance of lowstand systems tracts in the early sequences is a result of the deep basin filling that occurred after the rift climax at the end of Oxfordian time. These sequences change from aggradational (Sequences 2 and 3) to progradational (4 and 5). Within them, transgressive/highstand deposits formed only in two settings:

1. on the proximal part of the submarine fan system in the east of the subbasin, where the subbasin had filled sufficiently to make conditions shallow enough for carbonate deposition to have occured (Monte Gordo and Castanheira reefs) when the siliciclastic supply was shut down by a relative sea-level rise; and

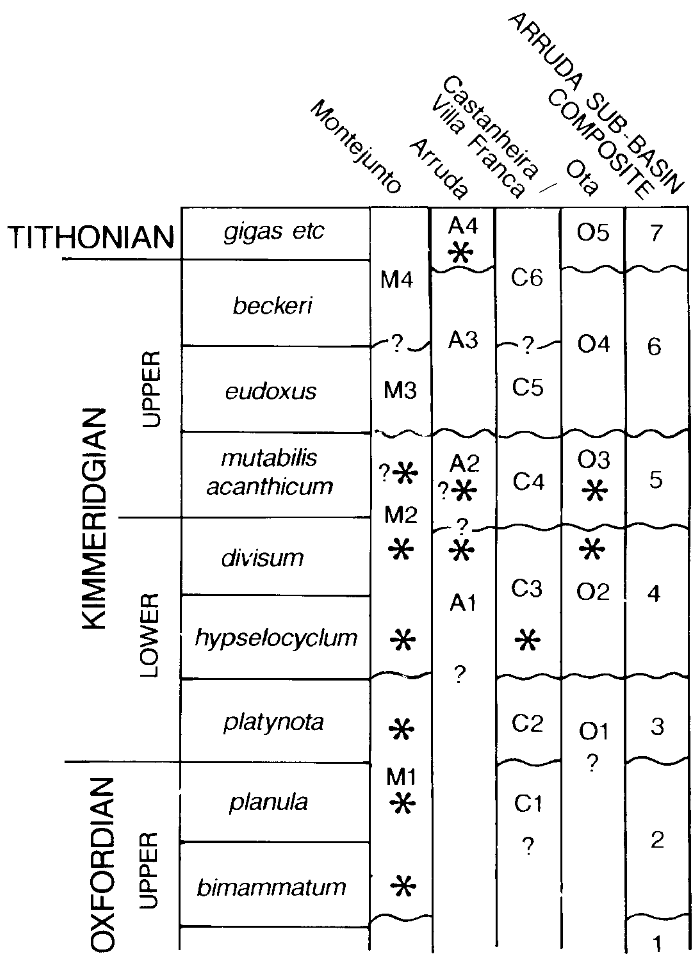

FIG. 13.—Summary of the probable ages of local depositional sequences and the proposed composite sequence stratigraphic scheme for the Arruda subbasin. Asterisks indicate presence of biostratigraphically significant ammonites.

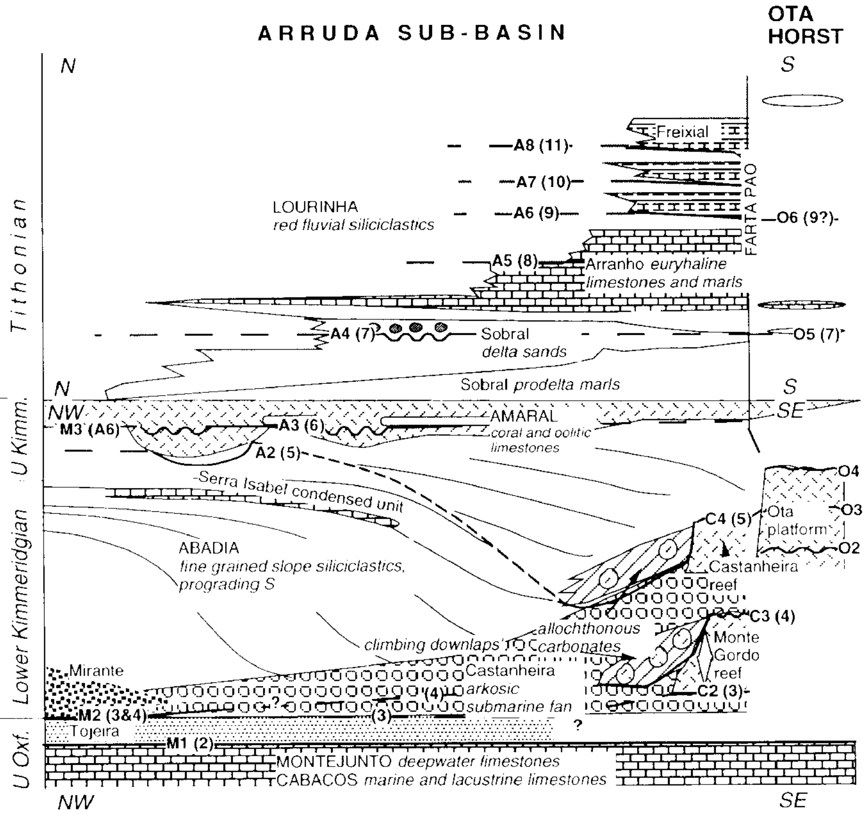

FIG. 14. Sketch section (not to scale) of the Upper Jurassic fill of the Arruda subbasin, summarizing the sequence stratigraphic interpretations presented in Figs. 8, 9, 11 and 12. Sequence boundaries are shown in bold lines and type for four areas in the subbasin (M: Montejunto northwest flanking anticline; A: Arruda-basin center; C: Castanheira-eastern basin margin; O: Ota platform-footwall crest of eastern boundary fault system), with the numbers of the sequence boundaries identified across the subbasin shown in brackets (the ages of these are indicated on Fig. 13). The transgressive part of the 2nd-order fill begins with carbonates, but from the rift climax at the end of the Oxfordian, deep water siliciclastics were deposited as successive third order sequences dominated by lowstand systems tracts (Sequences 2–4), followed by progradational stacking (part of sequence 4 and 5) after the basin was partially filled by aggradational arkosic sands and gravels. Almost complete filling of the basin is indicated by the change to aggradational 3rd-order sequences containing only transgressive and highstand systems tracts in sequences 6–11, and the spread of formations occurring in the basin onto the eastern footwall crest (where they are preserved as relics above the Ota carbonate platform).

2. on the uplifted footwall of the eastern boundary fault system (the Ota platform).

At the end of Sequence 6 time, the Arruda subbasin was virtually full of sediment so that only during periods of relative sea-level rise and highstand was space available for sediments to accumulate. It is also notable that from Sequence 6 onwards, relics of formations present in the basin are preserved above the Ota platform on the footwall of the eastern boundary fault zone, indicating that by this time the basin was beginning to overflow. The footwall crest would have remained a relatively positive feature due to the compaction of the thick pile of sediments in the basin to the west.

Our work shows that from Middle Oxfordian to middle late Kimmeridgian time, the nature and location of depositional systems were not controlled primarily by 3rd-order relative sea level changes but were only modified by them. Relative sea level rises and highstands appear to have shut down the influx of siliciclastic sediments into the subbasin during the time of Sequences 2 to 5. From Sequence 6 time onwards, siliciclastic systems were still effectively shut down during relative rises, but were able to prograde during highstands. Lack of accommodation space prevented deposition during lowstands.

Comparison with Proposed European 3rd-Order Sequence Chart.—

Up to this point, applying the sequence stratigraphic approach has not relied on the use of so-called global sequence correlation charts. For Upper Jurassic sequences, such charts (e.g., Haq, 1987; Ponsot and Vail, 1991a, b; Jacquin et al., this volume) are based largely on studies of successions that accumulated on relatively tectonically undifferentiated ramp settings in contrast to the rift origin of the Arruda subbasin. Nonetheless, from the *planula* zone (uppermost Oxfordian) to the top of Tithonian stage, 3rd-order sequences of the Arruda subbasin can be tied to the scheme for European basins proposed by Jacquin et al. (this volume) as summarized in Fig. 15. Sequence boundary 2 of the Arruda subbasin can be tied with SB Ox8 of Jaquin et al. (this volume) but Sequence 2 of the Arruda subbasin corresponds to two sequences (Ox 8, Ox 9). It is possible that Sequence Ox 8 has not been identified in the Arruda subbasin because of the poor exposure of the top part of the Tojeira member, where it would be expected to occur. Recognition of the earlier Oxfordian sequences (Ox 0–7) in the Arruda subbasin is not possible due to poor exposure and tectonic deformation of rocks of this age in the Montejunto area.

European-wide biostratigraphic and hence sequence stratigraphic correlation of the Upper Oxfordian/lower Kimmeridgian strata is far from being resolved. Problems exist particularly between the correlation of zones from the boreal to sub-Mediterranean realm. Taxonomic revisions of Upper Jurassic ammonites from southern Germany resulted in the recent recognition of *Amoeboceras bauhini* in the uppermost *bimammatum* zone, a classical "Upper Oxfordian" biozone of the sub-mediterranean realm. However, this ammonite is the index fossil for the base of the Kimmeridgian (base of *baylei* zone) in Great Britain (i.e., in the boreal realm, G. Schweigert, 1995). This discovery shows that the definition of base of the Oxfordian in the sub-Mediterranean zonation (base of *platynota* zone) does not coincide with the definition of the base of the Oxfordian in the boreal classification (base of *baylei* zone). The Lusitanian Basin stratigraphy is based on the sub-mediterranean classifi-

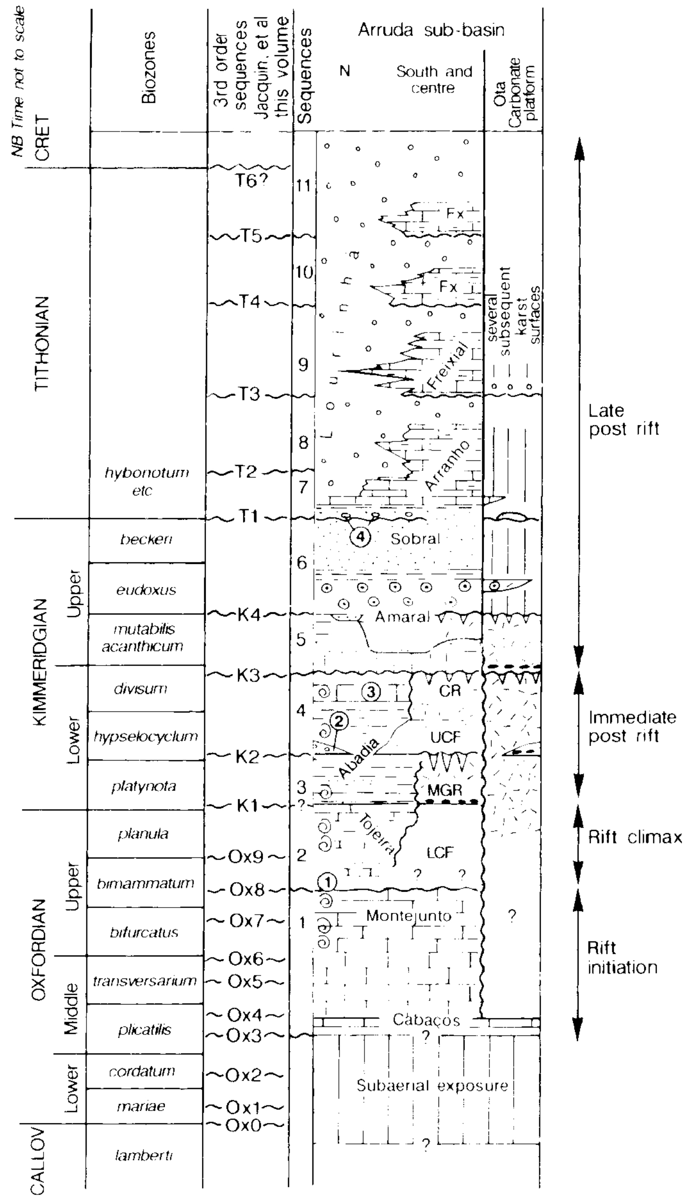

FIG. 15. Composite sequence stratigraphic interpretation of the Upper Jurassic strata of the Arruda subbasin compared with the 3rd-order sequence chart Jacquin et al. (this volume). Key to letters and numbers: LCF: lower part of Castanheira submarine fan; MGR: Monte Gordo reef; UCF: upper part of Castanheira submarine fan; CR: Castanheira reef; Fx: Freixial member; 1: change from dominantly carbonate to siliciclastic deposition; 2: Mirante sand interval in Montejunto area; 3: condensed interval exposed beneath Serra Isabel (Fig. 10); 4: reworked caliche nodules in marine conglomerate within Sobral member.

cation. In the light of these new results, the top of the Montejunto formation and the entire Tojeira member may be early Kimmeridgian age in the boreal sense. Since 3rd-order relative sea-level curves were largely established in the boreal realm, a complete revision of the curve for the Oxfordian/Kimmeridgian transition interval may be necessary.

Constraining the Timing of Rifting and Major Sedimentary Infilling.

The sequence stratigraphic interpretation and correlation presented in Figures 14 and 15 enables the timing of the rift climax and subsequent basin filling to be constrained (Table 1). Most of the subsidence probably occurred during the rift climax phase that coincides with Sequence 2 (Ox 8 and 9) times, and nearly 2 km of arkosic sands and gravels were deposited during Sequence 3 (K1) time. According to Jacquin et al. (this volume), these two intervals span about 1.3 my, which gives subsidence/sedimentation rates in the order of 2 m/ky, more than double the tectonic subsidence rates obtained by Wilson et al. (1989) using the total thickness of the Castanheira member and the total time duration estimated for its deposition. However, exact dates will only be obtained once the problems in biostratigraphic correlation of the Oxfordian/Kimmeridgian boundary, as outlined above, are solved.

CONCLUSIONS

The overall distribution in space and time of major depositional systems within the 2nd-order sequence of the Arruda subbasin was linked to tectonic subsidence, but shorter and smaller-scale variations in facies distributions were controlled by 3rd-order changes in relative sea level. Table 1 provides a summary of the relationships between lithostratigraphic units, rifting phases and third order sequences discussed in this paper.

Four major depositional systems fed sediments into the Arruda subbasin (Fig. 3): (1) carbonate buildups and associated deep-water sediments; (2) coarse-grained siliciclastic submarine fan, sourced from the east through a gap in the eastern boundary fault zone; (3) prograding fine-grained siliciclastic slope showing clinoform reflectors on seismic sections capped by shallow-water carbonates; and (4) coastal plain and shelf. The distribution of these systems in space and time was controlled largely by changes in accommodation space caused by tectonism and sediment infilling, resulting in a 2nd-order transgressive-regressive sequence (Fig. 6).

Increased subsidence rates during middle Oxfordian time compared with those earlier in Jurassic time marked the onset of rifting. Differential subsidence during rift initiation resulted in aggradational carbonate buildups forming along the eastern margin of the subbasin, with hemipelagic carbonates being deposited to the west. Rifting climaxed around the Oxfordian-Kimmeridgian boundary, resulting in footwall uplift of the eastern margin of the subbasin that caused meteoric diagenesis and shedding of blocks of earlier Oxfordian carbonates. At the beginning of Kimmeridgian time, it is probable that the Arruda subbasin was a deep "hole" in which over 2500 m of largely siliciclastic postrift sediments subsequently accumulated. The 2nd-order maximum flooding occurred during Late Oxfordian *bimammatum* zone time.

The coarse arkosic sediments of the Castanheira member were deposited by new drainage systems that were established in the recently rifted source area to the east and northeast. They formed the immediate postrift fill of the subbasin, which eliminated much of the accommodation space created during the rift climax. The late postrift phase is characterized by progradation of the slope-shelf system over the arkosic submarine fan sediments. This filled the basin virtually to sea level, after which coastal plain and shallow shelf sediments accumulated during a period in which subsidence largely resulted from sediment loading and differential compaction.

Four key findings result from our sequence stratigraphic interpretation at the 3rd-order scale of the sedimentary fill of the

TABLE 1. TECTONIC PHASES, 3RD ORDER SEQUENCES AND LITHOSTRATIGRAPHIC UNITS OF THE UPPER JURASSIC ARRUDA SUBBASIN

Rifting phase/tectonic systems tract and ***age***	**3rd order sequences** A: in Arruda subbasin (O), (K) and (T): correlation with European sequences (Jaquin et al., this volume)	**Lithostratigraphic units**	**Comments**
Late Postrift *Late Kimmeridgian–Tithonian*	A6–11 (K4, T1–26)	Lourinhã fm. (up to 400 m: fluviatile red beds, with deltaic Sobral member at base) interfingering southwards with: Farta Pão fm. (up to 100 m: Arranhó and Freixal mbrs.): limestones and marls with euryhaline to brackish bivalves. Top Abadia fm. (550 m): southward-prograding fine-grained siliciclastic slope capped by coral boundstones and ooid grainstones of the Amaral fm (~80 m). Top part of Castanheira mbr. (~350 m): arkosic submarine fan with carbonate buildups. Ota limestone (~160 m): aggradational reef-rimmed carbonate platform situated on horst in boundary fault complex.	Very low basement subsidence rates partly due to compaction of older sediments, so that eustatic control of accommodation space may have become very significant. Formations can be identified across several subbasins, in contrast to the greater complexity of facies distributions in earlier systems. Third order sequences changed from progradational lowstand dominated (top Abadia) to transgressive and highstand dominated from the Amaral fm. onwards.
Immediate Post rift *Latest Late Oxfordian to Early Kimmeridgian*	A3–5 (K1–3)	Lower part of Castanheira mbr (~2000 m): arkosic sandstones and gravels built westwards from gap in eastern boundary fault complex.	The influx of coarse clastics was probably caused by the establishment of a drainage system that crossed inactive fault systems and so could transport basement debris from the east and northeast. Carbonate clasts within the Castanheira member may be derived from footwalls of boundary fault complex and/or further fault systems to the east. Aggradational lowstand systems only were deposited.
Rift Climax *Late Oxfordian*	A2 (OX 8, 9)	Tojeira mbr. (~100 m): carbonate and siliciclastic turbidites and debris flows with allochthonous karstified shallow-water limestone blocks.	Rifting and regional subsistence resulted in hanging wall drowning of earlier carbonate depositional systems, and footwall uplift resulted in meteoric diagenesis and shedding of allochthonous blocks of earlier carbonates into the basins. Basement rocks became exposed in postulated footwall blocks to the east, which resulted in significant siliciclastics being deposited for the first time since the Late Triassic Epoch.
Rift Initiation *Middle to Late Oxfordian*	A1 (OX 3–7)	Montejunto fm.: deep-water carbonates in basin (2–400 m) carbonate buildups above footwall of eastern boundary fault complex (500 m). Cabaços fm. (2–400 m): lacustrine and shallow-marine limestones, with anhydrite.	Initial uplift produced hiatus followed by lacustrine and shallow-water carbonates. Faulting produced topographic differentiation into subbasins though flexuring (i.e., fault tip folds) leading to carbonate buildups forming on eastern margin. Salt movement was triggered by faulting.

Arruda subbasin. (1) 3rd-order sequences developed during all stages of the infilling of the subbasin, suggesting that 3rd-order changes in relative sea level controlled smaller scale facies distributions. (2) Aggradational followed by progradational lowstand depositional systems tracts dominated the 3rd-order sequences in the early regressive part of the subbasin fill. Slightly progradational to aggradational transgressive/highstand-dominated 3rd-order sequences formed once the subbasin was filled near to sea level, from *eudoxus* time onwards. (3) Biostratigraphic calibration, though varying in precision in different parts of the successions, is sufficient for 11 sequence boundaries to be identified within the rift-climax and postrift fill of the subbasin (mid-*bimammatum* zone to top Tithonian).

Despite the limited biostratigraphic control, the ages of these boundaries appear to correlate well with the European sequence boundaries proposed by Jacquin et al. (this volume), though their OX 9 boundary has not been identified. (4) The identification of 3rd-order sequences enables the timing and rates of tectonic subsidence and subsequent deposition to be estimated with greater precision, suggesting that during the rift climax phase they approached 2 m/ky over a relatively short period of time (1–2 my).

ACKNOWLEDGMENTS

We acknowledge the contributions of the following colleagues: G. Schairer, G. Schweigert, M. Nose, G. Manuppella and M. Ramalho. We thank reviewers Angela Coe and Sarah Prosser for their constructive criticisms and comments. R.R.L. acknowledges financial support from the Deutsche Forschungsgemeinschaft (DFG-Projects Le 580/1, 580/4). We thank Anita Chhabra, Denise Swann and Liz Lomas for their help in word processing the paper, and John Taylor for preparing most of the figures.

REFERENCES

ATROPS, F. AND MARQUES, B., 1986, Mise en évidence de la zone à Platynota (Kimméridgien inférieur) dans le massif du Montejunto (Portugal): conséquences stratigraphiques et paléontologiques: Géobios, v. 19, p. 537–547.

ATROPS, F. AND MARQUES, B., 1988, Précisions stratigraphiques sur les formations à ammonites du Jurassique supérieur dans le massif du Montejunto (Nord du Tage, Portugal): Proceedings 2nd International Symposium Jurassic Stratigraphy, Lisbon, p. 517–524.

ELLIS, P. M. WILSON, R. C. L., AND LEINFELDER, R. R., 1990, Controls on Upper Jurassic carbonate build-up development in the Lusitanian Basin Portugal, *in* Tucker, M. E., Wilson, J. L., Crevello, P. D., Sarg, J. R., and Read, J. F., Carbonate Platforms: International Association Sedimentologists Special Publication, v. 9, p. 169–202.

ELIET, P. P. AND GAWTHORPE, R. L., 1995, Drainage development and sediment supply within rifts, examples from the Sperchios basin, Central Greece: Journal of the Geological Society of London, v. 152, p. 883–893.

ELLWOOD, P. M., 1987, Sedimentology of the Upper Jurassic Abadia formation and its equivalents Lusitanian Basin, Portugal: unpublished Ph.D. thesis, Open University, Milton Keynes, 337 p.

FELBER, J., HOFFMANN, R., LEINFELDER, R., AND OSCHMANN, W., 1982, Biofaziesanalyse randmariner Ablagerungsbereiche im Oberen Jura Portugal.II.

Paläogeographie und Faziesverteilung in der Serra da Arrábida: Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, v. 163, p. 301–330.

HAQ, B. U., HARDENBOHL, J., VAIL, P. R. AND EHRLICH, R. N., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1166.

HILL, G., 1989, Distal alluvial fan sediments from the Upper Jurassic of Portugal: controls on their cyclicity and channel formation: Journal of the Geological Society of London, v. 146, p. 539–555.

LEINFELDER, R. R., 1983, New mapping results on sheet Setúbal (Sesimbra to Portinho da Arrábida, Serra da Arrábida, Portugal): Communicações Serviços Geológicos de Portugal, v. 69, p. 295–324.

LEINFELDER, R. R., 1985, Cyanophyte calcification morphotypes and depositional environments (Alenquer oncolite, Upper Kimmerridgian?, Portugal): Facies, v. 12, p. 255–274.

LEINFELDER, R. R., 1986, Facies, stratigraphy and paleogeographic analysis of Upper? Kimmeridgian to Upper Portlandian sediments in the environs of Arruda dos Vinhos, Estremadura, Portugal: Münchner Geowïssenschaftliche Abhandlungen, A, v. 7, p 1–215.

LEINFELDER, R. R., 1987a, Multifactorial control of sedimentation patterns in an ocean marginal basin: the Lusitanian Basin (Portugal) during the Kimmeridgian and Tithonian: Geologische Rundschau, v. 76, p. 599–631.

LEINFELDER, R. R., 1987b, Formation and significance of black pebbles from the Ota Limestone (Upper Jurassic, Portugal): Facies, v. 17, p. 159–170.

LEINFELDER, R. R., 1992, A modern-type Kimmeridgian reef (Ota Limestone, Portugal): Implications for Jurassic reef models: Facies, v. 26, p. 11–34.

LEINFELDER, R. R., 1993, A sequence stratigraphic approach to the Upper Jurassic mixed carbonate-siliciclastic succession of the central Lusitanian Basin, Portugal: Profil, v. 5, p. 119–140.

LEINFELDER, R. R., 1994, Karbonatplattformen und Korallenriffe innerhalb siliziklastischer sedimentations bereiche (Oberjura, Lusitanisches Becken, Portugal) (Carbonate platforms and coral reefs within a siliclastic setting (Upper Jurassic, Lusitanian Basin, Portugal: with chapter summaries in English) Profil, v. 6, p. 1–207.

LEINFELDER, R. R., ERBENICH, A. AND RAMALHO, M., 1988, Age and general facies development of the Ota Limestone (Estremadura, Portugal): Proceedings 2nd International Symposium in Jurassic Stratigraphy, Lisbon, p. 917–932.

LEINFELDER, R. R., KRAUTTER, M., NOSE, M., RAMALHO, M. M. AND WERNER, W., 1993a, Siliceous sponge facies from the Upper Jurassic of Portugal: Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, v. 189, p. 199–254.

LEINFELDER, R. R., NOSE, M., SCHMID, D. AND WERNER, W., 1993b, Microbial crusts of the Late Jurassic: composition, palaeoecological significance and importance in reef construction: Facies, v. 29, p. 195–230.

LEINFELDER, R. R. AND WILSON, R. C. L., 1989, Seismic and sedimentologic features of Oxfordian—Kimmeridgian syn-rift sediments on the eastern margin of the Lusitanian Basin: Geologische Rundschau, v. 78, p. 81–104.

MOUTERDE, R., RAMALHO, M., RUGET, C., AND TINTANT, H., 1972, Le Jurassique du Portugal: esquisse stratigraphique et zonale: Bolletin Socieeade Geológicos Portugal, v. 18, p. 73–104.

NOSE, M., 1995, Vergleichende Faziesanalyse und Palökologie korallenreicher Verflachungsabfolgen des iberischen Oberjura: Profil, v. 8, p. 1–237.

PONSOT, C. M. AND VAIL, P. R., 1991a, Sequence stratigraphy of the Jurassic: New data from the Paris-London Basin: Strasbourg: EUG VI-Congress, Terra Cognita Abstracts, v. 28, p. 48.

PONSOT, C. M. AND VAIL, P. R., 1991b, Sequence stratigraphy of the Jurassic: new data from the Paris—London Basin compiled from well logs: Abstract, American Association of Petroleum Geologists, Bulletin, v. 75, p. 655.

PROSSER, S. P., 1993, Rift related linked depositional systems and their seismic expression, *in* Williams, G. D. and Dobbs, A., eds., Tectonics and seismic sequence stratigraphy: Geological Society of London Special Publication, v. 71, p. 35–66.

RAMALHO, M. M., 1971., Contribution à l'étude micropaléontologique et stratigraphique du Jurassique superieur et du Crétacé Inférieur des environs de Lisbonne (Portugal): Serviços Geologicos Portugal, Memoria, v. 19, 212 p.

RAMALHO, M. M., 1981, Note préliminaire sur le microfacies du Jurassique supérieur Portugais: Communicações Serviços Geológicos de Portugal, v. 67, p. 41–45.

RUGET-PERROT, C., 1961, Étude stratigraphique sur le Dogger et le Malm Inférieur du Portugal au Nord du Tage—Bajocien, Bathonien, Callovien, Lusitanien: Serviços Geológicos de Portugal, Memoria, v. 7, 197 p.

SCHWEIGERT, G., 1995, Zum Aujtreten der Ammontenarten *Amoeboceras bauhini* (Opel) und *Amoeboceras schlginae* Mesezhnikov im Oberjura der Schwäbischen: Jahreshefte Gesellschaft für Naturkunde Württemburg, v. 151, p 171–184.

STAM, B., 1985, Quantitative analysis of Middle and Late Jurassic foraminifera from Portugal and its implications for the Grand Banks of Newfoundland: unpublished Ph.D. thesis, Dalhousie University, Halifax, 212 p.

WERNER, W., LEINFELDER, R. R., FÜRSICH, F. T. AND KRAUTTER, M., 1994, Comparative paleoecology of marly coralline sponge-bearing reefal associations from the Kimmeridgian (Upper Jurassic) of Portugal and Southwestern Germany: Courier Forschungsinstitut Senckenberg, v. 172, p. 381–397.

WILSON, R. C. L., 1989, Mesozoic development of the Lusitanian Basin, Portugal: Revista de la Sociedad Geologica de España, v. 1, p. 393–407.

WILSON, R. C. L., HISCOTT, R. N., WILLIS, M. G., AND GRADSTEIN, F. M., 1989, The Lusitanian Basin of west central Portugal: Mesozoic and Tertiary tectonic, stratigraphy and subsidence history, *in* Tankard, A. J. and Balkwill, H., eds., Extensional tectonics and stratigraphy of the North Atlantic margins, American Association of Petroleum Geologists, Memoir, v. 46, p. 341–361.

WRIGHT, V. P. AND WILSON, R. C. L., 1987, A Terra Rossa-like paleosol complex from the Upper Jurassic of Portugal: Sedimentology, v. 34, p. 259–273.