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

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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 35 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 transgression 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) were aggradational lowstand arkosic submarine fan deposits. As accommodation was reduced by sedimentation, localized transgressive highstand reeval carbonates formed on the shallow proximal part of the fan. The late postrift phase was heralded by progradational sequences consisting of lowstand time-grained slope deposits capped by transgressive/highstand coral-boundstones and oolites. These filled the basin vertically 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 coeval 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 m.y., and that subsidence rates approached 2 m/ky in the center of the subbasin.

INTRODUCTION

The Middle Oxfordian to Tithonian successions of the central part of the Lusitanian Basin contain 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 line-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.](image-url)
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.

GEOLLOGICAL 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 transgressive 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 Rua 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 Tertiary subbasin. A piercing 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., 1989; Leinfelder, 1987a. (A) Late Oxfordian (Montejuvoto 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 (Castelhaua 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 (Lourinha formation) intertongue with the south with shelf carbonate and marls (Farta Pao 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:

- Late Aptian–Campanian: Ocean spreading around west and north Iberian margins.
- Valanginian–Early Aptian: Rifting around north and northwest Iberia.
- Middle Oxfordian–Early Berriasian: Rifting, and ocean spreading beneath the Tagus abyssal plain.
- 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 Candeceiros formations) blanketed the entire Lusitanian Basin and exhibit simple facies geometries indicative of a westerly inclined 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 intertonguing southwards and westwards with the marine carbonates of the Cacuin formation (Fig. 5).

**Introduction**

After a brief review of the Upper Jurassic stratigraphy of the Arruda subbasin, the evidence for its tectonic and sedimentary
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 siliciclastic mudstones, shales and silstones with sub-sidary sandstones. On seismic sections, it corresponds to a chinoform reflection package (Wilson, 1989; Leinfelder and Wilson et al., 1989) indicating southward progradation of a slope.

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 and 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
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 Amiral formation.

The progradation of the Abadia-Amiral slope/shelf system was the last episode of dominantly marine deposition, after which a mixed fluvo-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 m.y.) 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 scarp. 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 Montejo-Teixeira-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 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 Montejo to 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 Montejo area, basal deep-water lateral equivalents are exposed and were encountered in Bento do #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 facies-to-marine facies transition at the base of the Montejo formation shows 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 facies Caboções 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 Caboções fan (Fig. 2B). On most seismic lines, the anhydrite and top Montejo 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 facies and marginal marine conditions in which the Caboções formation was deposited. accommodation then increased rapidly so that hemipelagic carbonates of the Montejo formation were deposited over most of the subbasin. However, in the northern part of the eastern boundary fault complex in the east of the Montejo 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.

**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 binamomatum 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 arkose and carbonate sand. Bedded mertic amnoniate-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 footblock tilting ceases and that this is accompanied by strong onlap updpip 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 post rift 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 post rift 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 post rift 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 rectal 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 finer-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 amnoniate Ardea pseudoliticaf found at outcrop near the top of the member, indicates a middle early Kimmeridgian age (middle part of hypsocyclymum zone, Leinfelder, 1984).

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 Postri
t

Prosser (1993) stated that the late post rift systems tract is the result of the continued peneploplanation 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 filling-up sequences, and crustal 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 thinning-up trend, and contains two rectal intervals related to 3rd-order sequences (see below) that is identified as the basal late post rift systems tract. The uppermost unnamed part of the Abadia formation, the Ota limestone and Armaral, Lordinhel and Farra 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 interbedded with, the Castanheira and uppermost members of the Abadia formation.

The Ota limestone represents the immediate post rift 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 clinoform systems 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 resembeded ooid grainstones seen at outcrop are consistent with this interpretation. Occasional higher-amplitude reflections can be traced down-dip 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 Amoral 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 Amoral formation contains lenses of coral boundstones (some of which are thrombolitic) overlain by ooid grainstones (Leinfelder et al., 1993b; Nosc, 1995). Patches of grainstones that occur above the karstified top of the Ota limestone are relics of the Amoral 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 (Munlapella, pers. comm., 1994). Immediately to the east of the Ota platform, freshwater oncolid horizons occur that formed in spring-fed streams and lakes (Leinfelder, 1985). The Arranheiro 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 Arranheiro 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 builds 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, 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 Eleti and Gwathmey'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 Eleti and Gwathmey (1995) were not developed, though their rift, 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 biminimation 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 (Torreia 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 diageneisis 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 (Castañheira and Mirante members).—

IMR 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 Castañheira and Uppermost Unnamed Member of Abadia formation, Amaral, Lourinhã and Farra 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
- Castañheira—Vila Franca de Xira: transfer zone on eastern margin of the subbasin
- Ota carbonate platform: cretaceous position immediately to the east of the footwall of the northern boundary fault system

Biorstratigraphic 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 lacustrine beds.
trine and marginal marine deposits with evaporites of the Ca- 
baços formation. Above this shelf and deeper water carbonates of the 
Montejunto formation suggest transgressive and high-
stand 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 allogenous shallow-water lime-
stones. The contact with the underlying deep-water carbonate 
facies of the Montejunto formation is erosional in places (Ell-
wood, 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 Pragana, the Tojeira member contains a basal 
carbonate rudstone package at least 20 m thick, which is com-
posed of clasts and boulders derived from the Montejunto car-
bonate platform to the east. Some of the boulders were karst-
ified prior to transport. The sediments grade upward into a marl 
succession with intercalated beds of allogenous grainstones and 
packstones. To the south of Montejunto, these allogenous facies 
are largely absent and are replaced by an-
momint-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 Arruda areas, the lateral equiv-
alent 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.**—Anmomites from the Tojeira member 
indicate a Late Oxfordian stage (Late hinnatunium to planudam 

**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 conglom-
erate 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 quartz-
ites, 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 Castanhães 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 Castanhães 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 sec-
tions. The marls contain occasional sharp-based sandstones less 
that 1 m thick. These show flute and groove casts and contain 
Bouma sequences 1,2, and 3, or only parallel lamination or cur-
rent ripple cross stratification. Rare paraconglomerate intervals 
occur, containing large limestone boulders showing boundstone 
lithologies similar to those present in the overlying Amiral for-
mation, 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 high-
stand deposits are preserved in Sequence M2.

**Age of Sequence M2.**—Atrops and Marques (1986) reported 
platyntina zone and lowermost hinnatunium zone ammonites 
from the marls above the Tojeira member, indicating that Se-
quence M2 commences in the latter zone. Moutredelle et al. 
(1972) assigned the marls above the Mirante member to the 
division 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 Amiral 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 Se-
quence 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 LSB Abadia marls in the Ar-
руда 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 Amiral represents a carbonate-dominated TST/HST 
of the underlying sequence (Leinfelder, 1993) overlying silic-
iclastic lowstand sediments (Mirante member and overlying 
LST M2 marls).

**TST M3.**—Based on Ellwood’s (1987) description of the 
Amiral 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 
trench at Portela de Sol, some 3 km east of Vila Verde dos 
Franços. The remainder of the formation consists of fine 
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 Amiral 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 ab-
esence of hummocky, swaley and wave-ripple cross stratifica-
tion. The sequence stratigraphic approach leads to an alternative 
interpretation: the expected wave-dominated shoreface transi-
tional deposits between the top of the Abadia and the Amiral 
formations were eroded prior to deposition of the TST of Se-
quence M3 (i.e., during lowstand or as the transgression began). 
This interpretation also explains the absence of boundstone fac-
cies 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 theMontejunto area.

The nature of the contact between the Amaral and Lourinhã formations is not exposed in theMontejunto 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 division and aequantica zones (Ruget Perrot, 1961; Moutet and Moutet, 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 Arranã 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 Castanheira 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 theMontejunto area (Fig. 9). In addition, marine carbonates of the Faria Piao formation intertongue 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 Fracos. 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 thrombolites reaching 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 in a fairly shallow-water setting, the abundance of authigenic glauconite, and the presence of clusters of the dysaerobic 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 hypersalinity to division 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).
TST A2.—Coral thrombolitic bioherms and pure thrombolitic bioherms occur within a marl succession immediately above the sandstone channels and grade into a discontinuous carbonate coral bioherm/biostromic level of the lower Amalur formation that is interpreted as a flooding surface. This lower biotermal level is overlain by biostromatic limestones and oolitic carbonates. This parasequence is in turn overlain by a second, more prominent and continuous parasequence occurring over much of the Arrula 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 Amalur formation are in sharp contact with the underlying Abadia marls. This probably represents a ravine 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 Amalur formation was deposited in a very shallow subtidal to intertidal environment. It consists of cross-beded 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 shell carbonates of the upper Amalur 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 Amalur formation may largely represent the top part of the acuaticum and the endoconus zone of mid-late Kimmeridgian age (Nose 1995). Therefore, the lower 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 calcite pebbles occurs in the top part. This is interpreted as a transgressive lag deposit overlain by 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 Arranhão member of the Farta Pio 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 Arranhão 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—Based on microfossil assemblages, the entire Arranhão formation is early Tithonian in age (Leinfelder, 1986; Ramalho, 1981).

Sequence A5.—

A further southward retreat of the Arranhão member is taken to mark SB A5; the shallow-water carbonate sediments of the
upper Arranhó and the tongue of the fluvial Lourinhá 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 Lourinhá 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 reeval limestone intervals developed on siliciclastic-starved areas of the fan and shed large allochthonous blocks into adjacent areas (Fig. 11).

**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, 

**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 framstones 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 terrigenous 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.

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**Fig. 11.—3rd-order depositional sequences in the Castanheira and Vila Franca de Xira areas. Asterisk indicates occurrence of ammonites indicative of the *biplicatula* zone, ovals within Sobral member indicate conglomeratic horizon. For key see Fig. 8. Not to scale.**
Sequence C4.—

SB & LST C4.—The Castanheira reef limestone contains karstic cavities filled with siliceous 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 reeval block beds 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 reeval limestone. The marls exhibit a more proximal character compared with the Arruda or Montejeunto 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 Amoral 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 Montejeunto area). The Amoral 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 Amoral formation in the Arruda area, exposures of this formation north of Castanheira show no reeval 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 Montejeunto area, the red beds of the Lourinha formation lie above the Amoral formation; a sequence boundary is interpreted to occur between them. However, without reference to the interpretations made in the Montejeunto, 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 Amoral 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 Amoral limestones at the base of the Lourinha 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 Aidesca pseudolocitor was found at the top of the Castanheira member, indicating a mid-eariy Kimmeridgian age (middle part of the hypselocycloc zonal) 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 build up 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 dasyacoid and charophyte limestones of the Middle Oxfordian Caibacós 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 oncolithic 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 lithophagous bivalves (Leinfelder, 1994), representing an amalgamation of SB O3 and a transgressive surface at the base of TST O3. The oncitic 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 karsted top of Sequence O3 and the presence of relics of the Amural formation and the Sobral and Arranê municipalities (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 overlapped 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 Amural 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 Kimeridgian 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 occurred (Monte Gordo and Castanheira reefs) when the siliciclastic supply was shut down by a relative sealevel 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.](image-url)
2. on the uplifted footwall of the eastern boundary fault system (the Ota platform).

At the end of Sequence 6 time, the Arruda sub-basin 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 Kimmernian 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 sub-basin 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; Jaquin 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 sub-basin. Nonetheless, from the planula zone (uppermost Oxfordian) to the top of Tithonian stage, 3rd-order sequences of the Arruda sub-basin can be tied to the scheme for European basins proposed by Jaquin et al. (this volume) as summarized in Fig. 15. Sequence boundary 2 of the Arruda sub-basin can be tied with SB Ox8 of Jaquin et al. (this volume) but Sequence 3 of the Arruda sub-basin corresponds to two sequences (Ox8, Ox9). It is possible that Sequence Ox8 has not been identified in the Arruda sub-basin because of the poor exposure of the top part of the Tojena member, where it would be expected to occur. Recognition of the earlier Oxfordian sequences (Ox 0–7) in the Arruda sub-basin is not possible due to poor exposure and tectonic deformation of rocks at this age in the Montejunto area.

European-wide biostratigraphic and hence sequence stratigraphic correlation of the Upper Oxfordian/lower Kimmernian strata is far from being resolved. Problems exist particularly in the correlation of zones from the boreal to sub-Mediterranean realms. Taxonomic revisions of Upper Jurassic ammonites from southern Germany resulted in the recent recognition of Ammobaculus bantiani in the uppermost bimniannia zone, a classical “Upper Oxfordian” biozone of the sub-Mediterranean realm. However, this ammomite is the index fossil for the base of the Kimmernian (base of braueri 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 planulata zone) does not coincide with the definition of the base of the Oxfordian in the boreal classification (base of braueri zone). The Lusitanian Basin stratigraphy is based on the sub-Mediterranean classifi-
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 arkose 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 mky, 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 eustatic depression 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 Kimmeridgian 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 prostriatal fill of the subbasin, which eliminated much of the accommodation space created during the rift climax. The late prostriatal 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
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) Aggradation 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 endorgen 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-biunatum 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 Jaquet 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/k.y. over a relatively short period of time (1-2 m.y.).

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REFERENCES


THIRD-ORDER SEQUENCES IN AN UPPER JURASSIC RIFT-RELATED SECOND-ORDER SEQUENCE


