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A sequence stratigraphic approach to the Upper Jurassic mixed carbonate - siliciclastic succession of the central Lusitanian Basin, Portugal

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Abstract

The Upper Jurassic of the Lusitanian Basin, west-central Portugal, represents a marine to terrestrial syn-rift succession. The major depositional systems are determined by general basin setting and synsedimentary tectonic activity, controlling amount and direction of terrigeneous input as well as formation and location of shallow-water platforms. They comprise long-lived systems such as an east-derived coarse siliciclastic fan delta, a largely coeval, northwest-derived fine-grained terrigeneous prograding slope system, and isolated shallow-water carbonate platforms on structural or halokinetic uplifts.

Sea level changes of third order only modify these structurally controlled depositional systems. During sea level rise coral biostromes and bioherms as well as oxygen-controlled thrombolites occurred within siliciclastic fan and slope settings. In terrestrial settings characterized by red bed development shallow-water ramp carbonates occurred as thin intercalations during transgressive phases and early highstand. Third-order sea-level drops terminated such short-lived carbonate development causing subaerial unconformities and karstification. They also resulted in phases of black pebble formation, subaerial erosion, and shallow karst horizons on the long-lived, structurally controlled carbonate platforms on intrabasinal highs.

Due to a generally high terrigeneous influx into the basin, third-order sequences are not identifiable at all sites due to frequent overcompensation of accomodation rate. As a result of this, progradation frequently occurred even during sea level rises. Particularly basinal settings show such overcompensation effects and, hence, poor sequential resolution. On the other hand, sequences tend to amalgamate on shallow uplifts due to low subsidence rates. Moderately deep settings show the best sequential resolution. By combining the local sequences to a composite pattern, 11 depositional third-order sequences can be identified for the Arruda Subbbasin, which represents the central part of the Lusitanian Basin.

Although the biostratigraphic framework is not very dense, the Lusitanian Basin third-order sequences can be perfectly matched with the sequences of PONSOT & VAIL (1991a,b). Since this is also true for many other European regions such as southeastern Portugal, France or southern Germany, the PONSOT & VAIL sequences seem to reflect at least western/ central Europe-wide sea level changes. However, in the Lusitanian Basin, third-order sequence boundaries frequently coincide with tectonic activity, causing angular disconformities or collapse structures. It is therefore assumed that the Upper Jurassic sequences of PONSOT & VAIL (1991a,b) reflect regional tectonic rift activity rather than glacioeustatic cycles.

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INTRODUCTION

The Upper Jurassic mixed siliciclastic - carbonate succession of the Lusitanian Basin, west-central Portugal, experienced increasing interest due to its enormous, often small-scale facies variety. For most depositional systems as well as for their spatial and temporal arrangement preliminary or detailed descriptions exist (e.g. LEINFELDER 1986, 1989, 1992, in press; LEINFELDER & WILSON 1989, ELLIS et al. 1990, HILL 1989). However, many of these represent case studies and were not tied to a dynamic stratigraphic analysis. A major problem in dynamic basin evaluation was the lack of chrono-stratigraphic markers, so that time-slice interpretations were partly a matter of model considerations (LEINFELDER 1987a, 1988). On the other hand, the succession contains a wealth of sedimentary features suitable for application of sequence stratigraphic concepts. Additional seismic and stratigraphic data are meanwhile available, so that dynamic sequence interpretation appears possible now. However, it will be shown that the complex architectural pattern of the mixed carbonate-siliciclastic basin fill cannot be solely explained by fluctuations in global or regional sea-level. Besides sea-level changes, the existing pattern must be explained by biotic and climatic processes, and above all, by the enormous synsedimentary tectonic activity, leading to block and strike-slip faulting, salt pillow movement, and to siliciclastic input from various sources at various times (LEINFELDER 1987a, 1989, in press, LEINFELDER & WILSON 1989). Hence, three-dimensional sequential interpretation of the Upper Jurassic succession of the Lusitanian basin should allow for the evaluation of responsible interactive processes. This paper is a first sequence stratigraphic evaluation of Upper Jurassic outcrop data of the central Lusitanian Basin (cf. LEINFELDER 1986, 1989, in press). A composite evaluation of both outcrop and subsurface data, including seismic data, will be given elsewhere (LEINFELDER & WILSON in prep.).

OVERVIEW OF BASIN DEVELOPMENT

The Lusitanian Basin is an ocean marginal basin which heralded the opening of the North Atlantic. Terrestrial red beds, grading into salt and marginal marine dolomite deposits represent the first rift sediments of latest Triassic and early Liassic age. Ramp-like carbonate platforms at the basin margins and carbonate-marl successions in the shallowing basin centre are of Early and Middle Jurassic age and represent a quiescent gulf stage of the basin. This first tectonostratigraphic mega-unit is bounded by an almost basinwide subaerial unconformity, largely of Early Oxfordian age. The second tectonostratigraphic unit spans the Upper Jurassic mixed carbonate-siliciclastic succession of the second rift stage treated in this paper and is again bounded by a major erosional unconformity. Cretaceous and Early Tertiary sediments can be subdivided into three additional units which are also bound by unconformities. They are composed of prograding and retreating, mostly terrestrial, siliciclastic, and shallow marine deposits in the basin centre around Lisbon (Fig. 1) (WILSON et al. 1989, HISCOTT et al. 1990).

THE UPPER JURASSIC SUCCESSION OF THE ARRUDA SUBBASIN

The Arruda Subbasin is one of three depocentres of the Lusitanian basin to the north of Lisbon, which developed during the Late Jurassic rift phase (Fig. 2). It has a rhomb-like shape due to strike-slipe reactivation of old Hercynian basement faults and represents a classical intra-continental pull-apart basin with enormous differences in thickness and facies of syntectonic sediments (LEINFELDER & WILSON 1989). It actually exhibited basinal morphology during the Late Jurassic, with basinal sediments in the subbasin centre around the town Arruda dos Vinhos and shallow-water sediments on some uplifted blocks at the basin margin. The eastern margin of the Arruda Subbasin also corresponds to the eastern margin of the entire Lusitanian Basin. Since the Upper Jurassic succession of the western and northern "subbasins" are not well exposed in their lower part and dominated by terrestrial sediments in their upper part, the succession of the Arruda Subbasin is crucial for the understanding of the dynamic stratigraphy of the entire basin.

General succession

The middle Oxfordian Cabaços beds represent a succession of marginally marine to lacustrine carbonates of very variable salinity regimes. In the subsurface anhydrite is common and the Cabaços serves as a good seismic reflector (LEINFELDER & WILSON 1989).

In the subbasin centre the upper Oxfordian to Uppermost Kimmeridgian succession is, in general terms, composed of basinal ammonitic limestones (Montejunto beds, upper part of Middle Oxfordian to Upper Oxfordian), overlain by marls with micritic and carbonate debris flow intercalations (Tojeira beds, upper part of Upper Oxfordian). This is followed by the Kimmeridgian Abadia succession, which contains a coarse basal, debris-flow-dominated interval (Cabrito sandstones and conglomerates) in its lower part. The Cabrito grades into a shallowing-upwards marl-sandstone turbidite succession (Abadia marls) topped by shallow-water limestones rich in coral facies and oolites (Amaral beds). Above follow, partly oolitic, sandstones and marls with a euryhaline shallow-water fauna (Sobral beds), which have a presumed age of latest Kimmeridgian, perhaps passing the boundary into the earliest Tithonian.

At the basin margins the situation is partly different during the Oxfordian and Kimmeridgian. At

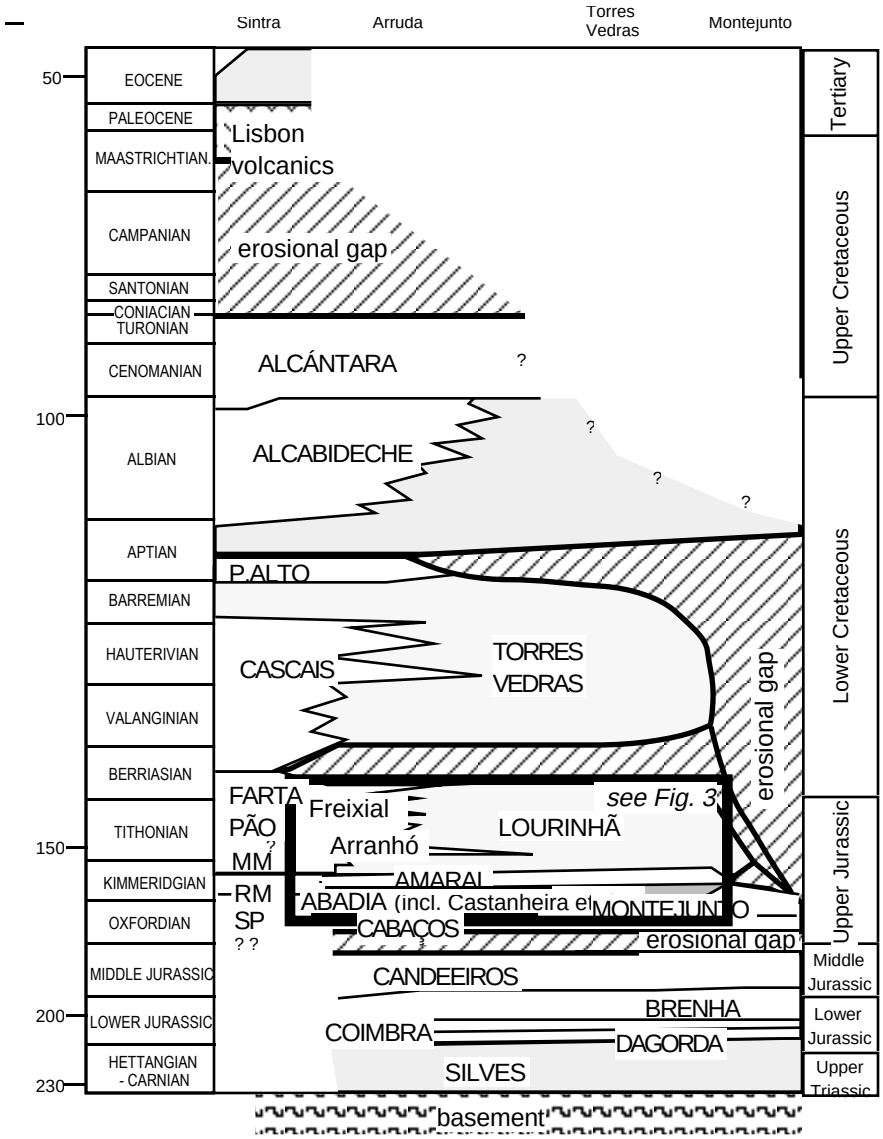

Fig. 1: The general Mesozoic succession of the Lusitanian Basin showing the development of five major tectonostratigraphic units (after LEINFELDER & WILSON 1989 and WILSON et al. 1989). Given is an informal lithostratigraphic classification currently under discussion. Siliciclastics are stippled, the rest are argillaceous and carbonate rocks. SP: São Pedro fm; RM: Ramalhão fm; MM: Mem Martins fm. For more details on the Upper Jurassic part of the succession see Fig. 3.

the northwestern subbasin margin a shallow water carbonate platform developed during the Late Oxfordian and, possibly, earliest Kimmeridgian (Montejunto platform carbonates). This platform developed on an uplifted basement block, a structure which later was additionally modified by salt pillow formation. On another narrow uplift structure at the eastern basin margin another carbonate platform, representing a well-zoned coral-microbial crust reef complex developed (Ota Limestone; LEINFELDER 1992). The exposed part of the Ota Limestone contains microorganisms diagnostic of a middle to late Kimmeridgian age (LEINFELDER et al. 1988). The Amaral beds onlap a karstified surface, so that the Ota Limestone is coeval with the Abadia Beds, although its development may have started already earlier. To the south of the Ota area, the Abadia marls are largely substituted by coarse fan conglomerates containing enormous quantities of basement

pebbles and boulders, allochthonous blocks of reefal carbonates and some in-situ reef relics (Castanheira conglomerates, Castanheira reef, Monte Gordo reef; LEINFELDER 1989, in press).

The Tithonian sediments, of very shallow-water origin, are composed of a limestone-marl succession rich in benthic macrofauna (Arranhó beds, formerly known as 'Pteroceriano') and is overlain by the mixed siliciclastic-carbonate Freixial beds, both of which may be grouped to the Farta Pão Formation. Both Arranhó beds and Freixial beds rapidly grade laterally into red terrestrial clastics towards north (Lourinhã beds) (cf. LEINFELDER 1986, 1987a) (Fig. 3).

Below follows a brief description of the sedimentary units of the Arruda Subbasin with emphasis on features diagnostic of sequence stratigraphic interpretation. For a more complete description of sediments and for structural and field relations see LEINFELDER (1986, 1989, in press).

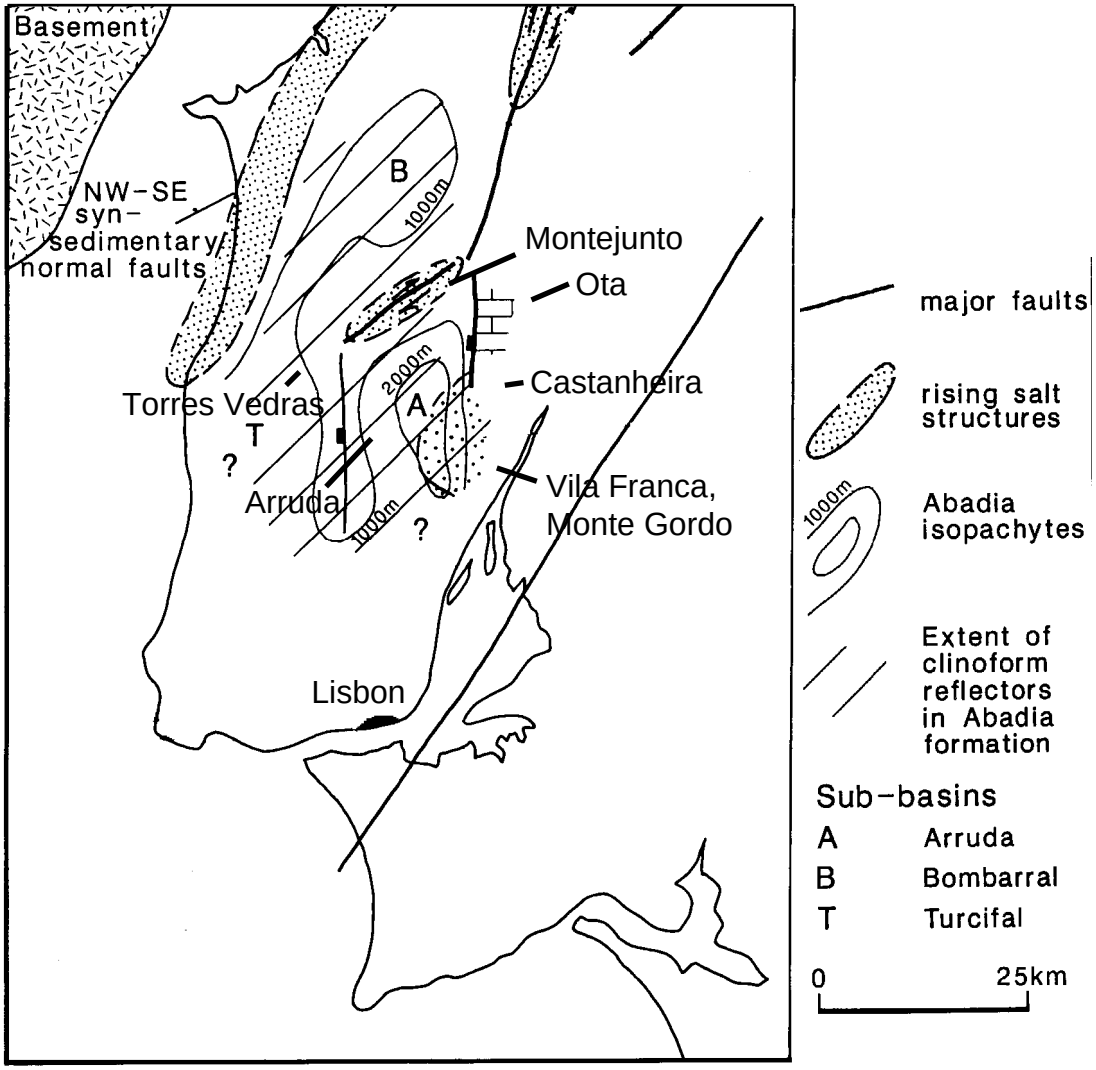

Fig. 2: Map of the central part of the Lusitanian Basin, showing principal structural elements, subbasins and localities mentioned in the text. Simplified after LEINFELDER & WILSON (1989).

Lithostratigraphic units

Cabaços beds: The base of the Cabaços beds is rarely exposed in the Arruda Subbasin. In the south and north of the Lusitanian Basin, the top of the Middle Jurassic corresponds to a major subaerial unconformity with karstification, rubification and calichefaction processes (FELBER et al. 1982, LEINFELDER 1983, WRIGHT & WILSON 1987, EHSES 1989, KLINGEL 1991). From the Arruda Subbasin, RUGET-PERROT (1961) mentioned absence of ammonites from the Lower Oxfordian, which together with the abrupt facies change also makes the existence of the same unconformity likely. The mixed-salinity, calcareous Cabaços beds themselves are not studied in detail in the Arruda Subbasin. However, normal marine salinity sediments seem to be restricted to their middle part,

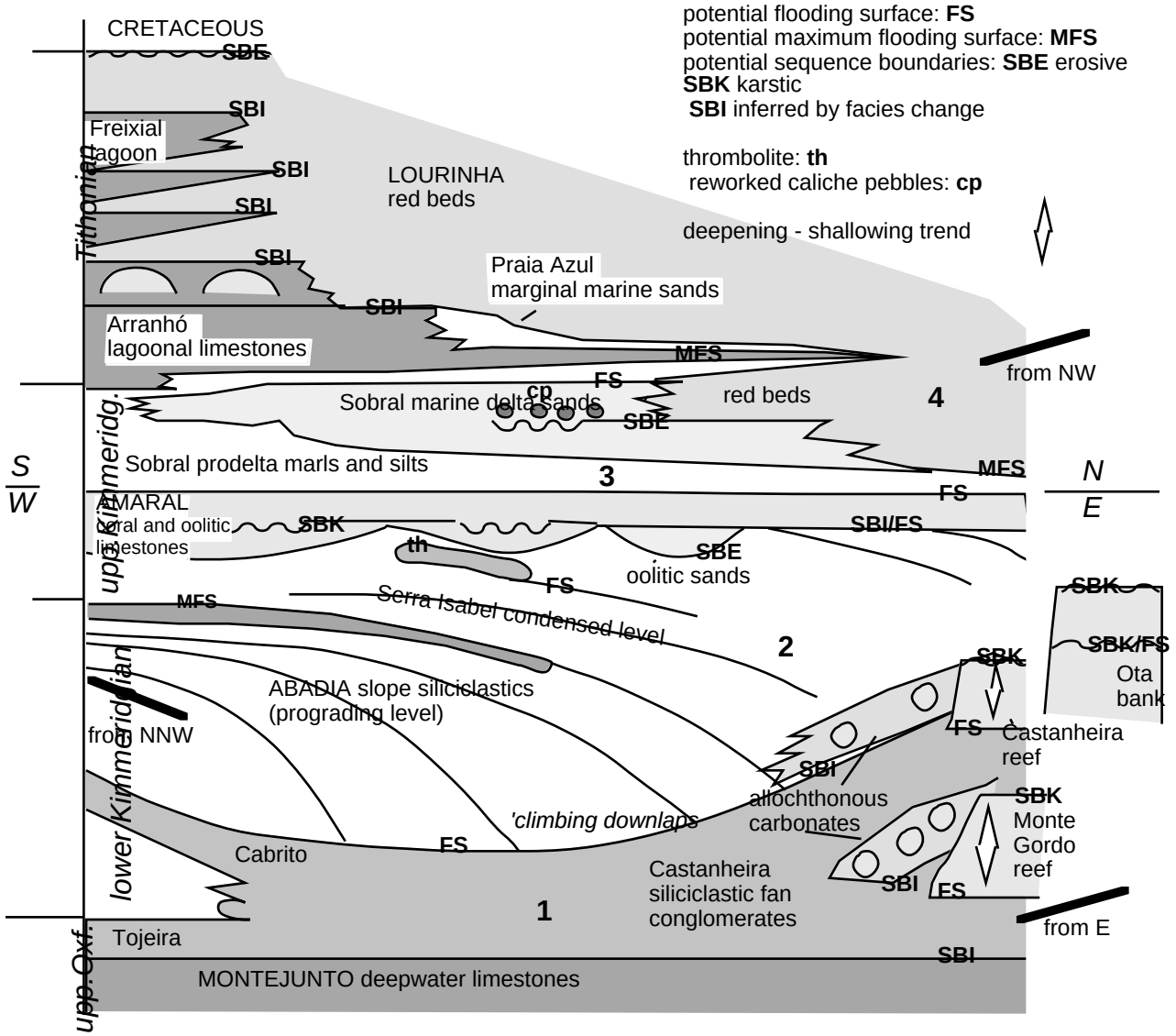

Fig. 3: Conceptual lithostratigraphic and architectural sketch of the Upper Oxfordian to Upper Tithonian succession of the Arruda Subbasin, indicating horizons and features relevant for sequence stratigraphic interpretation. Seismic pattern simplified, extrapolated from northern part of Arruda Subbasin and Bombarral Subbasin (cf. Fig. 2). Based on and compiled from LEINFELDER (1986, 1987a, 1992), LEINFELDER & WILSON (1989), WILSON et al. (1989), ELLIS et al. (1990), and further unpublished data (LEINFELDER in press). Without the local development of carbonates and karst features the top Upper Oxfordian to top Tithonian succession might be misinterpreted as only one major depositional system comprising lowstand fan conglomerates (1), followed by a prograding shelf margin wedge (2), overlain by shallow-water carbonates and prodelta silts during transgression (3) and by highstand terrestrial siliciclastics (4).

whereas the lower and upper part are composed of charophyte-rich dasycladacean wackestones and packstones, and thinly laminated micrites, which partly are brecciated in-situ, representing collapse brecciation due to dissolution of anhydrite. According to ATROPS & MARQUES (1986, 1988) the Cabaços beds encompass the plicatilis-zone (lower part of Middle Oxfordian).

Montejunto ammonitic limestones: The boundary between the Cabaços and Montejunto limestones is mostly tectonic at outcrop. Montejunto limestones are only exposed in the western part of the basin and represent medium bedded lime mudstones, rarely wackestones with occasional ammonites, ophiuroid fragments, lagenid foraminifers and sponge spicules. Thin marl horizons occur occasionally. Intercalations of packstones and grainstones composed of allochthonous shallow-water particles increase towards north, i.e. towards

the Montejunto shallow-water carbonate platform (RUGET-PERROT 1961, ELLIS et al. 1990). The well-studied ammonite fauna indicates a late Mid to early Late Oxfordian age for the Montejunto basinal limestones, corresponding to the transversarium, bifurcatus and the lower part of the bimammatum-zone (ATROPS & MARQUES 1986, 1988).

Tojeira beds: The Tojeira beds crop out in the Montejunto area, i.e. in the the western part of the subbasin. They represent an alternation of marls, thin turbiditic sandstone beds, micritic ammonite bearing limestones similar to the Montejunto beds and allochthonous blocks of shallow-water limestones, some of which show karstification which occurred prior to the transport of the blocks. Their age is late Late Oxfordian (upper part of the bimammatum-zone and planula-zone; ATROPS & MARQUES 1986, 1988).

Cabrito sandstones and conglomerates: The Cabrito unit consists of poorly sorted, coarse sandstones and greywackes, as well as very coarse conglomerates composed of quartz pebbles and rare basement clasts up to 15 cm in diameter. Relics of marine fauna, such as oyster fragments occur. Channel structures exist, though massive bedding is the most common feature, indicating that debris flow processes were of major importance. Normally the Cabrito is intercalated between the Tojeira beds and the Abadia marls. However, in the Montejunto anticline, the Cabrito is thin and occurs within the lower Abadia beds. This indicates a point source input and the development of an upward widening submarine fan leading to the outward spreading of a Cabrito tongue. Cabrito facies apparently does not occur higher than the hypselocyclum-zone (early Mid Kimmeridgian; ATROPS & MARQUES 1986, 1988). In the Arruda borehole, situated in the direct centre of the Arruda Subbasin, massive arkosic conglomerates with a thickness of 2.200 metres were drilled in a local subgraben, which could be interpreted likewise as Cabrito or Castanheira conglomerates (see below).

Abadia marls and sandstones: The Abadia beds crop out widely in the southern centre of the Montejunto anticline as well as in the broad Arruda valley, though exposures are fairly poor and extensive logging is not possible. Marls dominate by far, but sandstones, which are mostly turbiditic or represent debris flows, form frequent intercalations. Slumpings, mud-pebble breccia and southeastward dipping seismic clinoforms are diagnostic of a huge prograding slope system. It appears that around Arruda the lower part of the Abadia is rich in sand, whereas the upper part is marl-dominated, although structural relations are not very clear. Many bedding planes are rich in mica and plant litter. Bioturbation is common, belemnites and ammonites are enriched in some horizons, though poorly preserved specimens or undiagnostic forms occur scattered throughout the succession. In the higher part of the Abadia benthic macrofauna is common in places. About 40 metres below the Abadia top exists a condensed level, the Serra Isabel level (cf. Fig. 3), which is rich in ammonites and at places contains occasional coral-calcisponge-crinoid-thrombolite biostromes and bioherms (WERNER et al. 1993). Elsewhere, in about the same stratigraphic position a thick limestone bed rich in thrombolithic crusts occurs containing some siliceous sponges at the base and corals at the top. Such sudden changes as well as the occurrence of clusters of *Aulacomyella* might be due to occasional shifts in bottom water oxygen concentrations (LEINFELDER et al. 1993). The top part of the Abadia is locally rich in marly coral meadows and small coral-thrombolite bioherms (NOSE 1990, in prep.). In seismic sections the upper part of the Abadia shows clinoform reflectors indicating progradation towards SSE (LEINFELDER & WILSON 1989)(cf. Fig. 2).

The age of the Abadia is difficult to decipher. *Orthosphinctes* and *Ardescia* are the most common ammonite genera. However, poor preservation mostly does not allow discrimination at the species level. In South Germany and Swabia, *Orthosphinctes* normally does not appear higher than the Lowermost Kimmeridgian (platynota-zone, rarely hypselocyclum-zone). In the Celtiberian basin of Spain, the genus is, however, still common in the divisum-zone and known until the Upper Kimmeridgian (mutabilis-zone, one unclear case even in the eudoxus-zone) (FINKEL 1992). The Serra Isabel level, 40 metres below the top of the Abadia, additionally yielded *'Orthosphinctes*' ex. gr. *O. freybergi*, diagnostic of a late Early Kimmeridgian age (possibly hypselocyclum to divisum-zone).

According to ATROPS & MARQUES (1988) the Abadia should span the entire Kimmeridgian. The present author agrees that the base of the Kimmeridgian, at places where no Cabrito is developed above the Tojeira (Montejunto, Casal Ramada Section), sedimentation of the Abadia starts in the platynota-zone (Lowermost Kimmeridgian). Most ammonites were found in the higher part of the Abadia beds, around 80 to 40 metres below the top of the unit, which are attributed to the divisum and, possibly mutabilis (acanthicum)-zones (RUGET-PERROT 1961, MOUTERDE et al. 1972, ATROPS & MARQUES 1988). Whereas this is in accordance with our investigations, the extended duration of the Abadia into the lower Tithonian is doubtful. Such extension was postulated by ATROPS & MARQUES (1988), on grounds of some unnamed ammonites of the hybonotum-zone (Lowermost Tithonian) found on the supposed top of the Abadia in the eastern part of the Arruda Subbasin. Structural and facies relations are complicated there (cf. LEINFELDER & WILSON 1989: Fig. 6) and it can be assumed that the new specimens found in this area are derived from the Sobral unit exhibiting comparable facies or from marls of the Arranhó which crop out in a narrow, poorly exposed stripe along the Tejo valley. To date, and based on the apparent lack of younger ammonites in regions with

clear stratigraphic relations, the present author follows earlier workers (e.g. MOUTERDE et al. 1972), placing the upper boundary of the Abadia not higher that in the eudoxus-zone.

Castanheira conglomerates: At the eastern margin of the Arruda Subbasin, corresponding to the eastern margin of the entire Lusitanian Basin, a large, coarse submarine fan to fan delta system developed during deposition of the Abadia beds elsewhere. It is composed of up to 800 metres of coarse, arkosic conglomerates rich in up to several decimetre-large basement pebbles and cobbles such as granites, gneisses, slates. Quartz cobbles up to 20 cm in diameter occur as well as huge boulders of reefal carbonates and clay boulders measuring up to eight metres in length. The massive, chaotic fabric, rare amalgamated channel structures, occasional large logs of fossil trees and upright position of some of the large clay boulders are diagnostic of debris flow processes. A fan-like distribution can be directly traced in the fields and is obvious by chaotic seismic reflection in the subsurface (LEINFELDER & WILSON 1989). Reef blocks represent relics of coeval coral reefs developing within the fan (see below), hence indicating that fan environments also included fairly shallow settings (fan delta). Allochthonous oolites rich in oyster fragments, detrital quartz and feldspar, and belemnites can be found within the Abadia beds surrounding the fan and are diagnostic of the coeval occurrence of both Castanheira fan facies and Abadia basinal facies. The Abadia generally onlaps the retreating fan system. The ammonite *Ardescia pseudolictor*, indicating a mid Early Kimmeridgian age (middle part of the hypselocyclum-zone), was found in the distal part of the fan, but structural relations (downlapping and onlapping Abadia and Amaral) suggest that the fan developed at least until the early part of the Late Kimmeridgian (LEINFELDER & WILSON 1989). Possibly, fan development already commenced during the Oxfordian, since no Cabaços or Montejunto beds are drilled or at outcrop in the vicinity of the fan.

Relics of the Monte Gordo Reef and Castanheira Reef: Two relics of larger reef bodies occur within and on top of the Castanheira fan. Although the structural situation is not very clear, the Monte Gordo reef relic developed partly on Abadia-type marls, partly on Castanheira conglomerates. Rich in black pebbles and dominated by grainstones at the base, the 60 m thick reef relic deepens upwards as indicated by increasing lime mud content and a faunal association of corals dominated by microsolenid forms, siliceous and calcareous sponges, and microbial crusts. Towards the top, the dominance of coral bafflestones together with the lack of siliceous sponges is indicative of shallowing. The reef top exhibits a palaeokarst surface. Laterally, the reef immediatedly disintegrates into large, parautochthonous to allochthonous limestone boulders embedded in the Castanheira conglomerate. Block formation seemed to be particularly caused by karstification together with tectonically or gravitationally induced collapse. Both allochthonous blocks and the reef relic are overlain by coarse marine sandstones containing reworked reef pebbles and poorly preserved ammonites. The Monte Gordo reef seems to be situated in the deeper portion of the Castanheira fan. A level of allochthonous reef boulders in the lower part of the fan may indicate a time of more extensive reef growth within the fan (LEINFELDER 1989, in press).

The Castanheira reef relic at the Castanheira hilltop represents a much smaller rest of a former reef, which is situated on the top of the fan. The underlying sediments become increasingly richer in carbonate matrix to suddenly pass into a reefal carbonate rich in a diverse coral fauna (only about 3 metres preserved). Again the reef passes laterally into parautochthonous to allochthonous blocks of reefal limestones, which often were karstified prior to transport. These blocks are not positioned at the boundary between the Castanheira conglomerates and the onlapping Abadia marls but well within the lower portion of the Abadia marls. This indicates that the former reef was much thicker and that block building is related to the final stage of reef formation, most likely again to a mixed process of block karst formation and collapse. Large boulder fields, which in part may represent autochthonous reef relics are common along the transition from the fan conglomerates to the Abadia beds and in the lowermost Abadia beds at various places, indicating a second phase of more widespread reef growth.

Ota limestone: The Ota limestone represents a narrow reef-rimmed platform developing on a basement horst in close vicinity to the eastern margin of the Lusitanian basin (LEINFELDER & WILSON 1989). The shallow-water, high-energy coral reef is highly diverse and rich in microbial crusts; inner platform areas were well protected (LEINFELDER 1992). Although coeval with the Abadia beds (LEINFELDER et al. 1988), sheltering from sand and clay-sized siliciclastics was perfect. The aggradational geometry of the platform with perfect facies zonation is thought to be due to the existence of a steep, tectonic bypass margin and is not related to sea-level situation. One intraformational black pebble horizon crosscuts the entire platform and is associated with caliche crusts, subaerial erosion, subsequent submarine hardground formation and slight tectonic tilting of the platform. Another, older one, is only locally developed and is also due to tectonic movements resulting in the blackening and reworking of Middle Oxfordian Cabaços limestones which were shed into the Kimmeridgian platform carbonates (LEINFELDER 1987b). The Ota limestone was covered by a, to date mostly removed grainstone cap, prior and posterior to which several phases of karstification occurred. Amaral beds and younger sediments onlapped the Ota structure and are in places still preserved above the Ota limestone (LEINFELDER et

al. 1988, LEINFELDER 1989, in press).

Amaral beds: The boundary between the Abadia beds and the superimposed Amaral beds is partly sharp, more commonly, however, transitional. At many places, i.e. south of Arruda, a second thrombolitic carbonate unit occurs in the top part of the Abadia marls, laterally grading into peloid packstones. Above a 3-8 metre thick Abadia type marl level the base of the Amaral is sometimes represented by coral-bearing thrombolites, which laterally pass into coral boundstones (NOSE 1990, in prep.). At other places, marly coral meadows of the Abadia grade upwards into, commonly lense-like, coral boundstones. Elsewhere, coral boundstones occur above cross-bedded thick oolitic sandstones and bioclastic grainstones marking the transition from Abadia to Amaral facies. The Amaral beds are rarely thicker than 50 metres and normally consist of thick-bedded coral boundstones in the lower part, grading into oolitic grainstones with increasing quartz content in the upper part. Oolites may, however, also occur in the lower part and coral boundstone lentils also appear in the top oolites. Marls and sandstones are sometimes intercalated but are not laterally persistent. At places, either the coral boundstones or the entire Amaral unit are not developed. A most interesting feature is an irregular surface within the coral boundstones which though could be found only at some localities. Beneath the surface residual marls rich in calcitic hardparts occur in lentils so that the surface is interpreted as an intraformational erosional surface modified by early karst processes (NOSE in prep.; NOSE & LEINFELDER 1992; cf. CREVELLO & HARRIS 1984).

Younger units: The units superimposing the Amaral, i.e. the Sobral, the Arranhó and the Freixial beds are described in detail by LEINFELDER (1986), so that only a very brief description is given here.

The Sobral beds consist of marls rich in brackish benthic bivalve fauna, marine, partly cross-bedded sandstones and oolitic sandstones, as well as red bed facies and are interpreted to represent an estuarine delta complex. The delta facies wedges out towards southeast. In the lower and upper part of the Sobral delta red beds were only developed to the north, but they widely prograded towards south in its middle part. Further south, where the delta was only marine, oyster-rich conglomerates rich in reworked and transported caliche occur in one level in the middle part of the succession (Fig. 3). The age is thought to be largely Late or latest Kimmeridgian (LEINFELDER 1986), possibly extending into the earliest Tithonian (MANUPPELLA, Lisbon, pers. comm.).

The Arranhó unit (ex 'Pteroceriano') consists of limestones and marls rich in euryhaline to partly brackish benthic mollusks in its lower part and coral meadows and biostromes in its upper part. The depositional environment had a shallow gulf-like to estuarine character. The unit is only developed in the southern part of the subbasin. Lateral extension was largest directly at the base of the unit where the sea rapidly expanded over formerly terrestrial areas (of the Sobral delta). Subsequently, the sea withdrew again rapidly towards south. At the present coast, the basal Arranhó transgression is represented by a mixed carbonate - siliciclastic marine to brackish unit (Praia Azul facies). At Sintra, to the west of Lisbon, an ammonite of lowermost Tithonian age was found at the base of the unit. The base of the unit may also be correlated with a lowermost Tithonian peak in microfossil diversity at Cabo Espichel further south (LEINFELDER 1987a, cf. RAMALHO 1971).

The Freixial unit tops the Arranhó unit in the south and represents a succession of alternating carbonates, marls and siliciclastics. The depositional environment was a shallow ramp with mixed salinity characteristics deepening towards south. Red terrestrial siliciclasics prograded three times from north and northwest into southerly directions.

Terrestrial red beds of Uppermost Kimmeridgian and Tithonian age substitute the marine succession above the Amaral in the northern part of the Arruda Subbasin. These were termed Gres Superiores (i.e. 'Upper Sandstones') by many authors (e.g. RUGET-PERROT 1961, WILSON 1979). Other names used for the unit are Bombarral Formation (LEINFELDER 1986, 1987a) or Lourinhã formation (LEINFELDER & WILSON 1989). As mentioned above, a tongue of the basal Arranhó is intercalated over large parts of Lourinhã distribution. Due to poor exposure conditions no detailed examination of the succession is possible. Worth mentioning is an extensive, up to 2 m thick caliche development in one level. Comparable terrestrial sediments are well studied at the present day coast cliff exposures, where they represent humid subaerial fan, braided river and maeandering river systems (WILSON 1979, HILL 1989). Shallowing/ deepening patterns of the marine Arranhó and Freixial were tentatively related to base-level fluctuations and corresponding terrestrial facies shifts by LEINFELDER (1987a, 1988).

SEQUENCE STRATIGRAPHIC INTERPRETATION

Local identification of depositional sequences

In this chapter a sequential subdivisions of sections from the Arruda Subbasin is presented. From the foregoing it is obvious that the lateral arrangement of depositional systems in a tectonically active continental pull-apart-type basin cannot be described along classical shelf-basin gradients, but is strongly controlled by local synsedimentary tectonics, so that sequence stratigraphy cannot act as a general predictive tool in such settings. However, it can be expected that a sequence stratigraphic approach can help decipher the role of basin rift tectonics versus regional to global sea level fluctuations on sedimentation

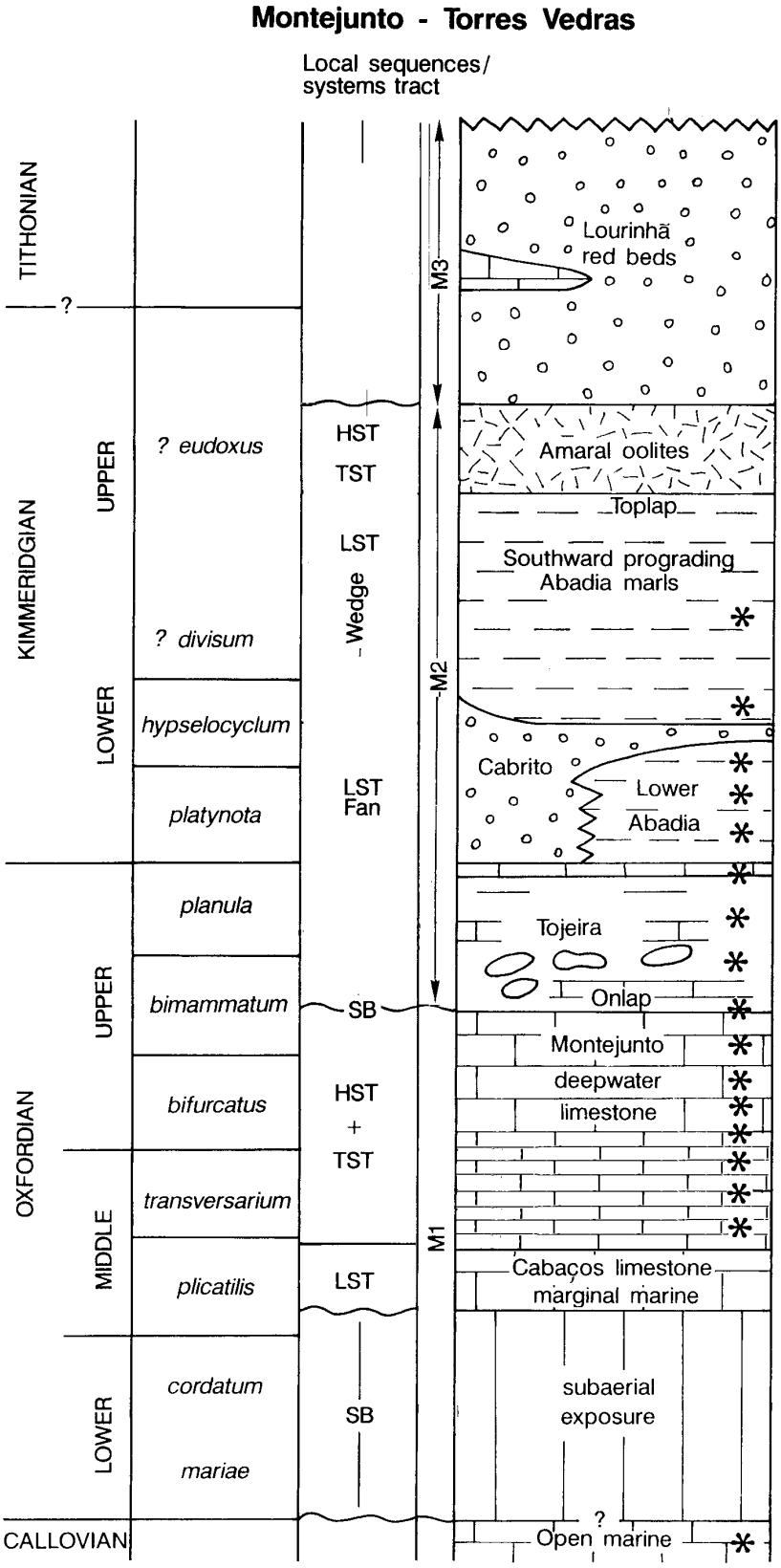

Fig. 4: Local depositional sequence identification in the Montejunto-Torres Vedras area. Stars indicate biostratigraphic control by ammonites.

patterns. Furthermore, the interpretation of palaeogeographic development can be refined by an identification of additional tie lines, providing a narrower spacing of available time slices.

It will be also shown that a complete set of sequences can be identified only by considering and combining both basinal and shallow-water settings (cf. Fig. 3).

In the following chapters SB, LST, TST and HST means sequence boundary, lowstand systems tracts (not further differentiated), transgressive systems tracts and highstand systems tracts, respectively.

Sequence identification in the Montejunto - Torres Vedras area (M1 - M3; Fig. 4)

A set of features allows discrimination of local depositional sequences in the Montejunto area:

SB M1: Presumed subaerial unconformity at the boundary between the Middle and the Upper Jurassic.

LST M1: Anhydrite-containing Cabaços Beds (Middle Oxfordian).

TST M1 and HST M1: Montejunto basinal limestones and Montejunto platform carbonates (lower part of Upper Oxfordian). Establishment of platform carbonates was not caused by a slowly rising or stable high sea level, but rather due to the shallow position on a structural/halokinetic uplift. Allochthonous grainstones within the basinal carbonates increase upwards and may be interpreted as highstand calciclast shedding. This was connected with slight progradation of the platform carbonates (cf. ELLIS et al. 1990: Fig. 7).

SB M2 and LST M2: The onset of siliciclastic sedimentation at the base of the Tojeira unit (upper part of Upper Oxfordian) marks the sequence boundary and subsequent lowstand shedding. Allochthonous limestone blocks shed from the platform area and occurring within the Tojeira were commonly karstified prior to transport, i.e. during SB M2, marking the final stop of platform edge growth. The Cabrito sandstones, passing laterally into the lower Abadia beds (Lower Kimmeridgian pp) are seismically characterized by subhorizontal reflectors (LEINFELDER & WILSON 1989) and hence could be interpreted as a lowstand fan or a lowstand wedge. A sudden outbuilding of Cabrito sandstones just at the top of its development (hypselocyclum-zone) is noteworthy.

The interior areas of the Montejunto platform possibly remained productive during the Lowermost Kimmeridgian and are characterized by tidal flat deposits during LST M2.

TST M2 and HST M2: The upper portion of the Abadia marls (Middle Kimmeridgian pp) in the Montejunto area is characterized by southwards dipping prograding clinoforms (LEINFELDER & WILSON 1989) interpretable as a highstand systems tract. The respective downlap surface indicates the position of the top of the transgressive systems tract. The Amaral unit topping the Abadia consists mostly of oolites in the Montejunto area, which could be interpreted as a prograding limestone cap belonging to the same depositional slope system than the Abadia prograding marls.

SB M3 and sequence M3: Terrestrial redbeds of Upper Kimmeridgian to Tithonian age superimpose the Amaral in the Montejunto area and cannot be further subdivided sequentially.

Discussion: Sequential subdivision of the Oxfordian to Kimmeridgian succession in the Montejunto area appears simple, particularly due to the existence of a fan system and a prograding slope system. However, the resulting system is very longlived (one "depositional sequence" spanning the entire Kimmeridgian). Other problems are the final outbuilding of the Cabrito fan and the unlikely incorporation of the Amaral grainstones into the Abadia siliciclastic highstand slope system. An alternative, less likely interpretation could be to identify the Cabrito unit as lowstand fan, the prograding Abadia unit as shelf margin wedge, the Amaral as transgressive systems tract and the redbeds as highstand deposits. This would result in an even more longe-lived depositional sequence spanning the entire Kimmeridgian-Tithonian time interval (cf. numbers 1-4 in Fig. 3).

Sequence identification in the Arruda region (A1 - A8; Fig. 5)

SB A1 and LST A1: No Oxfordian carbonates are drilled or at outcrop in the Arruda valley. However, their existence is likely. SB A1 is thought to correspond with the onset of the Cabrito/Castanheira, LST A1 with the more than 2200 m thick succession of Cabrito/Castanheira sandstones and conglomerates, possibly of latest Oxfordian to Early Kimmeridgian age, and the lower portion of the prograding Abadia unit. The Cabrito/Castanheira succession represents a submarine fan system with enormous thicknesses due to a rapidly subsiding local graben structure (LEINFELDER & WILSON 1989), interpretable as a lowstand fan. The prograding lower Abadia above had to interpreted as a shelf margin wedge, although no onlap structures are detectable. Like in the Montejunto area, seismic evidence rather allows the definition of a downlap surface formed by the prograding Abadia unit (op.cit.). However, the downlap surface is curved upwards towards southeast, i.e. downlap terminations climb with age (LEINFELDER & WILSON in prep.). This geometry is thought to be due to input from different sources, where the southward prograding Abadia slope system interfingers with the westwards outbuilding Castanheira fan.

TST A1: A level topping the lower prograding Abadia interval, with features diagnostic of very reduced sedimentation (thrombolites, crinoid-coral thrombolites, early concretions, iron impregnation) around Arruda (Serra Isabel condensed level) suggests interpretation as a condensed section related to a transgressive systems tract (top hypselocyclum? to divisum zone; top of Lower Kimmeridgian). Features of local bottom water

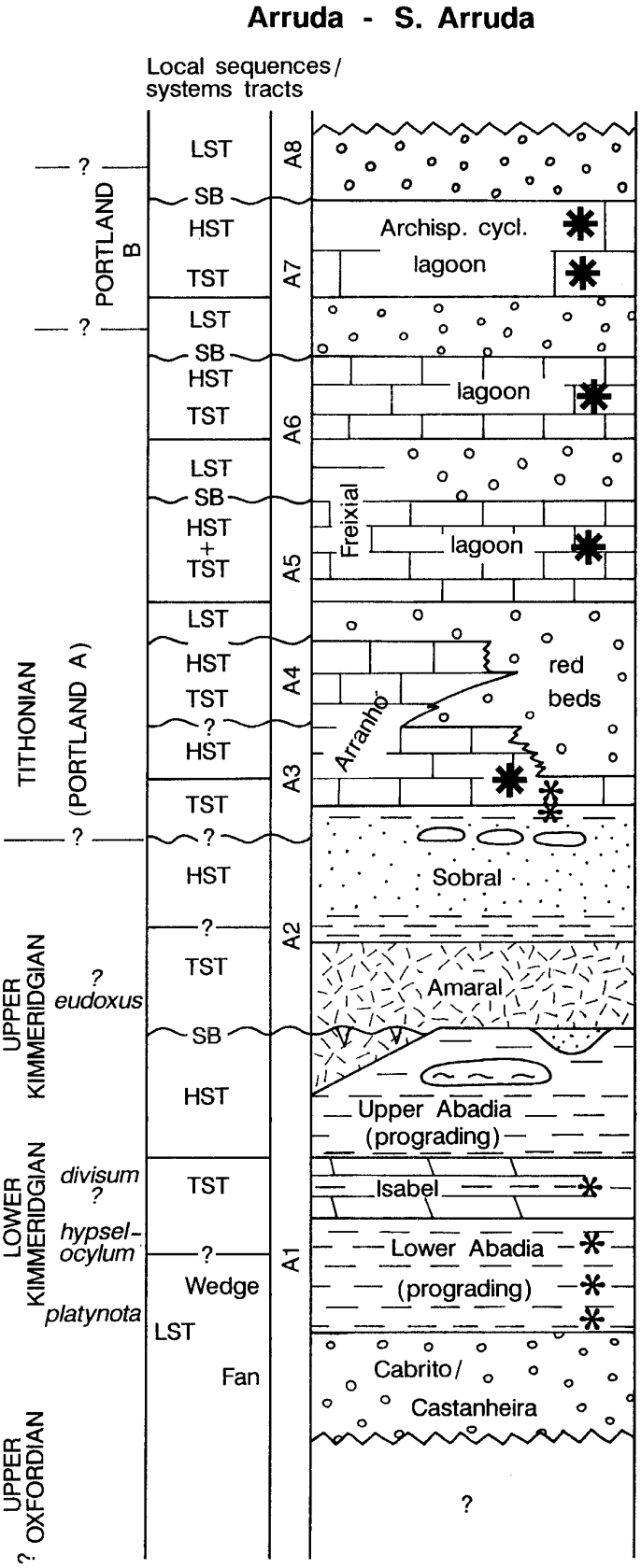

Fig. 5: Local depositional sequence identification in the Arruda dos Vinhos area. Biostratigraphic control is provided by ammonites (small stars) and microfossils (large stars).

depletion in this level (see above) can be related to reduced water circulation in the course of a major sea level rise (cf. WERNER et al. 1993, LEINFELDER 1993). Possibly, the top part of the underlying lower prograding Abadia unit formed during early TST.

HST A1: Most of the remaining part of the prograding Abadia unit (Upper Kimmeridgian pp) superimposing the Serra Isabel level is consequently interpreted as a highstand systems tract. At places, thrombolitic limestone lentils are intercalated in marls rich in foraminifera. These marls may pass into locally developed coral boundstones of the lower Amaral. The thrombolite and coral boundstone occurrences have to be related to an additional flooding event within the HST in this context.

SB A2, LST A2: In the uppermost part of the Abadia unit, the transition to the channeled oolitic sandstones at the base of the Amaral can be interpreted as lowstand deposits.

Elsewhere the Amaral development started earlier but is then subdivided by an intraformational erosional/karstic surface (base eudoxus-zone?).

TST A2: The part of the Amaral above the erosional surface (eudoxus-zone) and the superimposed basal part of the Sobral displaying deepening prodelta characteristics is interpreted as the subsequent TST. At places where no intra-Amaral erosional surface is developed, the SB2 is thought to be positioned not within but at the base of the Amaral (channeled sandstones, seismic toplaps) so that the entire Amaral plus the Sobral base relates to TST A2 in these cases.

HST A2: Rapid progradation of sand facies of the Sobral unit is interpreted to represent HST A2 (top eudoxus and beckeri-zone?)

SB A3 and LST A3: In the middle part of the Sobral, a widely occurring marine conglomerate with reworked caliche pebbles and a rapid basinward expansion of sandstones, commonly in red bed facies, is thought to represent the subsequent SB and LST.

TST A3: The widespread upper Sobral prodelta marls represent the following TST; the maximum extension of the sea at the base of the Arranhó is easily correlated with a maximum flooding surface (base of Tithonian or slightly higher).

HST A3: Lower part of the marly to calcareous Arranhó formation.

Sequence A4: The rapid retreat of the Arranhó can be related to a SB; the shallow-water sediments of the upper Arranhó represent sequence A4.

Sequences A5 - A8: The Freixial unit (upper part of Lower Tithonian to base of Cretaceous) exhibits distinct sedimentary cycles. Rapid red bed progradation is thought to have occurred during late highstand and particularly during late lowstand intervals whereas the marine to brackish shallow ramp deposits represent transgressive and early highstand phases.

Discussion: Sequence stratigraphic resolution into depositional sequences is much better than in the Montejunto area, particularly in the upper part of the succession. Very complicated is the subdivision of the Abadia and Amaral units. The fact that the Serra Isabel level clearly represents a classical condensed section allows the subdivision of the prograding Abadia interval into a late lowstand/early transgressive part and a highstand part. However, the intercalation of thrombolite lenses and coral boundstones in the supposed late highstand as well as the progradational character of the Abadia even during a supposed late LST/early TST causes problems. Progradation during transgression was possible only because of a high sediment imput, overcompensating the increasing accomodation except for the top part of this interval (Isabel level). Contrasting the interpretation of the Montejunto area, the Amaral limestone blanket is largely related to a transgressive systems tract in this interpretation. However, since onset of Amaral facies is very irregular and some of the lower part of the Amaral is identified as a highstand deposit due to its position below a erosional/karstic unconformity, the lowering of clastic input must also have reasons other than sea-level rise alone. Another problem is the interpretation of the intra-Amaral erosional unconformity: The irregular surface is accompanied by early meteoric karstic dissolution and enrichment of calcitic hardparts and terrigeneous material. Should the irregular unconformity not have developed as a subaerial surface but rather represents a subhorizontal early subsurface karst, the related sequence boundary had to be positioned higher up in the succession. Alternatively, since the horizon cannot be uninterruptedly traced in the Amaral, its formation could also be due to autocyclic or syntectonic shifts of environmental subsettings.

Sequence identification in the Ota area (O1 - O6; Fig. 6)

Besides the existence of Middle Oxfordian Cabaços limestones, the Ota limestone are the oldest sediments at outcrop in this area. The lowermost part of outcrops is of presumed "mid" Kimmeridgian age (top of sequence O1) and is topped by a local black pebble fan including reworked Middle Oxfordian limestones (SB O2, LST O2). Most of the lower Ota Limestone, that is the part between the black pebble fan and the widely developed main black pebble horizon, formed during TST and HST O2. The main black pebble horizon, which exhibits erosional relief and a low angle discordance, is related to SB O3 and base of TST O3 (hardground formation during first flooding). The Upper Ota Limestone formed during the rest of TST O3 and HST O3. Younger sediments (Amaral oolites, brown Sobral sandstones and terrestrial red beds, all of late Kimmeridgian to Tithonian age) onlapped the Ota during subsequent TSTs but became mostly eroded during respective SBs, so that they are normally only preserved in karst cavities. However, this allows the establishment of at least three other depositional sequences (sequences O4-O6, cf. LEINFELDER 1989, in press).

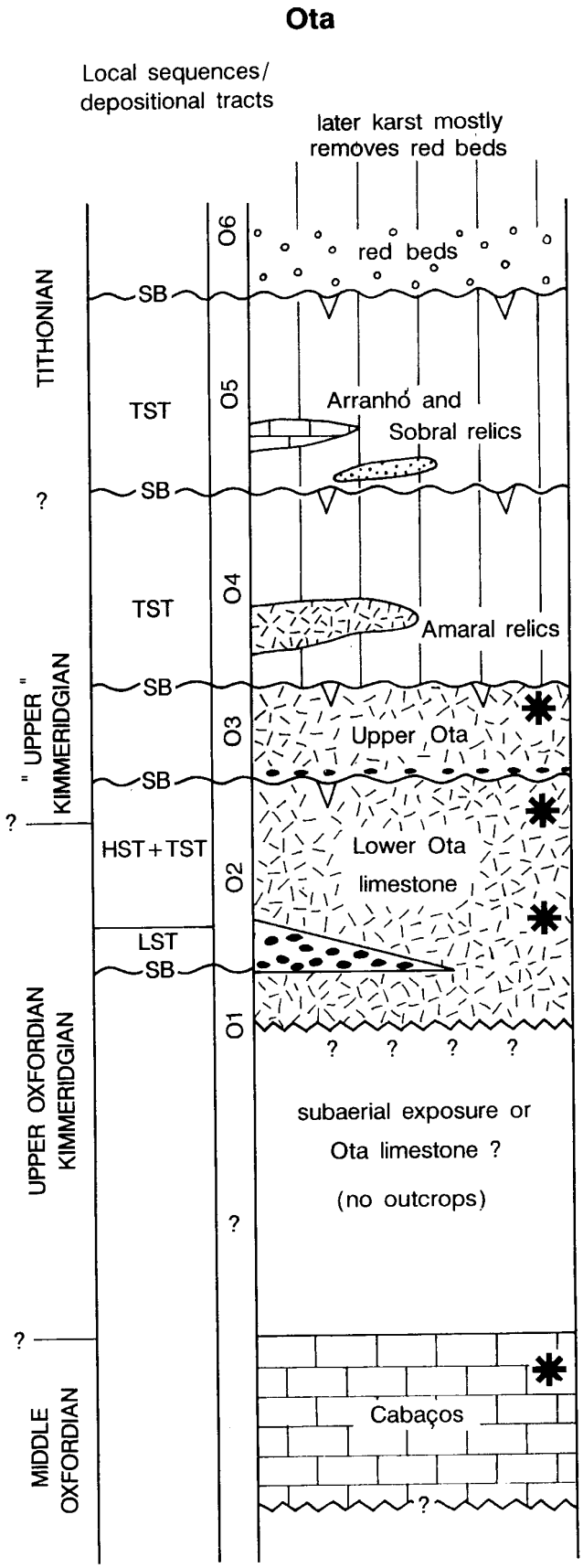

Fig. 6: Local depositional sequence identification in the Ota area. Stars indicate biostratigraphic control by microorganisms.

Discussion: The Ota succession and particularly its karst features are very helpful in supporting the identification of some of the depositional sequences established in the Arruda area. It should be noted that, based on the microfossil zonation given by RAMALHO (1981), the age of the outcropping part of the Ota was considered as younger than a transitional Upper Oxfordian/"lower" Kimmeridgian microbiozone and hence designated as "upper" Kimmeridgian by LEINFELDER et al. (1988). However, no correlation with ammonite zones is possible, so that the age of the Ota Limestone might well extend down to the Early Kimmeridgian.

Sequence identification in the Castanheira - Vila Franca area (C1 - C4; Fig. 7)

Again no information about a possible subsurface occurrence of Oxfordian limestones exists from this area. The lower part of the Castanheira fan can be tied to a sequence boundary and LST of sequence C1. The basal mixed terrigeneous-calciclastic grainstones of the Monte Godo reef are rich in black pebbles, and can be interpreted as a lowstand deposit. This level incorporated postulated, yet unknown TST and HST carbonates of sequence 1 which were blackened and reworked (SB C2, LST C2). Hence the Monte Gordo reef and related reefs are thought to have formed during TST C2 and HST C2 (Upper Oxfordian? to Lower Kimmeridgian). The deepening-shallowing trend of the Monte Gordo reef matches well with such an interpretation. SB C3 is represented by the karst horizon on top of the Monte Gordo reef; collapse breccia shedding represents LST C3. The upper part of the Castanheira fan is also considered as LST C3. Unlike the Monte Gordo reef, which grew on allochthonous calciclastics, the Castanheira reef developed directly on the fan conglomerates. Hence, the Castanheira reef and its parautochthonous relics are interpreted to have grown during TST C3 and HST C3 (upper part of Lower or "middle" Kimmeridgian); subsequent karstification and shedding of allochthonous blocks corresponds with SB C4 and LST C4. The onlapping Abadia and Amaral should represent the following TST C4. Younger sediments are poorly exposed and mostly consist of terrestrial red beds which cannot be further subdivided.

Discussion: The Castanheira - Vila Franca area is of great value to subdivide the Kimmeridgian megasequence, although autocyclic and syntectonic deactivation of fan lobes could, at least partly, also be responsible for reef development (cf. LEINFELDER 1989, in press). A simplified sequence stratigraphic interpretation would be possible, by considering both fan intervals as lowstands only and both the Monte Gordo and the Castanheira reef as TSTs and HSTs. This would result in a set of only three depositional sequences. However, the black-pebble rich interval at the base of the Monte Gordo reef clearly displays LST-characteristics so that the above interpretation of four local depositional sequences is favoured.

Correlation of local depositional sequences

As was shown, four different regions which are not very distant from each other, not only exhibit partly or completely different sedimentary successions but also very different sets of local depositional sequences. Unfortunately, biostratigraphic age determinations are not sufficiently exact and dense, to simply compare the different sequences within an exact time frame. The only possibility is to use the available age determinations and match the rest in a best fit pattern. Before doing so, other possibilities should be discussed.

Could it be that the depositional systems occurring in the Arruda Subbasin developed and modified themselves in an independent, partly autocyclic way? This is certainly true for the carbonate platforms developing on top of horst or halokinetic structures. Particularly the Ota platform developed penecontemporaneously with siliciclastic basinal sediments and was not only occasionally, i.e. during TSTs sheltered from terrigeneous pollution but rather during the entire time of its development. The likely sheltering mechanism was a longshore current system which developed due to the general palaeogeographic setting of the Lusitanian basin, independent of sea level fluctuations (LEINFELDER 1989, 1992, in press). Intraplatform cyclicity of smaller scale is also apparently driven by autocyclic mechanisms (LEINFELDER 1991). Another example is the prograding Abadia slope system which apparently was not restricted to a (general or local) HST situation but also occurred during (local) LST and early TST, indicates that progradation was rather caused by a generally high sedimentary input. Similar reasoning is true for the Castanheira fan system which apparently also spans at least two depositional sequences. Even reef formation within a fan system could, at least partly, be explained by autocyclic or tectonic activation and deactivation of siliciclastic lobes. However, the occurrence of reef relics in two distinct levels points to a more general deactivation of siliciclastic fan deposition, probably during rapid sea level rise. Karst formation on fan carbonates as well as on carbonate platforms may also be explained by tectonics, particularly since they are situated along the tectonically active pull-apart subbasin margins. Synsedimentary tectonics is a fact in the Arruda Subbasin (active horst structures and halfgraben flanks, angular discordances, collapse breccia, longlived fan systems). Should it be possible, in such an active setting, to nevertheless establish a convincing match between these very local developments, an additional control by a fluctuating regional or global sea-level would be apparent.

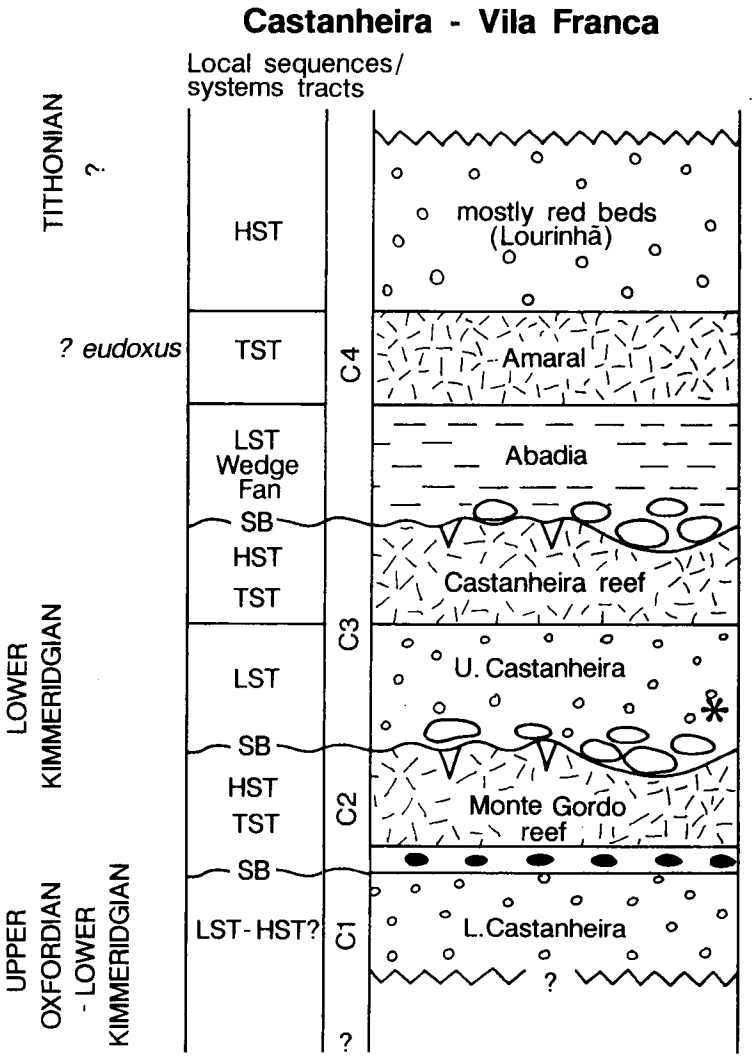

Fig. 7: Local depositional sequence identification in the Castanheira - Vila Franca area. Star indicates ammonite find.

Composite sequence stratigraphy of the Arruda Subbasin

Figs. 8 and 9 give a correlation of local depositional sequences across the Arruda Subbasin. Many of the local sequence boundaries and local systems tracts can be matched in a logic fashion. Particularly convincing is, for instance, the tying of the last outbuilding phase of the Cabrito with the lowstand deposits of the Upper Castanheira fan and the Ota main black pebble level. The Castanheira reef matches well with the Serra Isabel condensed section. The Amaral to Freixial sequences are partly preserved in the Ota region. Some incompatibilites of local sequence interpretation can be convincingly solved. For instance, the microbial limestones occurring below the Amaral in the Arruda area can be regarded now as representing an additional TST due to the identification of the karst level on top of the Castanheira reef. The Tojeira and Cabrito, appearing to belong to one LST in the Montejunto area can be differentiated into two LSTs by comparing with the Castanheira area.

Only the local, presumed, sequence boundary M3 (top of Amaral formation) in the Montejunto - Torres Vedras area is not correlatable with other localities, so that it is not considered for the composite sequence succession. Sequence boundaries M2 and C2, the latter from the Castanheira - Vila Franca area, cannot be verified in other localities, because the relevant levels are not exposed there (Fig. 8).

The combination and correlation of the locally identified depositional sequences results in a set of 11 depositional sequences for the Upper Jurassic of the Lusitanian Basin. Since the Middle Oxforian succession is still poorly studied, the picture might be oversimplified for the Cabaços beds. It is also obvious that the insufficient dating still would allow some other tie-lines, so that future adjustments may be necessary. To test the general correctness and compatibility of the pattern a brief comparison with successions from the the northern Lusitanian Basin, the eastern Algarve of Southern Portugal and other areas, and with the VAIL-group curve is given below.

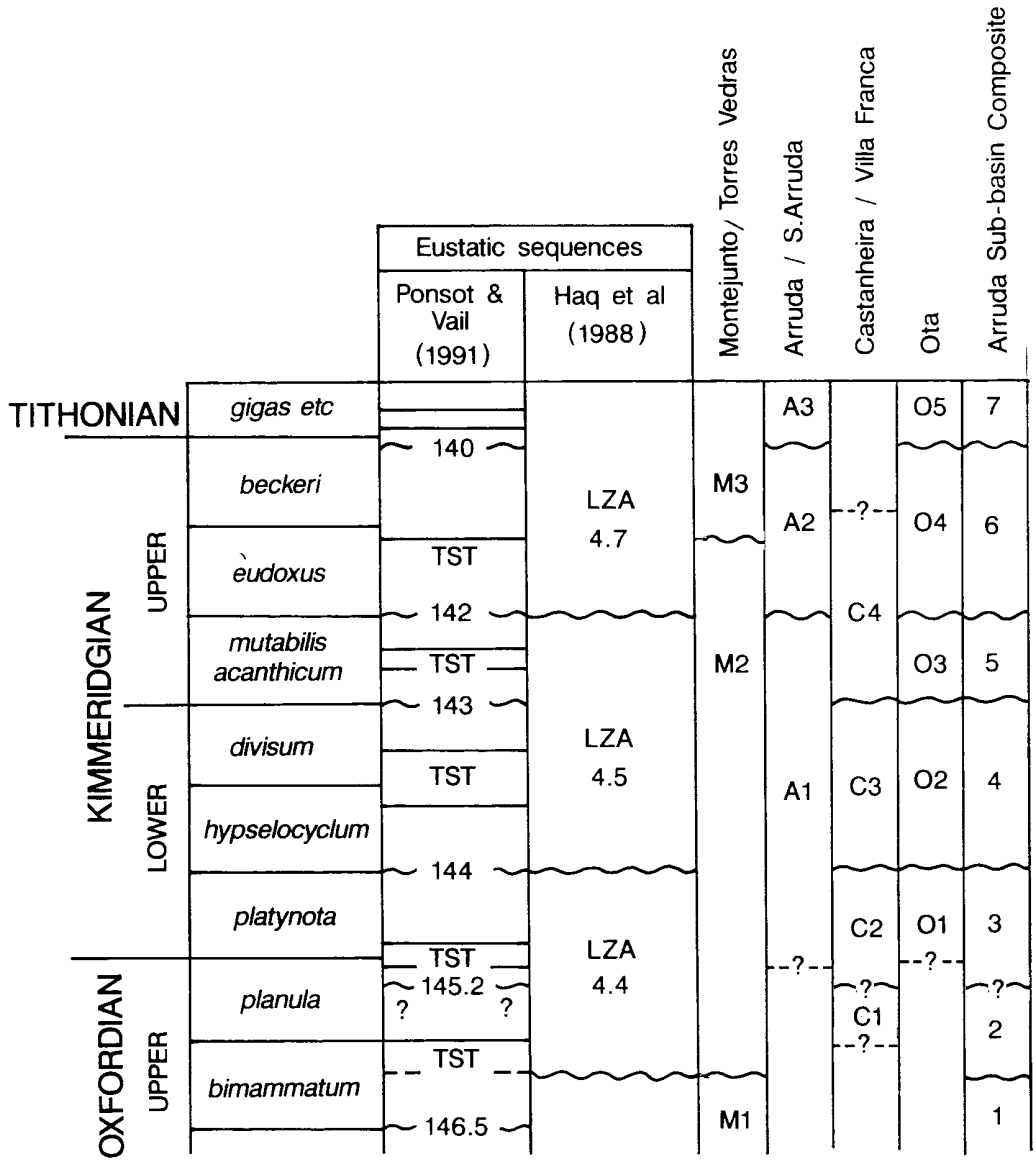

Fig. 8: Comparison of Upper Jurassic local depositional sequences from different localities of the Arruda Subbasin. Note that interpretations differ considerably, since sequential resolution varies greatly due to different accomodation potential and sedimentation rates.

Comparison with the northern part of the Lusitanian Basin

The Upper Jurassic succession in the northern part of the Lusitanian Basin is dominated by marginal marine to terrestrial siliciclastics, with rare intercalations of carbonate intervals (cf. WILSON 1979, LEINFELDER 1987a). A first sequence stratigraphic interpretation of this succession was recently given by BERNARDES (1992). She identified six depositional sequences spanning the middle Oxfordian to top Tithonian (JS1 - JS6, BERNARDES 1992: Fig. 106). JS1 comprises the Vale Verde beds which largely are equivalents to the Cabaços beds in the south. JS2 includes the marginal marine *Pholadomya protei* beds which can be partly correlated with the Montejunto beds. Both sequences are largely identical with the sequences 1 and 2, respectively, identified in the present paper. JS3 includes the entire Kimmeridgian and parts of the Lower Tithonian, thus spanning sequences 3 to 6 of the present study. Here it becomes obvious that sequential resolution in the northern part of the Lusitanian Basin is poor due to high terrigeneous input, overcompensating increase of accomodation and hence obliterating effects of base level shifts. The sequence boundary of BERNARDES´ JS4 is positioned at the boundary between the Kimmeridgian and Tithonian and hence can be

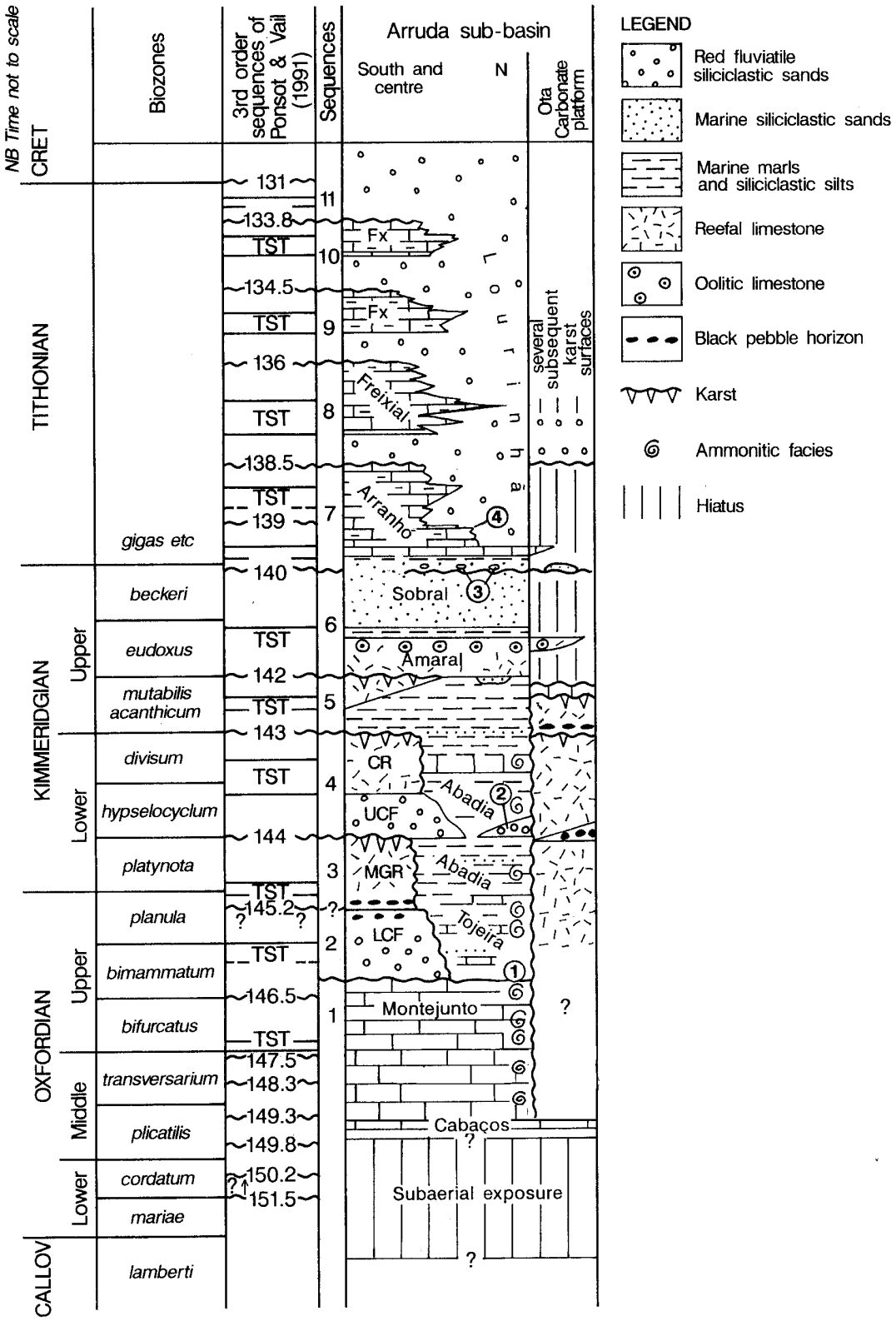

Fig. 9: Composite sequence stratigraphic interpretation of the Upper Jurassic succession of the Arruda Subbasin and best-fit with the PONSOT & VAIL (1991a,b) depositional sequences. Except for the Middle Oxfordian, match with the PONSOT & VAIL (1991a,b) sequences is excellent. (1) Onset of siliclastic sedimentation, (2) tongue of Cabrito, (3) reworked caliche nodules in marine conglomerates, (4) sudden basinward retreat of marine shallow-water carbonates in favour of red beds. LCF: lower Castanheira fan, MGR: Monte Gordo reef, UCF: upper Castanheira fan, CR: Castanheira reef.

correlated with the sequence boundary of sequence 7 of the present paper which is characterized by a horizon of reworked caliche pebbles. The maximum flooding of JS4 correlates with the Praia Azul member which is equivalent to the maximum expansion of the basal Arranhó limestones (see Fig. 3). This coincides with the transgressive phase of sequence 7. However, only three Tithonian depositional sequences could be verified in the north of the Basin (JS4 - JS6, the latter including parts of the Berriasian, whereeas in the Arruda Subbasin five Tithonian depositional sequences can be identified (sequences 7 to 11).

Comparison with the eastern Algarve Basin

The eastern Algarve Basin is characterized by an Oxfordian to Middle Kimmeridgian marl-limestone basinal succession rich in ammonites (MARQUES 1985). They are superimposed by middle to upper Kimmeridgian reefal and lagoonal limestones and by Tithonian lagoonal to Purbeck-type mixed facies. The entire Upper Jurassic succession exhibits shallowing-upwards characteristics similar to the Lusitanian Basin (LEINFELDER et al. 1993). A strong overprint of sea-level fluctuations is, however, obvious particularly in the Oxfordian - Kimmeridgian part of the succession: (1) Microbial, partly sponge-bearing mounds occur in various levels (e.g. RAMALHO 1988) and are thought to be due to omissions related with flooding surfaces (LEINFELDER et al. 1993). (2) Some sediment types such as boulder breccia and regionally developed quartz-pebble conglomerates can be easily identified as lowstand deposits (NOSE in prep.). (3) Frequent, ammonite dated omission surfaces, termed disconformities (MARQUES & OLORIZ 1989, MARQUES et al. 1991) punctuate the succession. They mostly represent condensed ammonite shell beds and are commonly rich in glauconite.

Most of the disconformities of MARQUES & OLORIZ (1989) can be very well tied to either presumed sequence boundaries or presumed maximum flooding surfaces and condensed sections of the Lusitanian Basin succession, supporting the idea of fluctuating sea level as a superimposed control on sedimentary processes (see LEINFELDER et al. 1993: Fig. 24). However, the partial match of Lusitanian Basin sequence boundaries with Algarve condensed disconformities needs further explanation.

Disconformities which match with the position of condensed sections or maximum flooding surfaces fit in the classical concept of sequence stratigraphy and are due to the rapid increase of accomodation potential during TST (VAN WAGONER et al. 1988). On the other hand, Algarve condensed disconformities which can be matched with Lusitanian Basin sequence boundaries are thought to be in part related to the breakdown of shallow-water carbonate factories during subaerial exposure and hence to a stop in the basinward shedding of allochthonous shelf lime mud. Additionally, climatic accentuation towards aridity during lowstand possibly also shuts down input of terrigeneous clay into the basin due to very low precipitation (LEINFELDER & BRACHERT 1991, LEINFELDER 1993). Both types of basinal disconformities, lowstand and TST-disconformities are characterized by condensation but may, at least in part, be differentiated, by a high amount of allochthonous shallow-water material in the first case and by a tendency towards dysaerobic features in the latter case, respectively.

Comparison with the Vail-group curves

Match of the composite Lusitanian Basin depositional sequences with the global sea-level curve given by HAQ et al. (1987, 1988) is only partly good (Fig. 8). Most of the HAQ-curve disconformities (i.e. sequence boundaries and maximum flooding surfaces or condensed sections) can be easily tied with the pattern established for the Arruda Subbasin. However, quite some of the Portuguese disconformities are either interpreted the opposite way (e.g. at 143 Mio a: maximum flooding surface of the HAQ-curve, whose position can be tied with a presumed sequence boundary in the Lusitanian Basin) or are not found in the HAQ curve at all. Recently, a modified version of the HAQ curve was published (PONSOT & VAIL 1991a,b), in which based on the Anglo-Paris Basin, several additional depositional sequences were identified. This updated curve can be extraordinarily well matched not only with the sequences from the Lusitanian Basin (Figs. 8, 9), but also with the disconformities described from the eastern Algarve and with many similar disconformities along the northern Tethyan shelf, e.g. of southeastern France, Switzerland and southern Germany (LEINFELDER & BRACHERT 1991, LEINFELDER 1993: Figs. 15, 16, this volume).

From the planula-zone (uppermost Oxfordian) up to the top of the Tithonian, all depositional sequences of the Arruda Subbasin can be perfectly tied to the PONSOT & VAIL (1991a,b) sequences. Sequence boundary 2 of the Arruda Subbasin occurs somewhat higher than the 146.5 Mio y sequence boundary of the PONSOT & VAIL (1991a,b) curve. Only the Middle Oxfordian sequences and the Tithonian/Berriasian unconformity of PONSOT & VAIL (1991a,b) cannot be verified in the Arruda Subbasin (Figs. 8,9). The latter seems, however, to be well developed in the western and northern regions of the Lusitanian Basin (cf. Fig. 1).

DISCUSSION

The fact that lithostratigraphic units of the Upper Jurassic of the Lusitanian Basin can be partly tied with time lines is not totally new. In a reverse geohistory-analysis approach LEINFELDER (1987a, 1988) modelled time slices based on averaged sedimentation rates, changes in water depths and terrestrial base level fluctuations. New sedimentological data in combination with the

application of sequence stratigraphic concepts result in a modification and higher resolution of such model-based stratigraphy. The good match with the eastern Algarve sections and with the modified Vail-curve (PONSOT & VAIL 1991a,b) is a convincing argument that sea-level fluctuations exhibited a major control on the Upper Jurassic sedimentation of the Lusitanian Basin despite its high synsedimentary tectonic activity.

It can be assumed that the Lower Oxfordian subaerial exposure and the general shift from the carbonate-dominated Oxfordian Cabaços and Montejunto limestones to marl and sand-dominated sedimentation of the Abadia and coeval units, and the backshift to the Amaral carbonate sedimentation is due to regional European tectonics (coupled uplifts/basin deepenings) in the course of North Atlantic and West Tethys rifting, since similar, roughly time-equivalent changes also occurred in other parts of Europe (cf. LEINFELDER 1993, this volume, for data and discussion).

Within this regional tectonic framework modifications were possible by local basin constellations and by third-order sea level fluctuations. Local constellations in the Lusitanian Basin led to either complete overcompensation of available accomodation in the north and hence to the dominance of terrestrial clastics there, or, on the other hand, to carbonate dominance at the southern ramp-type margin even during the Lower Kimmeridgian, i.e. the time of major basin subsidence, due to the remoteness of terrestrial input. Third-order sea-level fluctuations were, however, responsible for the development of condensed sections, short-termed spreading of marine facies over terrestrial areas, coeval occurrence of reefs within fan areas and condensed intervals in the basin, as well as correlatable karst phases. As outlined, these third order cycles can be matched very well with the depositional sequences as expected from the updated VAIL-group curve. Since, however, some of the third order lowstand features (karstification, collapse breccia) are also related to tectonics (e.g. block tilting in the Ota), it can be guessed that during the Late Jurassic even thirdorder sea level fluctuations were largely driven by tectonics, most likely also in connection with North Atlantic and West Tethys rifting and intraplate stress (cf. CLOETHING 1988). However, it remains to be proven whether these third order cycles can be only identified in Europe or are developed globally and hence represent true tectono-eustatic cycles.

CONCLUSIONS

1. The Upper Jurassic succession of the central part of the Lusitanian Basin (Arruda Subbasin) represents, in general terms, a mixed carbonate-siliciclastic basinal to terrestrial shallowing upward succession related to generally higher sedimentation/ production rates than accomodation rates. However, local modifications are numerous and can be related to both the synsedimentary tectonic framework (such as carbonate platforms on uplift structures along subbasin flanks; fan development from the eastern margin of the subbasin, slope progradation from the western margin towards southeast) and to third-order fluctuations in relative sealevel (coral reef development within delta fan and prograding slope systems, spreading of marine facies over terrestrial areas, development of condensed sections, karstification phases).

2. The Kimmeridgian part of the succession of the Arruda Subbasin can be subdivided into several large, long-lived depositional systems (marine fans, prograding slope, carbonate platforms) which owe their existence to the synsedimenary tectonic framework and to the related basin configuration. Sequence stratigraphic concepts cannot be applied to explain the arrangement and architecture of these major systems. Their general geometric development is largely unconnected from sea-level change in the Arruda Subbasin, but is related to the synsedimentary rift activity of this continental pull-apart structure. The development of a huge fan system and a fine siliciclastic prograding slope system was partly coeval and occurred on opposite sides of the subbasin. Decreasing tectonic activity on the eastern side of the subbasin led to the gradual retreat of the fan in favour of the prograding slope system. The aggradational architecture of a small intrabasinal zoned carbonate platform is also not related to sea-level rise but can be explained by the existence of a steep, tectonic by-pass margin preventing reef progradation.

3. Detailed sequential analysis of different parts of the subbasin (central part, marginal part, intrabasinal uplift area) reveals different degrees of resolution of sea-level effects. A combined approach, however, allows identification of a set of 11 depositional third order sequences. Considering basinal sections or shallow water sections alone would result in overlooking many of the depositional cycles, since sequences tend to amalgamate on very shallow carbonate platforms, and basinal condensed intervals will not develop in a high-sedimentation-rate regime. Particularly helpful in identifying third-order transgressive phases are correlatable carbonate intercalations in siliciclastic successions (coral reefs in siliciclastic fan; coral meadows and thrombolites in fine-grained siliciclastic slope system, shallow ramp-type limestones in terrestrial red beds). One of these transgressive levels, the Serra Isabel level clearly shows signs of occasional bottom water oxygen depletion related to changes in circulation patterns during sea level rise (cf. LEINFELDER 1993). The Kimmeridgian third order depositional sequences of the Arruda Subbasin occur only as overprints of the major sedimentary systems, without changing their general arrangement. Basin configuration and tectonic basin activity controlled the development of depositional systems to a much larger degree than sea-level oscillations, which is thought to be typical of active rift basins. Consequently systems tract

identification cannot be used as a tool to predict the general sedimentary development in such settings.

4. Critical surfaces (sequence boundaries, maximum flooding surfaces, first flooding surfaces) of third order cycles identified in the Upper Jurassic successions of the Lusitanian Basin can be well matched with condensed horizons, termed disconformities, of the eastern Algarve Basin (southern Portugal) and other central European regions. Such condensations can represent both maximum flooding surfaces or classical condensed sections as well as lowstand-related basinal condensation caused by shut-down of riverine clay input due to aridity and subaerial exposure of the lime-mud tributive carbonate factory. Match of the Lusitanian Basin sequences with the HAQ curve (1987, 1988) is moderate, match with the revised curve of VAIL & PONSOT (1991) is almost perfect (except for the Middle Oxfordian). However, for the Lusitanian Basin biostratigraphic data are scarce and match is achieved as a best-fit pattern. On the other hand, the major sedimentary changes within the Lusitanian Basin, from carbonate dominance to marl dominance and vice versa, were related to regional para-synchronous to heterochronous tectono-sedimentary changes probably related with rift pulses in the Northern Atlantic and Western Tethys region. These changes can be identified across entire Central and Western Europe and led to a crude second-order sediment cyclicity of marl versus limestone-dominated intervals which is not connected with sea level fluctuations.

5. Third-order sequence boundaries of the Upper Jurassic Lusitanian Basin succession are sometimes clearly related to tectonic events (tectonic tilting; tectonic collapse breccia). Connecting this fact with the regional good correlatability of third order sequences at least across western Europe leads to the assumption that most, if not all thirdorder sea-level changes of the Late Jurassic were driven by tectonics. Whether third-order correlation of sea-level cycles is possible only across western Europe or at a global tectono-eustatic scale remains to be proven in the future.

6. Understanding the mutual importance of regional tectonic gross scenarios (switching on and off of siliciclastic regimes), local basin configurations and the sedimentary and climatic effects of third-order sea-level fluctuations will result in a much more refined and dynamic basin analysis.

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