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Reefs and carbonate platforms in a mixed carbonate-siliciclastic setting. Examples from the Upper Jurassic (Kimmeridgian to Tithonian) of west-central Portugal

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1. INTRODUCTION

Modern tropical reefs and carbonate platforms grow within a relatively narrow window of environmental parameters, such as shallow water depth, warm water temperatures, carbonate supersaturation, normal salinities and oligotrophy. If occurring in close vicinity to a siliciclastic source area, effective sheltering mechanisms such as longshore currents or arid climate, or bypassing possibilities have to exist to allow for shallow water carbonate production and reef growth (Leinfelder, 1997; Doyle & Roberts, 1988; Roberts & Murray, 1983; Roberts, 1987). Only very specialised reefs, mostly with an „archaic", robust, pre-Pleistocene stock of reef corals can, to some degree, tolerate direct siliciclastic influx. This is the case for the Brazilian reefs off the Bahia and Pernambuco coast (Leão *et al.*, 2003).

The vulnerability of the tropical reef and carbonate platform system may be used as a perfect basin analysis and palaeooceanographic tool in ancient counterparts. Coral reefs and carbonate platforms being preserved within, or in close vicinity to, siliciclastic deposits allow for palaeotectonic, palaeoclimatic or palaeocurrent reconstruction or even may serve as a sequence stratigraphic indicator, with reefs and carbonate platforms growing preferably, but not exclusively, during transgressive episodes. However, such application is only possible if the evolutionary state of reefs and the palaeobiology of reef and carbonate platform organisms is taken into consideration. Ancient reefs may be composed of different reef builders with different biological adaptations and environmental demands, but even the same reef builder groups such as corals or sponges may exhibit partially or completely different demands and abilities depending on their state of development (Nose & Leinfelder, 1997; Leinfelder & Nose, 1999; Leinfelder, 2001).

Since about hundred years the Upper Jurassic of the Lusitanian Basin, situated in west-central Portugal (Fig. 1a), is studied for its rich fauna and its great diversity of sediment types (e.g. Koby, 1904/05; Geyer, 1955, Ruget-Perrot 1961). Coral reefs and carbonate platforms play an important part in the sedimentary history of the basin. The state of taxonomic and palaeoecological analysis is well developed, part of which is based on the fact that Upper Jurassic coral assemblages from the Lusitanian Basin often occur in terrigeneously influenced, soft deposits and therefore can be more easily collected and determined. Coral reefs occur as simple meadows, more complex biostromes, small to medium-scaled buildups or as part of small to large carbonate platforms. Besides various types of coral reefs, other types such as pure microbolite reefs, and bivalve reefs (oyster reefs, *Isognomon* meadows) occur as well. True siliceous sponge reefs are not developed in the Kimmeridgian and Tithonian of the Lusitanian Basin,

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but mixed siliceous sponge-coral examples are known. In some examples, coralline sponges (Calcarea and stromatoporoids) may play important roles in reef formation. Interestingly, most of the Kimmeridgian and Tithonian Lusitanian Basin reefs grew in a setting dominated by siliciclastics. Analysis of these examples hence contributes to the knowledge of (1) the sedimentology, ecology and controlling factors of Upper Jurassic coral-dominated reefs, (2) the structure, architecture, and origin of medium-sized Phanerozoic carbonate platforms, and (3) factors and control mechanisms allowing for penecontemporaneous siliciclastic and carbonate sedimentation which in turn can be used for basin analysis, including hydrocarbon exploration in subsurface basins.

This guide is based on an extensive period of investigation and much has been published by the authors and other working groups. Using all figures interesting for this field trip would be beyond the scope of this guide. The reader is referred to the cited references for more information. Field trip participants will, however, receive a handout add-on to this guide with additional figures.

2. GEOLOGICAL SETTING

The Lusitanian Basin is a Mesozoic Atlantic ocean marginal basin which, unlike most other Atlantic marginal basins, is exposed onshore (Fig. 1a,b). This is due to later inversion tectonics in the course of Alpine-Mediterranean compression. The character of the basin fill, and the calibration of its reef and carbonate platform characteristics as a basin analysis tool, may therefore serve as a model for similar, yet less accessible offshore basins.

The sedimentary and structural development of the Lusitanian Basin can be described by four tectonosedimentary megasequences, each of which is terminated by major subaerial erosional unconformities. Megasequence 1 spans Upper Triassic to Callovian sediments. It comprises sediments of the initial rift phase (red beds,

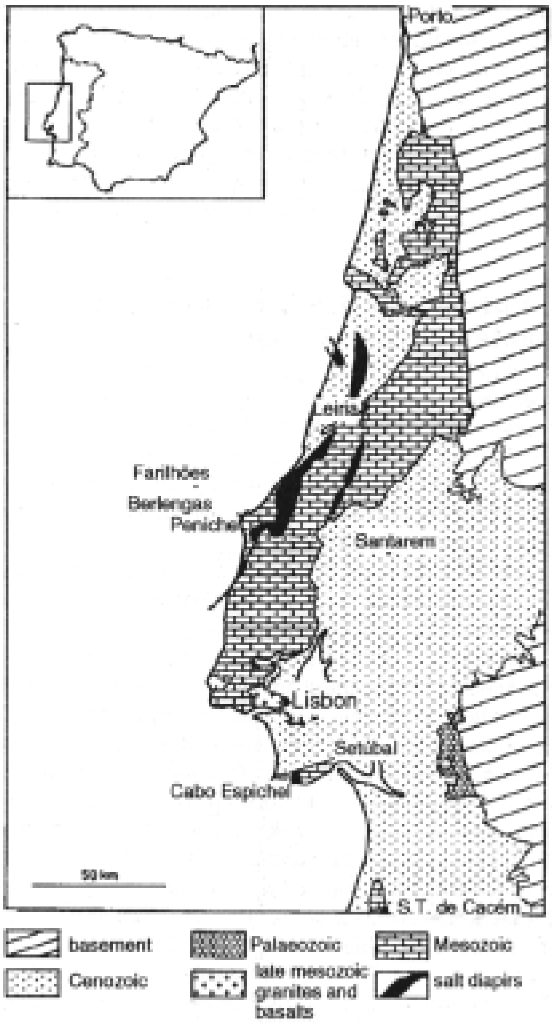

Fig. 1a - Geological map of west central Portugal.

Fig.1b - Map of the central part of the Lusitanian Basin showing principal structural elements and selected sites (after Wilson *et al.*, 1989, Ellis *et al.,* 1990). Black: outcrops of Upper Oxfordian and Kimmeridgian carbonate platforms. Dotted: Dagorda Formation. Smaller buildups and reefs are not indicated.

volcanics, evaporites) and the subsequent sagging phase (ramp-type carbonates, basinal marl-limestone successions). Megasequence 2 encompasses Oxfordian to Berriasian sediments and characterises a second, strike-slip dominated, rift phase of the basin, including the development of subbasins, and the more passive infill of the newly created basin morphology. Sediments are highly differentiated and include siliciclastic and carbonate deep-water to very shallow, marginal marine to lacustrine sediments, as well as an enormous amount of terrestrial red beds. Both source and reservoir rocks are frequent within this sequence. Siliciclastic influx recommences already during the Oxfordian in the North of the Basin, to largely dominate the Basin during the Kimmeridgian, and, to a lesser extend, Tithonian. Megasequences 3 and 4 comprise sediments from the Valanginian to the Turonian, and show again a more simple facies patterns, with red beds to the North passing into shallow marine sediments towards south. The rest of the basin is filled up by sediments of Late Cretaceous to Miocene age, most of which were eroded after inversion, which largely occurred during the Miocene. A more complete record of basin development is given by Leinfelder & Wilson (1989) and Wilson *et al.* (1989). More recent contributions to Lusitanian Basin analysis include Leinfelder & Wilson (1998) and Azerêdo *et al.* (1998, 2002).

The reefs and carbonate buildups which will be shown during the excursion grew during, or directly after, the rift peak of megasequence 2, which explains the highly differentiated morphology of the basin and the penecontemporaneous occurrence of carbonate and siliciclastic sedimentation.

3. THE KIMMERIDGIAN AND TITHONIAN REEF-BEARING SUCCESSION OF THE CENTRAL PART OF THE LUSITANIAN BASIN

The excursion demonstrates examples from the Kimmeridgian and Tithonian of the central part of the Lusitanian Basin. During this time interval, the basin was characterized by reactivated basement uplifts to the east (Iberian Meseta) as well as to the west (relics today as granites of the Berlengas islands, see Fig. 1b). The south (Serra da Arrábida-Cabo Espichel) and the nearby basin center (Sintra area) were much closer to the connection to the young Atlantic and consequently dominantly characterized by large scale, low-energy, partly steepened carbonate ramps during the Kimmeridgian (Sintra ramp, with fine terrigeneous influx during the Lower Kimmeridgian from the west, Ellis, 1984; Ellis *et al.,* 1990; Serra da Arrábida-Cabo Espichel area with strongly increasing siliciclastic influx from the West during the Late Kimmeridgian and Tithonian, Ramalho, 1971; Fürsich & Schmidt-Kittler, 1980; Felber *et al.*, 1982). The north was largely dominated by siliciclastic systems. In between the basin was differentiated into three subbasins, the Bombarral, Turcifal and Arruda subbasins. The Bombarral and Turcifal subbasins were separated from the Arruda subbasin by an reactivated hercynian basement lineament, causing halfgraben development. Along the lineament synsedimentary salt pillow formation caused additional uplift and structural modification (Montejunto fault system with southward extension to the Runa Fault, Figs. 1b, 3c). The Arruda subbasin developed distinct transtensional strike-slip characteristics, with intense facies differentiation and local Lower Kimmeridgian depocenters up to 2.5 km thick. Contrasting, subsidence in the other subbasins was more reduced and their vicinity to the strong west-derived basement uplifts caused a dominance of marginally marine to terrestrial siliciclastic successions, which were punctuated by marine ingressions (Fig. 2).

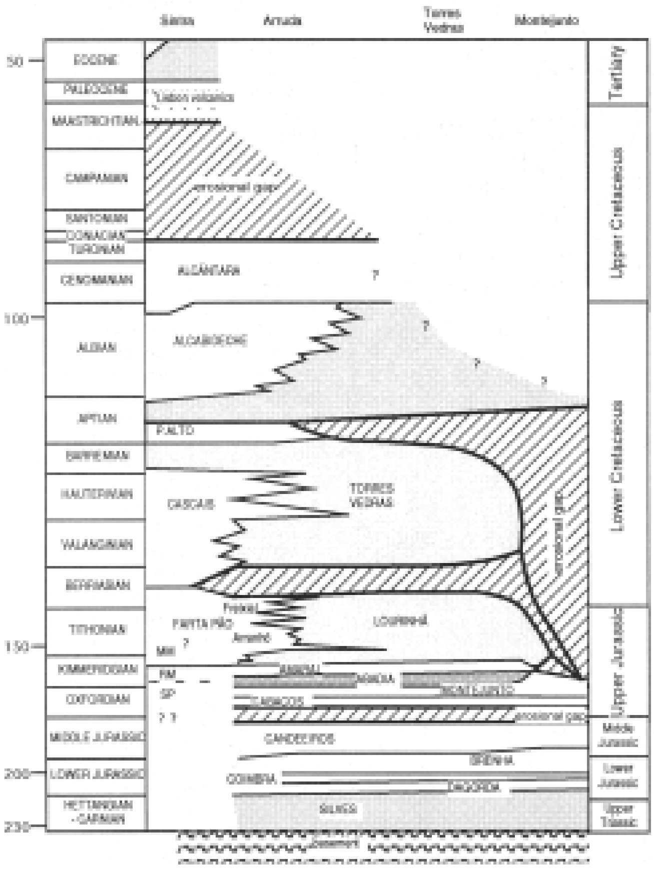

Fig. 2 - Lithostratigraphic succession of the Lusitanian Basin (after Leinfelder, 1994a).

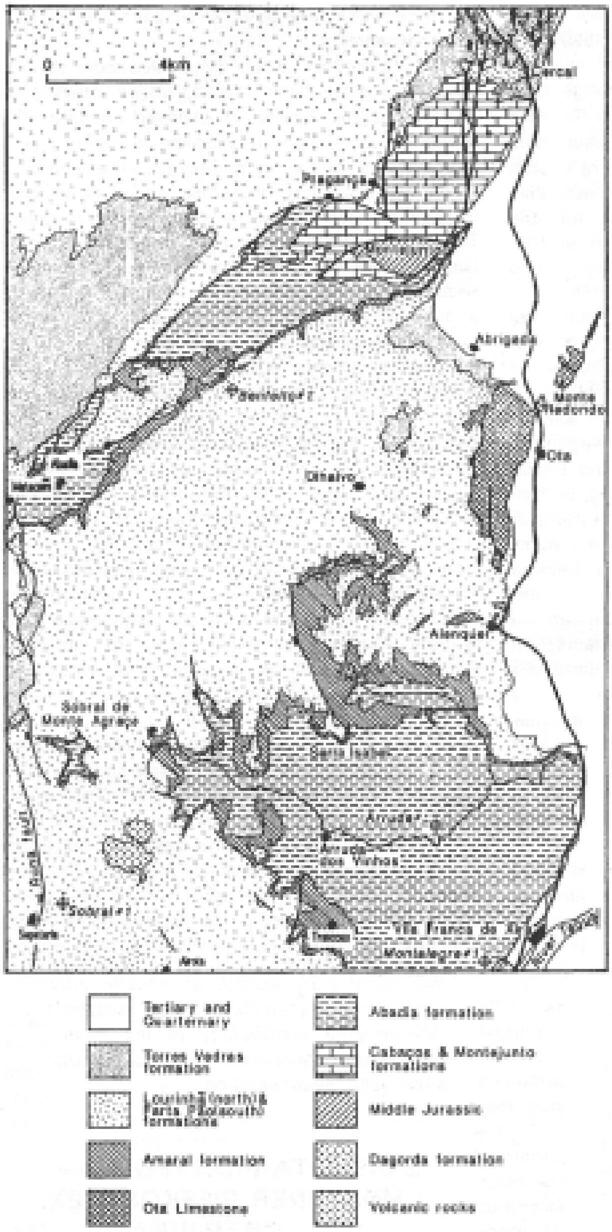

Fig. 3a - Geological map of the Arruda subbasin (after Zbyszewski & Torre de Assunção, 1965; Zbyszewski *et al.*, 1966; modified).

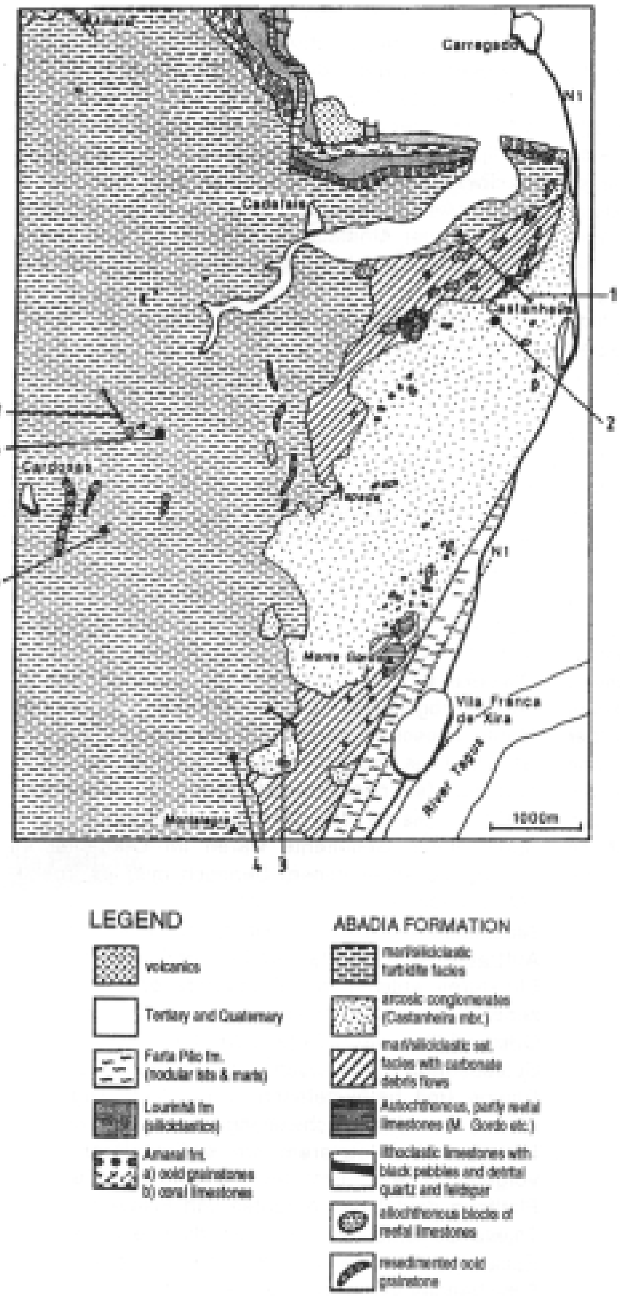

Fig. 3b - Geological map of the east side of the Arruda subbasin (cf. Fig. 6) between Carregado and Vila Franca. 1-7 indicate location of profiles and localities mentioned in Leinfelder (1994a).

3.1. Kimmeridgian and Lower Tithonian Reefs and Carbonate Platforms within Siliciclastic settings

We will not discuss here the Oxfordian to Kimmeridgian carbonate platform successions in the carbonate--dominated part of the Lusitanian Basin (Oxfordian interval and Kimmeridgian around Sintra and South of Basin). The reader is referred to Ramalho (1971), Felber *et al.* (1982), Ellis *et al.* (1990), Leinfelder (1994a), Azerêdo *et al.* (1998, 2002), Guéry (1984), Guéry *et al.* (1987), and Reyle (2003). The Montejunto platform, chiefly of Upper Oxfordian age, probably partially persisted to grow into the lowermost Kimmeridgian, but is also excluded here (see Ellis *et al.*, 1990; Guéry *et al.,* 1987; Leinfelder, 1994a).

3.1.1. Arruda Subbasin

The half-graben type basin is strongly, but differentially tilted to the east and structurally shows many internal basement uplift and subgraben-systems. Its strong facies differentiation clearly is an expression of the transtensional to transpressional strike-slip character of the subbasin (Fig. 3c).

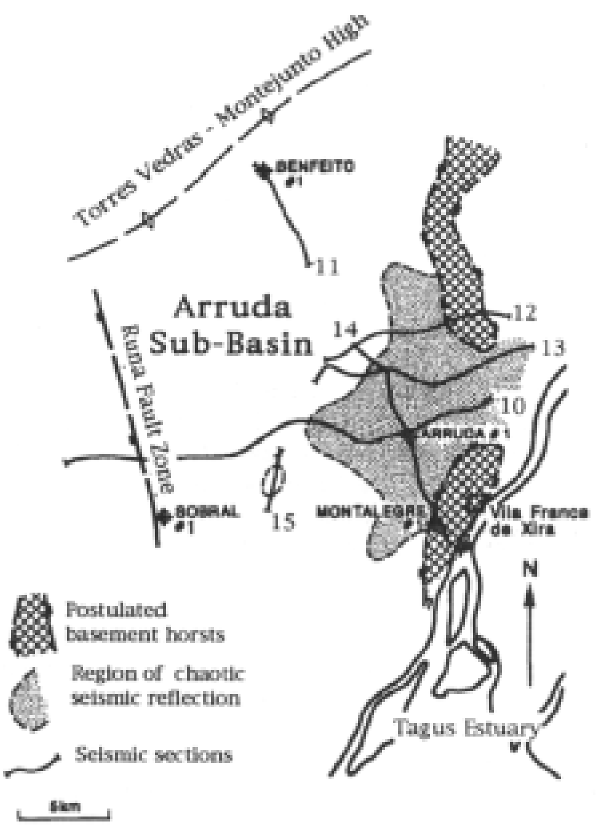

Fig. 3c - Seismic map of the Arruda subbasin (from Leinfelder & Wilson, 1989). The Ota-Platform is situated above the northern basement horst. The distribution of the proximal conglomeratic facies of the Castanheira fan is approximately outlined by the area with a chaotic reflection pattern. 10-15 refer to figures of seismic lines given in Leinfelder & Wilson (1989).

General succession and depositional systems: The general infill pattern for the Kimmeridgian and Tithonian part of the Arruda subbasin is dominated by two major siliciclastic depositional systems. A point-source fed, coarse submarine fan and fan delta (**Castanheira Fan**) positioned in the east accumulated up to 2.5 km of coarse siliciclastics in the center of the subbasin. Coral reefs (e.g. **Castanheira Reef**, **Monte Gordo Reef**) developed on abandoned parts of the shallow fan delta during episodes of tectonic quiescence and/or sea-level rise, to be mostly palaeokarstified and destroyed by collapse during subsequent sea-level fall and tectonic reactivation, leading to the shedding of large reef blocks into deeper parts of the fan slope and basin (Figs. 3b,c). The coarse siliciclastics were channeled through two large, marginal basement uplifts whose existence could be proven by seismics. During large parts of the Kimmeridgian, a narrow, aggradational pure carbonate platform developed on top of the northern uplift (**Ota Carbonate Platform**) irrespective of the adjacent coeval siliciclastic sedimentation. Coeval development is obvious by microbiostratigraphic markers typical of Lower to early Upper Kimmeridgian (incl. *Alveosepta jaccardi*, *Labyrinthina mirabilis*, *Clypeina jurassica*, *Campbelliella striata*; see Leinfelder *et al.*, 1988; Leinfelder, 1992), occasional wind-blown quartz grains and driftwood-root transported pebbles (Leinfelder, 1994a) as well as by another carbonate platform system (Amaral Carbonate Platform) capping both the Ota Platform and neighbouring siliciclastics. For more characteristics of the Ota Platform, the Monte Gordo Reef and the Castanheira Fan see excursion Stops below.

The Castanheira fan system interfingers with an initially aggradational, later prograding marl and siliciclastic silt dominated basin and slope system fed from the northeast, the **Abadia Slope System**. Slope-system characteristics are obvious by seismic clinoforms, sand-sized siliciclastic turbidites and major slump folding and slump breccia intervals. In the later part of its development the progradation of the slope system was punctuated by a transgressive pulse leading to sedimentary and faunal condensation, faunal telescoping from soft to firmground and occasional establishment of slightly deeper water coral or even coral-siliceous sponge reefs or pure microbolite reefs (**Serra Isabel level**, for details see Stops 6a,b).

Towards its top, the Abadia Slope System shows first establishment of marly coral associations, to then develop into a widespread, up to 80 m thick carbonate platform system, the Late Kimmeridgian **Amaral Carbonate Platform** (Fig. 4). Although generally being subdividable into a lower, coral-dominated part („Coráli-co") and an upper, oolite-dominated part („Oólito"), internal archi-tecture is much more complex, including oolites at places even in the lower part, irregularly developed subaerial unconformities, and even silici-clastic channels. Individual sections cannot be correlated over larger areas, which results in the interpretation of a highly complex origin of the Amaral Carbonate Platform, being partially coeval with siliciclastics, but at a subbasin-wide scale largely interrupting siliciclastic development (Nose, 1995). Thus the Amaral Carbonate Platform is not interpretable as an inner ramp cap developing penecontemporaneously as the proximal part of the Abadia Slope system, but rather as being caused by a progradational-retrogradational-aggradational mixture of stacked allocycles and autocycles during at least two sea-level transgressions. See Stops 7a-c for details on the Amaral Platform.

After the development of the Late Kimmeridgian Amaral Platform, siliciclastic influx commenced again, giving rise to the development of the estuarine delta

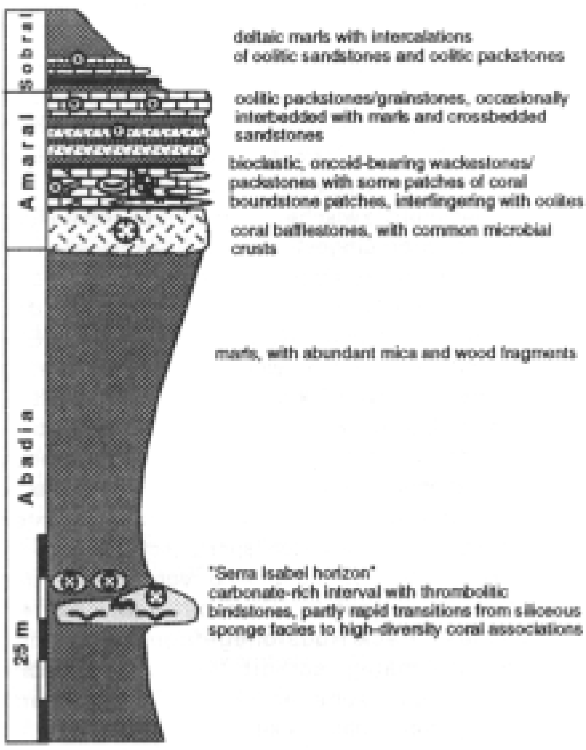

Fig. 4 - Simplified section of the upper Abadia beds and the Amaral formation to the east of Arruda dos Vinhos (from Leinfelder *et al.*, 1993a, slightly modified).

succession of the siliciclastic **Sobral Formation** of latest Kimmeridgian age, and the superimposed Tithonian **Arranhó Formation** (formerly known as Pterocericano). The Sobral formation may contain oyster reefs and other brachyhaline fauna, but occasionally shows levels with a more fully marine delta abandonment fauna, including sea-urchins and occasional corals. The Arranhó formation, whose base is strongly transgressive, is a succession of normally marine to restricted marine marls and clays, intercalated with muddy, mostly strongly bioturbated limestones. A combination of intense *Thalassinoides* and *Rhizocorallium*-burrowing together with differential hardening during early diagenesis gives these limestones a typical nodular appearance (shallow water nodular limestones). The fauna is dominated by infaunal, semi--infaunal and epifaunal bivalve assemblages but in the middle part of the succession, small coral patch reefs, sometimes with considerably elevated diversities occur (e.g. the **Alrota Patch Reefs**, for details see below). The Arranhó Formation is overlain by the late Tithonian Freixial formation, a still more restricted succession of shallow water carbonates, marls, clays and sandstones devoid of reef structures.

3.1.2. Kimmeridgian and Tithonian of the Western Part of the Lusitanian Basin

It is striking how different the Upper Jurassic developed west of the Montejunto – Runa line which was a major palaeogeographic element sheltering large parts of west-derived silics from the Arruda subbasin.

The Kimmeridgian to Tithonian coastal succession to the North is predominantly siliciclastic, being exclusively composed of terrestrial, deltaic to marginally marine deposits. A couple of marine ingressions allowed for the short-term development of brachyhaline to fully marine faunal associations most of which are bivalve dominated. Interesting reefal development occurred during the late Lower Kimmeridgian at Consolação where quite a variety of coral biostromes developed, but also brachyhaline oyster reefs which may show a short-termed peak development to coral-oyster reefs, highlighting an interval of largely fully marine deposits (see below for details).

Interestingly, towards the east, marine influence was much higher, which was particularly around the area of Alcobaça where another salt pillow rose. This salt pillow obviously kept major parts of the west-derived siliciclastic influx to the western part of the basin and allowed for a neat Late Lower Kimmeridgian carbonate platform (named **Caldas-Bolhos Unit** by Leinfelder, 1994a) to develop especially at the eastern flank of the diapir (Guéry, 1984; Leinfelder, 1994a) (cf. Fig. 1b). The excursion will visit one of the many coral-stromatoporoid reefs developed in this area as well as an outcrop with giant *Bacinella*-rich oncoids filling a tidal channel (see Stop 12 for details). The Caldas-Bolhos-Unit (which also may be called Middle Alcobaça beds) is a carbonate platform underlain and overlain by the Lower and Upper Alcobaça beds respectively, both of which are dominated by marginally marine siliciclastics, quartz-cored oolites and marls.The top part grades into red beds. The Alcobaça beds are largely equivalent to the Abadia Beds in the Arruda Subbasin. New ammonite finds and detailed sequential analysis (Klingel, unpubl. results) shows that the Caldas-Bolhos Unit is not a time-equivalent of the Amaral platform but rather of the Serra Isabel level (see Stop 6a,b).

Coastal sections to the south: Contrasting the more northern development, deeper water sediments developed during the Lower Kimmeridgian further to the south. Abadia beds similar to the Arruda subbasin outcrop at the beach of Santa Cruz, showing an important intercalation of a west-derived coarse-pebbled submarine canyon fill with basement material similar to the Castanheira fan at the eastern basin margin (Wilson, 1985; Ellis *et al.*, 1987). However, they shallow up rapidly to grade into terrestrial deposits, presumably already during the late Early Kimmeridgian (e.g. Hill, 1989; Hiscott *et al.,* 1990). A stack of marine ingression occurs further up (Praia Azul member) which can be correlated with the Amaral, Sobral and lowermost Arranhó Beds (cf. Leinfelder, 1987a; see Fig. 5). This Praia Azul member occurs at several outcrops and shows a dominance of marls, silstones and marine sandstones with well developed brachyhaline to, rarely, fully marine bivalve fauna, including *in situ* meadows of the semiinfaunal *Isognomon rugosus* and many oyster reefs. As a unique feature one location is known with a true brackish water coral-oyster biostromal reef (Leinfelder & Werner, 2004) (see Stop 10 for details). The rest of the succession is purely terrestrial, with a couple of marginally marine ingressions towards the south.

4. REEF TYPES, REEF ASSOCIATIONS, BIOLOGY OF JURASSIC REEF ORGANISMS

Jurassic reefs can be mostly grouped within the end members coral reefs, siliceous sponge reefs and pure microbolite reefs (Leinfelder, 1993, 2001). Some of the coral reefs may be rich in coralline sponges, and in rare cases these sponges might dominate. True siliceous sponge reefs did not develop in the Kimmeridgian and Tithonian of the Lusitanian Basin, simply because adequate ecospace in deeper water was not available (cf. Leinfelder *et al.*, 1993a, 2002). Pure microbolite reefs normally also occurred in lower mid- to outer ramp settings but locally developed in the Lusitanian Basin at very shallow depth probably owing to eutrophication or oxygen depletion (see Stop 6a,b). Microbial crusts were however an important attribute in most, but not all, coral reef types of the Lusitanian Basin (see Fig. 6).

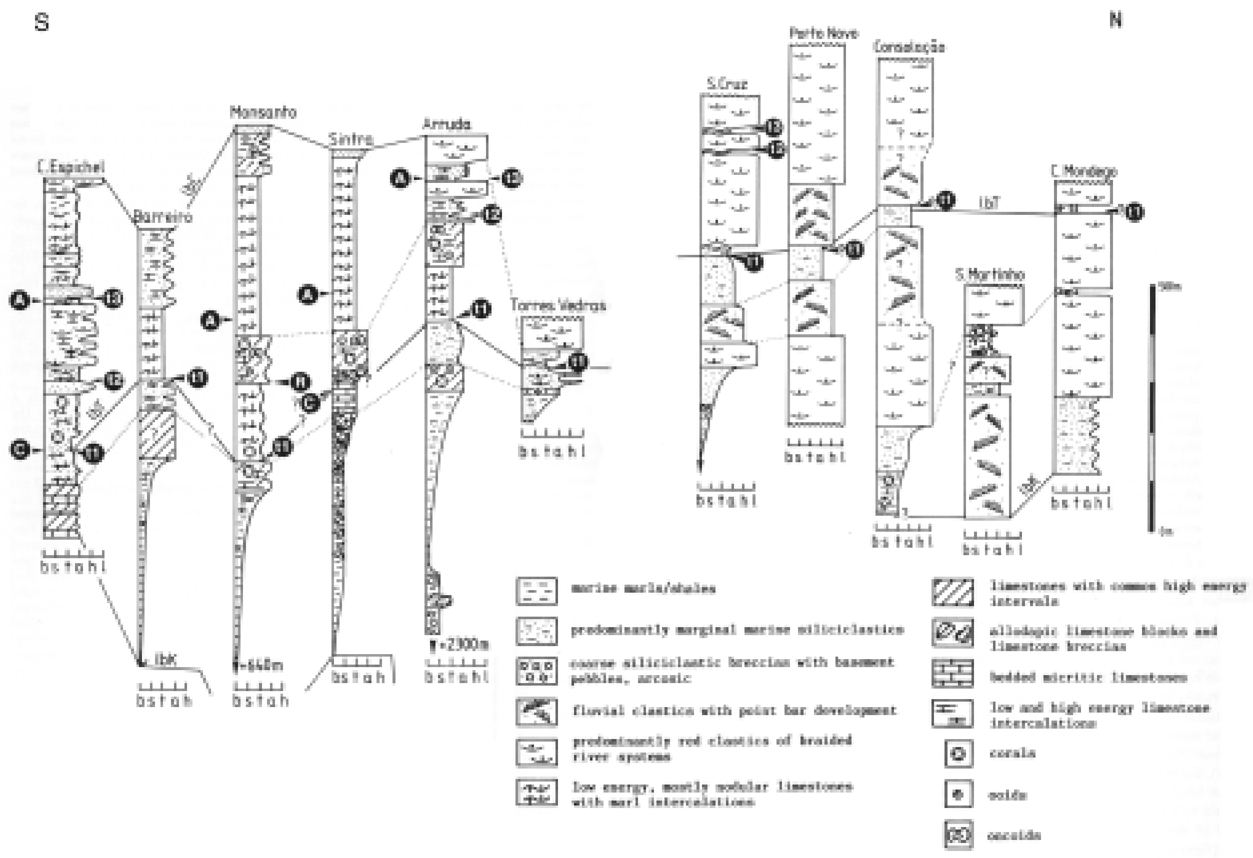

Fig. 5 - Simplified principal Kimmeridgian/Tithonian sections of the Lusitanian Basin (after different authors, compiled by Leinfelder, 1987a).

Jurassic coral reefs within the Lusitanian Basin and elsewhere occur in a great variety of different types. They encompass simple, monospecific to oligospecific, single population meadows, broad and partially complex biostromes, reworked, but largely in-place preserved, debris accumulations with or without microbial crusts and microbial crust-rich small patch reefs to large buildups with bafflestone and framestone characteristics. Faunal diversities and entire coral associations are largely variable, and different microencruster associations can be discriminated. Coral associations were largely determined by quantitative to semiquantitative methods (e.g. Leinfelder, 1986; Werner, 1986; Nose, 1995; Nose & Leinfelder, 1997), allowing to discri-

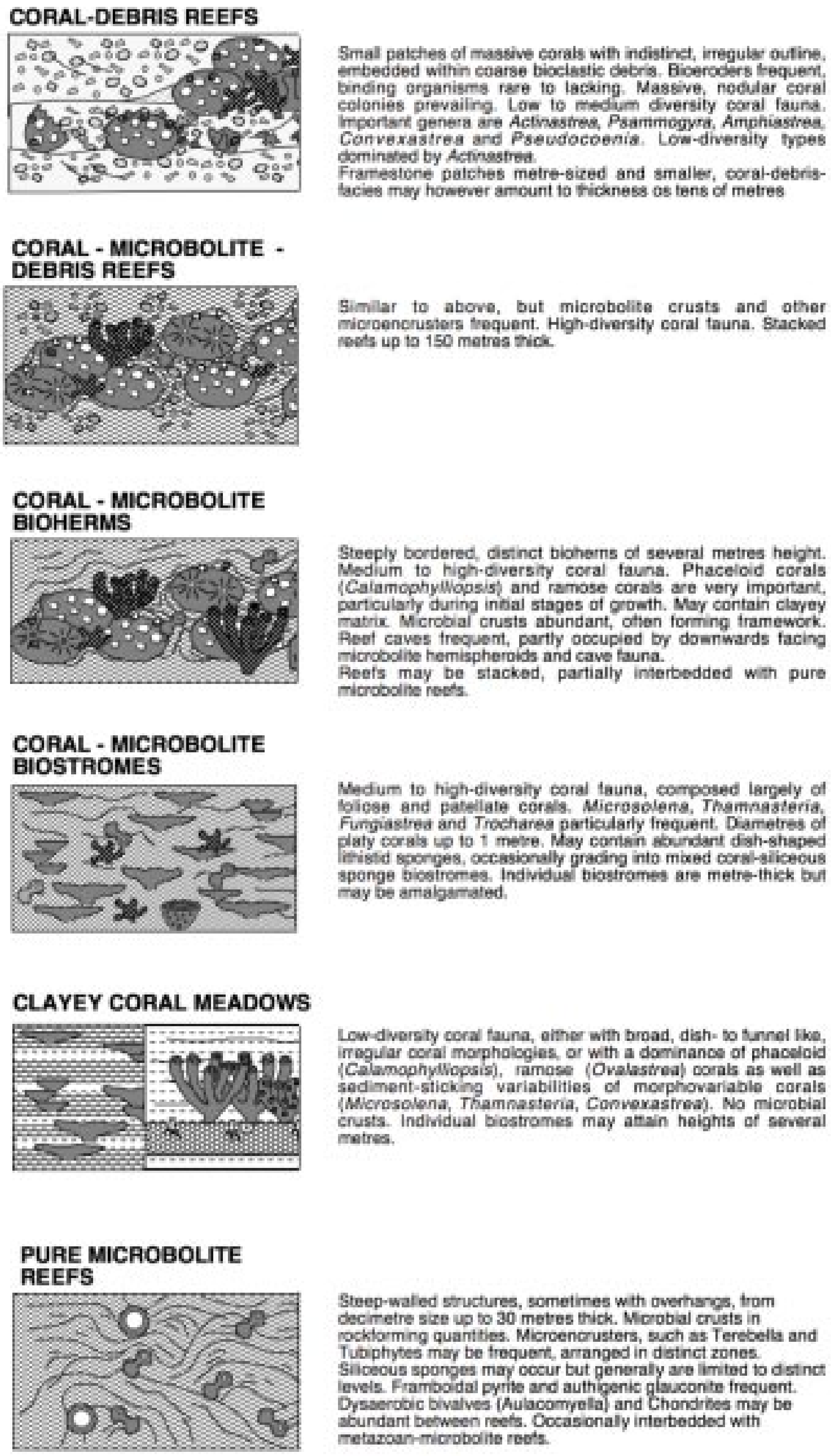

Fig. 6 - Some important coral and microbolite reef types of the Lusitanian Basin (from Leinfelder, 2001; modified).

minate low-, medium- and high-diversity associations. Additional diagnostic criteria are: absence or presence, and composition of microencrusters, microbial crusts, coral growth forms, additional fauna as well as sedimentological characteristics and relative position within large-scale shallowing upwards successions. Leinfelder *et al.* (1993a) and Nose (1995) could demonstrate in a cross-comparison of shallowing-upward successions with reef horizons from the Lusitanian Basin, the Algarve Basin and the Celtiberian Basin that water depth played a major role on the qualitative composition of the reef association, whereas background sedimentation rate as well as resedimentation processes have the strongest impact on overall coral diversity. Fig. 7 shows that Lusitanian Basin coral associations can be grouped along a bathymetric gradient, with high microbial crust participation and low contents of siliciclastic material in high-diversity associations and vice versa. A lot of adaptational strategies towards elevated sedimentation can be found in Lusitanian Basin corals, such as funnel growth shapes, transition from superstratal to constratal growth and dominance of phaceloid or plocoid to meandroid growth shapes (Nose, 1995; Leinfelder, 2001). An interesting feature is, however, that a small but noticeable amount of terrigeneous contamination was beneficial in terms of diversity development (Fig. 7). This was interpreted by Nose & Leinfelder (1997) as being due to a not yet perfect photosymbiontic relationship which caused many Jurassic coral reefs to grow in vicinity to siliciclastic hinterlands providing additionial nutrition through a moderate siliciclastic influx. Additional criteria for this interpretation are the slower growth rates and lower ratios of low-vs. high-density skeletal bands relative to modern corals (Nose & Leinfelder, 1997) as well as the general paucity of corals and entire coral reefs in large--scale, presumably superoligotrophic carbonate platforms of the southern Tethys (e.g. Saudi Arabia) (Leinfelder *et al.*, 2002). Specialised Jurassic coral associations could occur down to considerable water depths, probably down to about 50-60 metres (*Microsolena-Trocharea* community, see Fig. 11), and the ubiquitous cerioid form *Amphiastrea piriformis* could not only settle under strong siltation influx but also in brackish water settings forming large biostromal structures (Leinfelder & Werner, 2004, Stop 10).

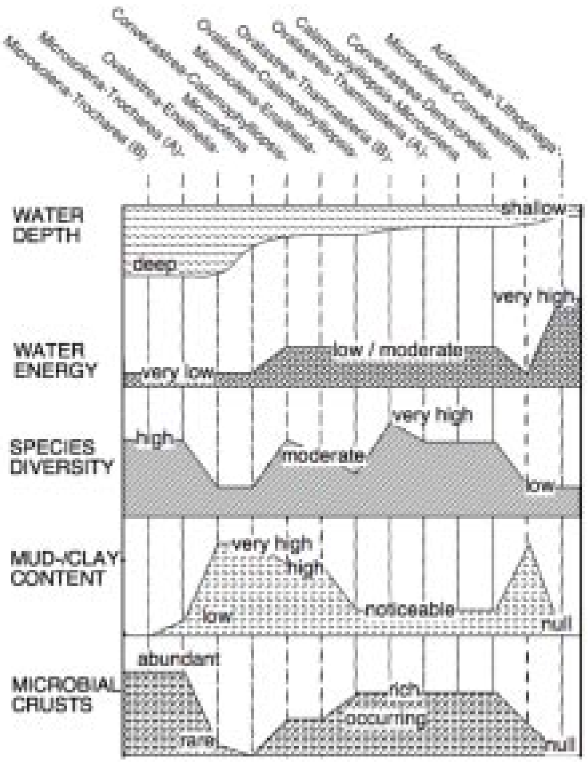

Fig. 7 - Coral associations of Portugal change along a bathymetric gradient. Relative bathymetric calibration and interpretation of water energy is possible by occurrence of reef associations within shallowing-upwards succession, by sedimentological features, by morphotype interpretation of diagnostic corals, and by associated fauna (compare with Fig. 11). Note that species diversity does not change uniformly along with bathymetry, but is mostly negatively correlated with terrigenous clay content in the groundmass and positively correlated with the amount of microbial crusts, pointing to sedimentation rate as the major modifier of diversity. Highest diversities occur, however, in associations with a low, but noticeable clay content, indicating the importance of nutrient availability for Jurassic reef corals (see text for further explanation; after Nose, 1995 and Nose & Leinfelder, 1997, modified).

Lusitanian Basin coralline sponges were largely not cryptic as compared to Permian or modern reefs but could occasionally form extensive meadows (Fürsich & Werner, 1991). Unfortunately, formerly well developed outcrops do not exist any longer. In other cases, coralline sponges are additional, sometimes frequent elements in coral associations (Werner *et al.*, 1994; Schmid & Werner, *in press*).

Microencruster associations from the Lusitanian Basin are highly sensitive to water depth (see Fig. 11). The high-diversity *Lithocodium-Bacinella* association is strongly light dependant. Lusitanian Basin material allowed the enigmatic *Lithocodium* of supposed algal character to be reeinterpreted as an encrusting loftusiid foraminifer (Schmid & Leinfelder, 1996). Similarly, *Tubiphytes morronensis* was reinterpreted as a miliolid foraminifer (Schmid, 1995; Henssel *et al.*, 2002) which not only occurs in deeper settings but also in very shallow reefs, where it does show a significantly thicker outer layer, a dynamic feature which can be used as a palaeo-dipstick (Schmid, 1996).

Microbial crusts are typical indicators of very reduced sedimentation rates. High amounts of microbial crusts within coral reefs were recently interpreted as representing high-frequency environmental shifts from oligotrophic coral associations to mesotrophic microbial crust associations for French Jurassic reefs (Olivier, 2004). Whilst this might be true in some examples, the mesotrophic character of many Lusitanian coral reefs and true intergrowth shows that at least the majority of crusts grew together with the corals. Except for the demand of very reduced sedimentation, microbial crusts tend to be rather eurytopic. Pure microbolite reefs, or pure microbolite parts of mixed reefs might grow whenever other, less eurytopic organisms may be excluded, be it hypersalinity, amphibic environments, overheating of waters, eutrophy, extreme oligotrophy or dysaerobic settings (cf. Leinfelder *et al.*, 1993b; Leinfelder, 2001). Parts of the pure microbolites of the Serra Isabel level are interpreted as due to dysaerobic waters being pulled up during transgression to relatively shallow levels (see Stop 6). Microbial crust fabrics and growth forms may allow closer differentiation of sedimentation rate and water depth (Schmid, 1996; Leinfelder & Schmid, 2000), although microencruster associations within the crusts typically are better indicators of water depth.

5. BASIN APPLICATIONS

5.1. Using reefs and carbonate platforms to interpret sequence stratigraphy of the Kimmeridgian and Tithonian

Sequence stratigraphic models of Jurassic reef growth (e.g. Leinfelder, 1993, 1994b, 2001; Leinfelder *et al.*, 1993a, b, 1996) were, to a large part, developed in the Kimmeridgian and Tithonian of the Lusitanian Basin. Refined biostratigraphy is not possible in the Kimmeridgian of the Lusitanian Basin. Ammonites exist in the Abadia System, but are rare and in part endemic. Microbiostratigraphic resolution of the reefs and carbonate platforms is insuffcent for lateral refined correlation. Therefore, sequence stratigraphy appeared to be the only promising method to allow for better time slice resolution.

At first sight, the Kimmeridgian succession may be easily interpreted in sequence stratigraphic terms. The Castanheira Fan could be interpreted as a lowstand fan, the Abadia marls and turbidites as a lowstand wedge, the Amaral Formation as the Transgressive Systems Tract and the marginally marine to terrestrial Sobral Delta succession as the Highstand Systems Tract.

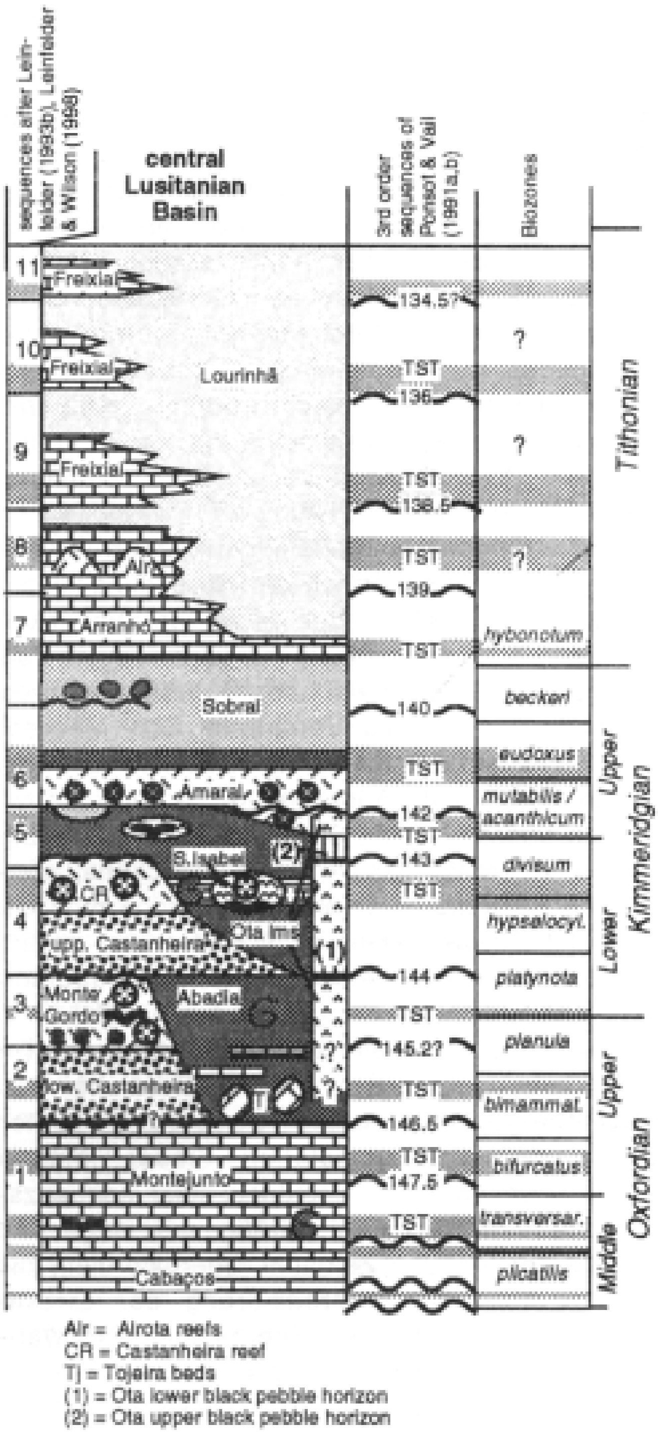

Fig. 8 - Sequence stratigraphic interpretation of the Upper Oxfordian to Tithonian succession of the Arruda subbasin (modified from Leinfelder, 1993b). The development of reefs in the Castanheira fan, calcareous intercalations in the upper Abadia beds, the Amaral formation, and the limestone dominated intercalations in the Arranhó and Freixial beds is correlatable with transgressive intervals. Growth of the Ota-Platform was, however, not interrupted by lowstand siliciclastics. Above the Oxfordian, correlation with depositional third-order sequences of Ponsot & Vail (1991a, b) is possible.

However, this oversimplified picture does not take the following features into account:

- The fan system itself contains two levels with occasional reef development, part of which shows their own deepening-shallowing trend (Monte Gordo reef).

- Coarse grainflows and reef material shed from the Castanheira System are intercalated in the basinal to slope succession of the Abadia System, showing coeval development of both systems. Moreover, both systems are derived from different basement sources (Fan from West, Slope from NE).
- The Ota Carbonate Platform is not a local thickening of the Amaral system, but again coeval with the Abadia and the Castanheira siliciclastic systems. The Amaral system unconformably overlies the Ota Platform. In addition, the Ota Platform shows several synsedimentary subaerial exposure surfaces.
- The Serra Isabel level with its strongly transgressive characteristics would be situated within a lowstand system.
- The Amaral Carbonate Platform exhibits a complex architecture including subaerial exposure surfaces.
- The Sobral succession also locally exhibits an internal unconformity characterized by a conglomerate of reworked caliche.

Using both sedimentary features and organismic features, reefs could be used to highlight the relative degree of sediment influx, water depth and general stability of environment, which can be applied to the interpretation of sea-level state and development (Leinfelder, 1994b, 2001; Nose, 1995; Nose & Leinfelder, 1997; Schmid, 1996; Leinfelder & Wilson, 1998; see Figs. 8,9,10).

5.2. Using reefs and carbonate platform characteristics to reveal other basin analyis parameters

Kimmeridgian and Tithonian Lusitanian Basin reefs and carbonate platforms may be used for several other basin analysis purposes:

Water depth interpretation: Jurassic reef associations have been calibrated by comparative studies using shallowing upwards successions from different parts of

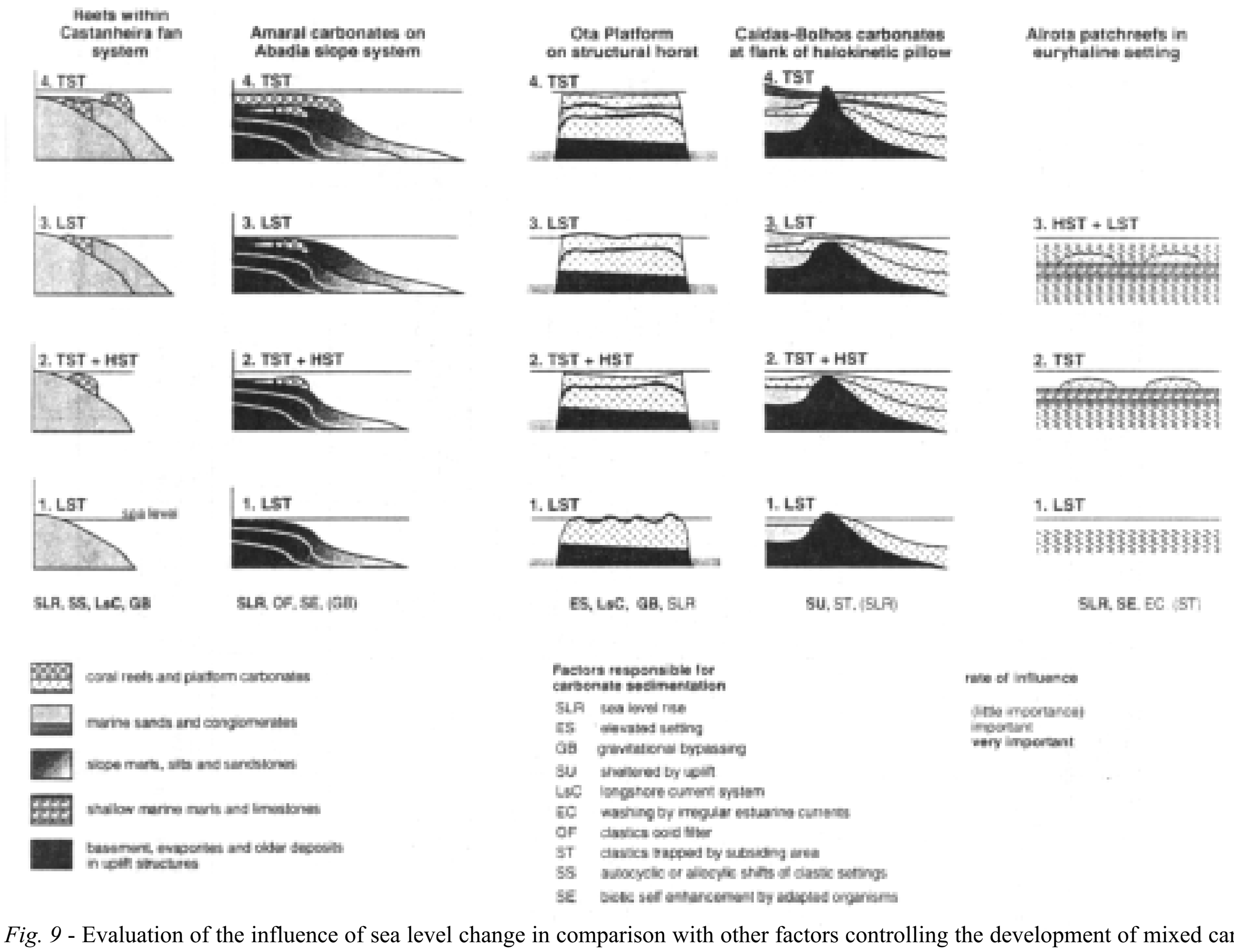

Fig. 9 - Evaluation of the influence of sea level change in comparison with other factors controlling the development of mixed carbonate--siliciclastic depositional systems (based on the case studies presented here). Sea level rise is the major prerequisite for many, though not all, systems discussed here, but has to be accompanied by other control mechanisms to result in carbonate deposition within a siliciclastically dominated basin. Structural uplift is another powerful mechanism to support carbonate development within siliciclastic basins, but also does not work without other accompanying factors. An ‘aridity’ factor can be ruled out due to the widespread sediment types indicating vast freshwater areas and semiarid to semihumid climate (after Leinfelder, 1994a).

Iberia, France and Germany. There are several coral taxa and coral associations as well as bivalves, sponge groups and microencrusters which mirror water depths. Fig. 11 shows an example for the Lusitanian Basin.

Shelf configuration and slope angles: Together with their bathymetric distinctness, the reactivity of Upper Jurassic reefs to various degrees of background sedimentation or resedimentation not only allows for sequence stratigraphic analysis but also for interpretation of slope angles and general shelf configuration (Leinfelder, 1992, 1994b, 2001). Fig. 12 sums up the existing models. Upper Jurassic high energy reefs on ramps and depositional margin platforms are mostly coral-debris piles with very little original framework preserved. A distinct coral-microbolite-debris reef is the Ota reef at the margin of the platform. Microbial incrustation had a chance since much of the excess debris could be exported along a steep bypass margin, making this reef type diagnostic of such steep shallow platform breaks (Leinfelder, 1992; Leinfelder *et al.*, 2002). Owing to bypass possibilites for shallow-water material, slope reefs are usually extremely rich in microbial crusts, and depending on the water depth coral-siliceous sponge thrombolites, siliceous sponge thrombolites or even pure thrombolites (if dysaerobic) may develop. Inner ramp or enclosed lagoonal reefs are normally of low diversity and adapted to background sedimentation or resedimentation. Sponge mudmounds only occur in lower mid to outer ramp position if mud and debris exporting shallow water platforms are sufficiently far, which is not the case in the Lusitanian Basin.

Synsedimentary basin tectonics: Examples from the Lusitanian Basin are the interpretation of an active uplift zone with a steep escarpment by the purely aggradational, but overall very shallow development of the Ota Platform (Stops 1-3), the timing of salt pillow activity as seen by sheltering effects and carbonate platform development at the internal flank of the salt pillow (Caldas-Bolhos Platform, Stops 12,13) or collapse structures of the Castanheira and Monte Gordo reefs highlighting renewed tectonic activity at the eastern basin margin (Fig. 13).

Climate and current systems: In the Lusitanian Basin, the close vicinity of coral reefs, carbonate platforms and siliciclastics cannot be explained by an arid climate since there are many indicators of humid climates, such as sheet flood and meandering river systems, delta systems, lignite formation, or freshwater and brackish deposits. The purely carbonate Ota Platform, having developed in close vicinity to the basement uplift and the siliciclastic Castanheira Fan must have been sheltered from terrigeneous fines by a powerful longshore current system (Fig. 13) similar to modern Nicaragua coast (Leinfelder, 1994b). Similar lagoonal systems might have helped establishing zones for coral reef growth during the Tithonian (Leinfelder, 1986, 1987a).

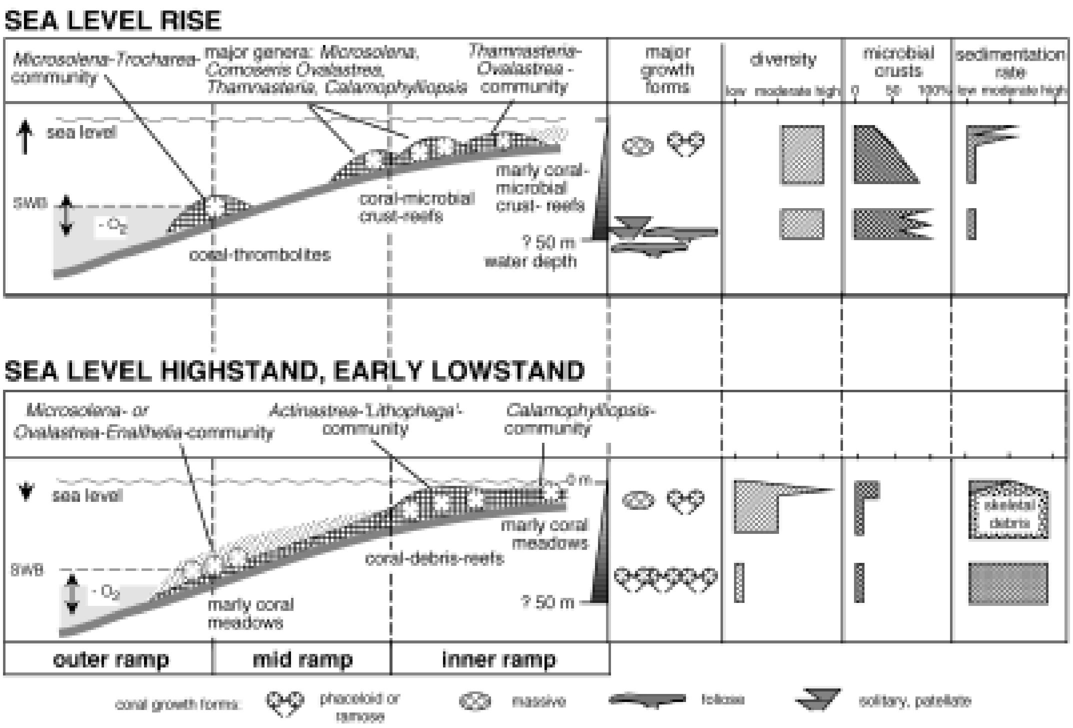

Fig. 10 - Distribution of coral reefs and coral communities from the Lusitanian Basin in relation to sea-level (after Leinfelder *et al.*, 1996; Nose & Leinfelder, 1997).

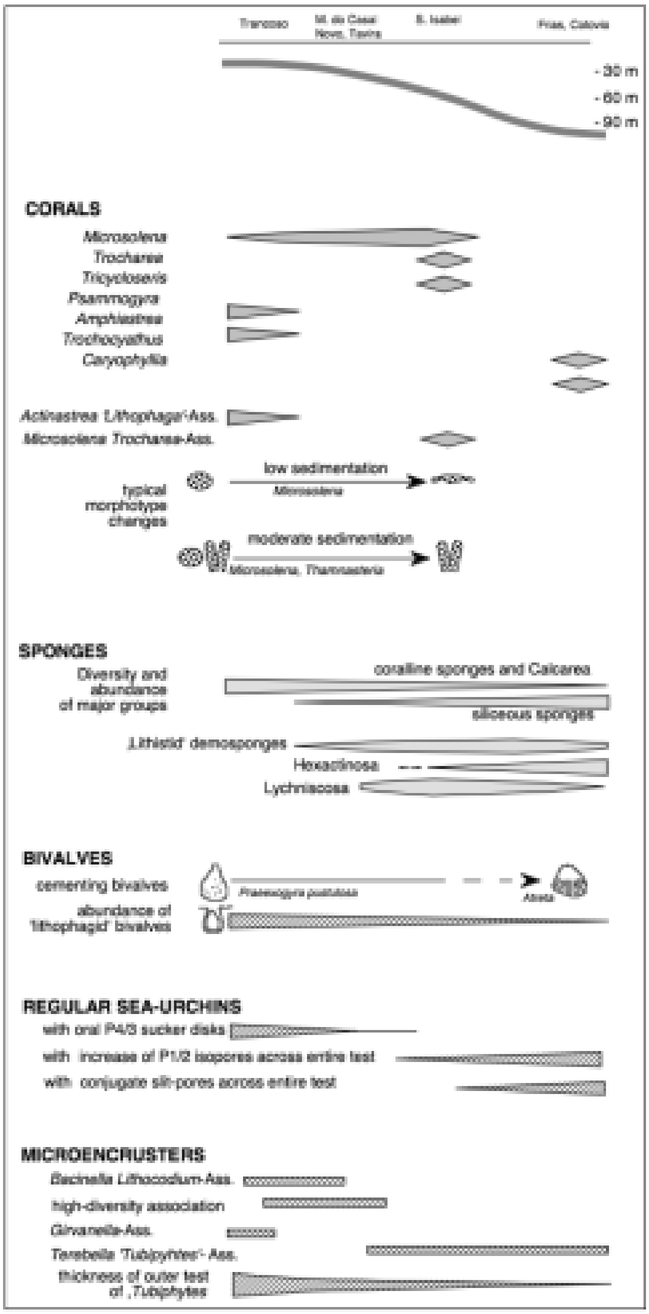

Fig. 11 - Bathymetric distribution and comparative palaeoecology of Upper Jurassic reef organisms and associations from Iberia, modified and expanded after Leinfelder *et al.* (1993a, b) and Werner *et al.* (1994).

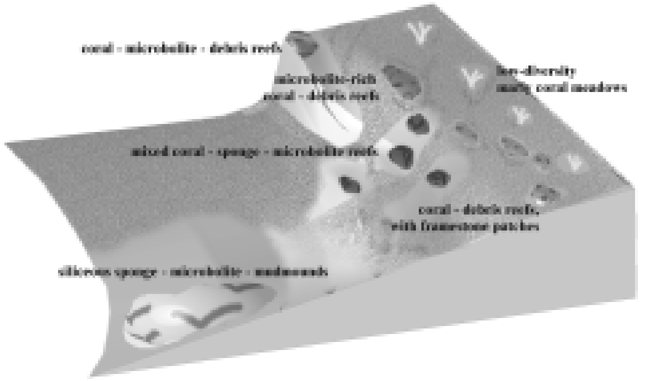

Fig. 12 - Jurassic reef types differ also according to different shelf configurations and positions. Given are some characteristic examples. Homoclinal ramps (foreground) show characteristic coral-debris reefs in agitated water and siliceous sponge mounds or biostromes in the lower mid to outer ramp. Steepened ramps and rimmed shelves may suppress sponge mound development in deeper waters because of proximity to mud and sand-exporting, shallow-water carbonate factories. Steepened depositional slopes are the preferred site for crust-rich reefs of moderately deep water, whereas coral-microbolite--debris reefs are indicative of a position in close proximity to a bypass margin, enabling enhanced gravitational export of surplus calciclastics generated within the reefs (from Leinfelder, 2001).

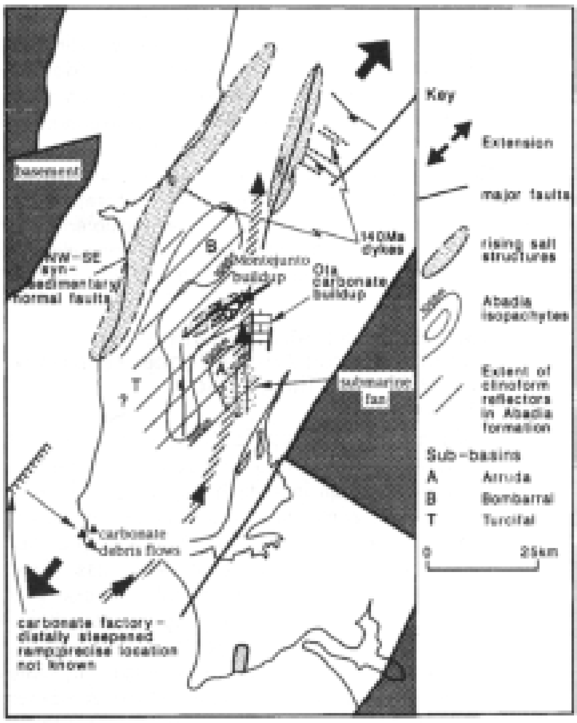

Fig. 13 - General configuration of the half-graben, pull-apart-type Arruda subbasin during the Kimmeridgian and Tithonian (modified from Leinfelder & Wilson, 1989), and dominating factors controlling the various mixed carbonate-siliciclastic depositional systems discussed here. Cross-hatched arrow: supposed Kimmeridgian longshore current system, entering from Atlantic. During the Tithonian, the Arruda Subbasin was influenced by irregular estuarine currents (cf. Leinfelder, 1994a).

Hydrocarbon exploration: Owing to Tertiary compression, hydrocarbons which must have been widespread in the Lusitanian Basin underwent microbial alteration and decay. Occasionally, bituminous seeps occur from former reservoirs such as the Castanheira fan. Strong facies differentiation, synsedimentary tectonic and halokinetic activity, widespread occurrence of source and reservoir rocks with primary and secondary porosity, sedimentary or tectonic migration paths and good sealing conditions make the Lusitanian Basin nevertheless a case model for other Atlantic marginal basins preserved offshore. Fig. 14 gives a sketch of possible hydrocarbon relations. See more in Leinfelder (1994a).

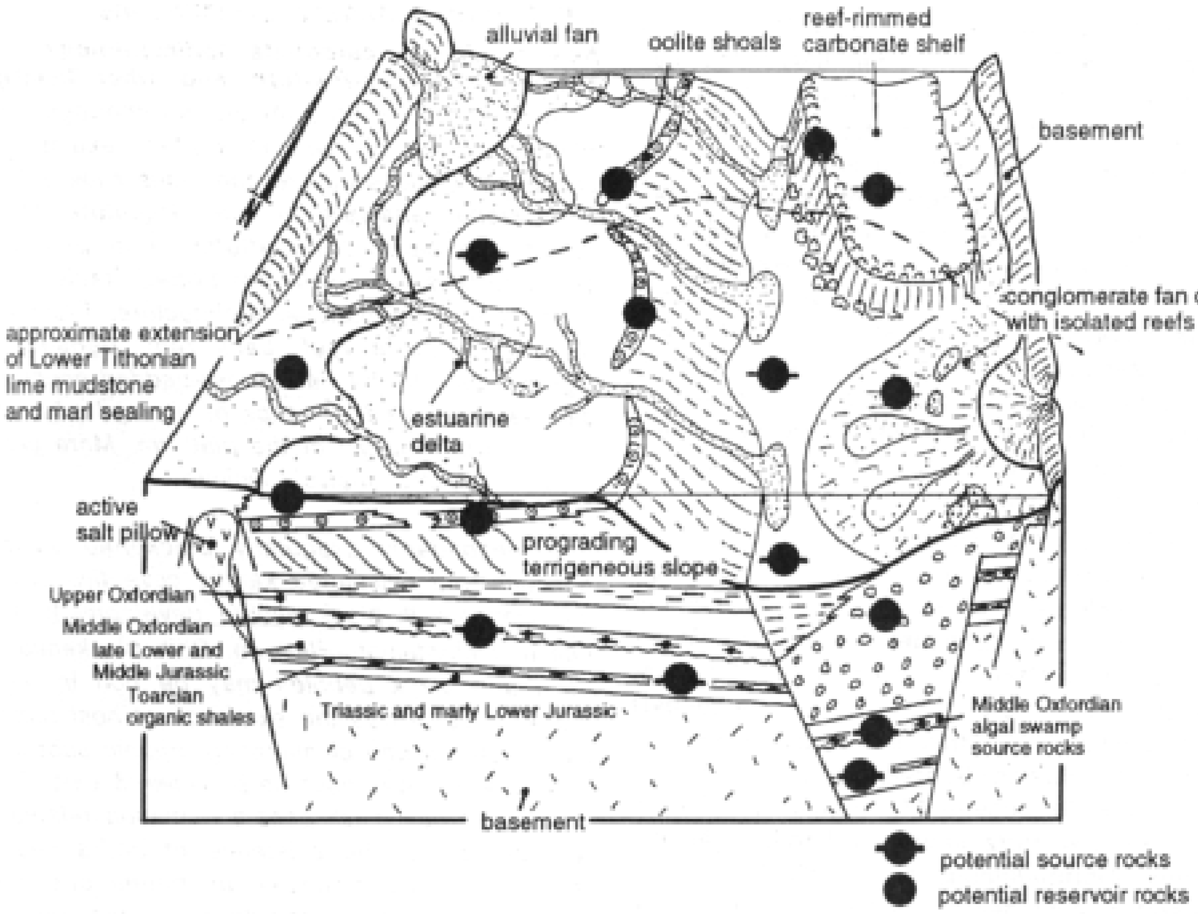

Fig. 14 - Strongly simplified reconstruction of the dominant depositional systems of the Arruda Subbasin during the Kimmeridgian, and oil play situations. Potential source and reservoir rocks were abundant, and were connected as well as sealed by structural or sedimentary constellations. Maturation occurred by continuous subsidence and superposition of younger sediments. During later inversion, these were eroded and hydrocarbons were largely destroyed (from Leinfelder, 1994a).

6. EXCURSION STOPS

Please note that many Lusitanian Basin outcrops are matter of rapid change or accessability owing to quarrying, intense development of new roads and housing areas as well as an enormous agricultural reorganisation. Which outcrops can be shown will therefore also be dependant upon a final inspection of outcrop conditions directly before the excursion as well as the actual number of participants. For location of the below mentioned excursion Stops see Fig. 15.

First Day: Arruda Subbasin (Stops 1-8), start at Lisbon Airport, end in Torres Vedras

Stops 1 to 3: Ota Carbonate Platform

The Ota Carbonate Platform of Kimmeridgian age is a unique narrow intrabasinal platform system which is situated on an uplifted basement block in vicinity to the eastern basin margin. It stretches about 8 km NS and 2 km EW, with the eastern reef-rimmed margin being largely, and the western carbonate-sand dominated margin occasionally preserved. The narrow platform with an exposure thickness of about 160 metres exhibits a perfect facies zonation with a marginal high-energy reefal belt to the west, followed by a partially broad intertidal zone with Lofer-cycle development, a muddy lagoonal zone and a carbonate-sand dominated inner margin (Figs. 16, 17, 19). Despite having developed through several 3rd order sea-level cycles and despite being highly productive (as highlighted by its broad peritidal zone directly leeward to the reef zone as well as the shallow character of the lagoon exhibiting mud-ridge development) it exhibits aggradational architecture throughout its entire growth. Reason for this is a steep bypass-margin preventing any progradation. This margin was postulated by the character of the reef zone (see Stop 2) and corroborated by seismics revealing the steeply faulted character of the basin uplift (Fig. 19). Sea-level changes are nevertheless obvious by two black pebble horizons (Leinfelder, 1987b), which are useful for time correlation between different facies zones, by

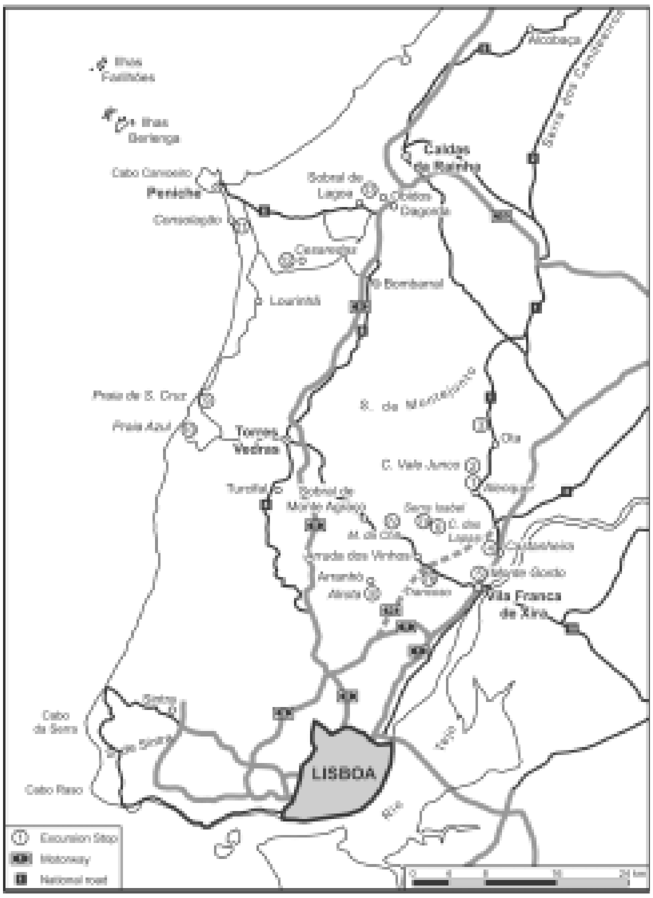

Fig 15 - Simplified road map with location of excursion Stops.

early subaerial dissolution features, and by several well developed subaerial unconformities in the top part of the platform. The platform is to a large part coeval with the coarse siliciclastic Castanheira Fan to the south (Stop 4) and the prograding fine siliciclastic Abadia Slope System. While coarser clastics could be possibly bypassed around the platform, the very pure character of the Ota Limestone demanded additional sheltering from floating fines by a well developed longshore current system which is in accordance with the configuration of the basin during the Kimmeridgian (Fig. 13).

The Ota Limestone is a major reservoir for pavement stones, concrete industry and pharmaceutics owing to his highly pure character (cf. Manuppella & Balacó Moreira, 1984), and therefore is heavily exploited by many, meanwhile partially gigantic quarries which since the major investigations undertaken between 1985 and 1989 have been removed major amounts of the outcropping carbonate.

Stop 1: Old quarry at the northern margin of Alenquer

Formerly a most interesting quarry to study the reef zone of the Ota Platform (Leinfelder, 1992, 1994a), it is now almost completely filled up with waste material. However, a distant view at the top of the quarry wall reveals a strong subaerial, palaeokarstic unconformity capping the Ota Platform with subvertical palaeocave development along joints, highlighting palaeotectonic activity. The unconformity is overlain by red siliciclastics which revealed dinosaur remnants, dated as Tithonian using palynostratigraphy.

Stop 2: Quarry Casal Vale Junco (abandoned part), north of Alenquer

This quarry is also increasingly filled with quarried material but still allows insights into the southern part of the Ota reef zone. The Ota Reef is of the coral--microbolite-debris type which means that there is little

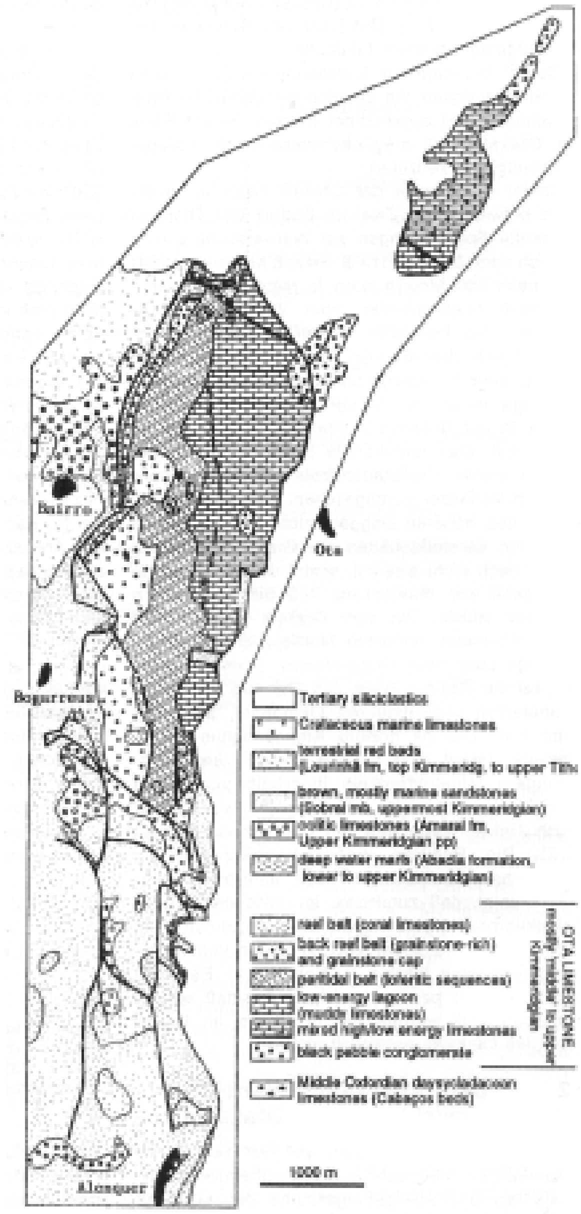

Fig. 16 - Geological and facies map of the Ota region (from Leinfelder, 1994a). For general location see also Figs. 1b and 3a.

coral framework preserved *in situ* owing to the mostly high-energy character of the reef. Contrasting other Jurassic coral-debris reefs, the Ota reef material is strongly stabilised by microbial crusts and a great variety of microencrusters, including *Lithocodium*, *Bacinella* and *Tubiphytes*. This was considered as diagnostic of a steep bypass margin which allowed much of the generated reefal debris to be exported to greater depths, whereas the remaining debris could be stabilised by microbial crusts (Figs. 18, 19). Elsewhere, particularly in the high--energy zone of ramps, accumulating debris remains relatively in place causing too much of friction and abrasion for microbial crusts to develop (Leinfelder, 1992, 1994a).

The northern quarry wall shows *in situ* preservation of a large *Calamophylliopsis* bafflestone which is strongly encrusted by *Tubiphytes* as well as other in-place preservation of corals in a locally less agitated zone. Violet colouration and complex infilling of a palaeocave gives an example of the syn- to early postdiagenetic history of the carbonate platform. Of particular interest are leached cave fills with lag enrichments of originally calcitic material such as echinoderms, brachiopods and oysters, whereas all of the originally aragonitic material has been fully or strongly leached. These early cave fillings are indicative of a strong freshwater phreatic event at a time where the limestone has already been (partially) hardened but not yet recrystallized to calcite.

The western wall shows many different coral taxa, preserved as fragments, together with other reefal fauna (see Leinfelder, 1992 for details). Loose unstabilized grainstone pockets are visible but the majority of the bioclastic limestone appears as an inhomogeneous micrite which is caused by the indistinctness of microbial crusts at outcroup. Many areas are however bored by lithophagid bivalves which is a good field criteria for early hardening due to microbial stabilisation.

The eastern wall is capped by well bedded limestones representing the grainstone cap of the Ota Platform.

Corals of the Ota reef zone are of high diversity including the genera *Actinastrea, Amphiastrea, Stylina, Ovalastrea, Pseudocoenia, Heliocoenia, Thamnasteria, Fungiastrea, Microsolena, Latusastrea, Psammogyra, Rhipidogyra, Calamophylliopsis, Stylosmilia, Thecosmilia, Dermosmilia, Dermoseris* and *Montlivaltia*. Stromatoporoids, chaetetids and pharetronid sponges occur at random with taxa including *Dehornella, Actinostromaria, Ptychochaetetes, Baueina, Corynella* and *Neuropora*. Nerineid gastropods are widespread, with frequent *Nerinea* sp. and the typical huge *Cryptoplocus* sp.. Echinoderms, bivalves, serpulids, occasional solenoporoids, *Marinella* (cf. Leinfelder &

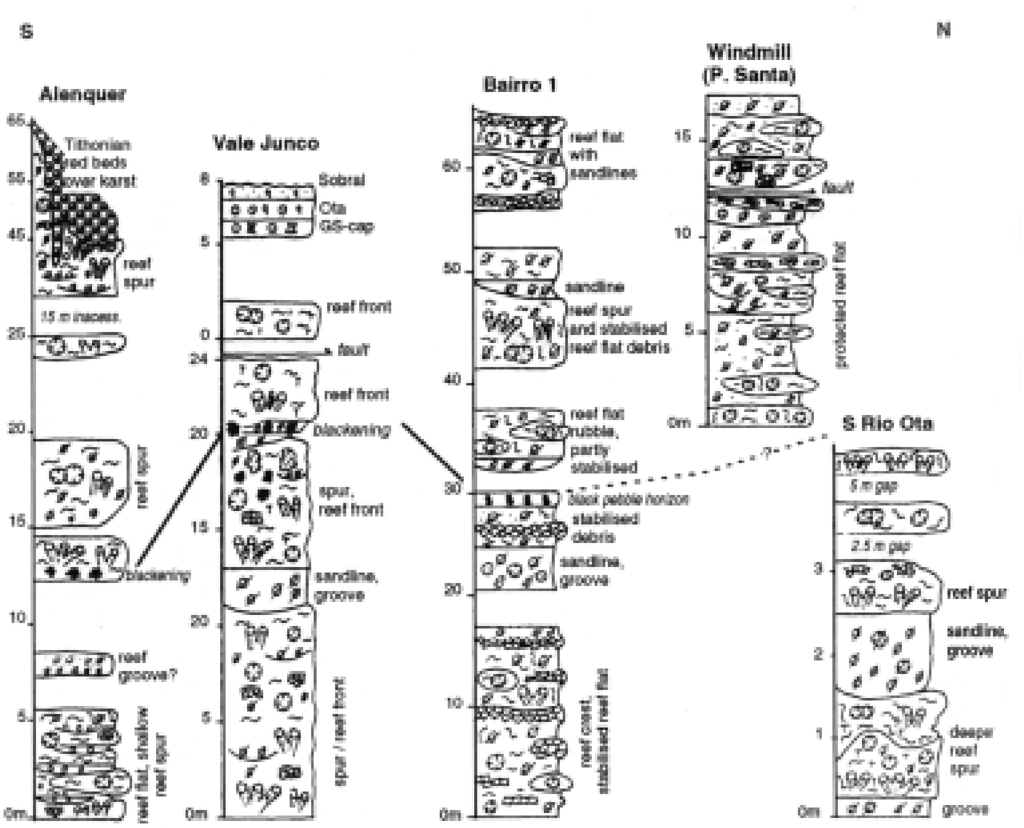

Fig. 17 - Simplified lithological sections from the marginal reef belt of the Ota-Platform (from Leinfelder, 1994a; for detailed logs see Leinfelder, 1992).

Werner, 1993), the massive dasyclad *Petrascula*, lituolid foraminifera and various types of shallow-water microencruster associations occur as well.

Sections from the marginal reef zone of the Ota Platform cannot be correlated, thus showing the complexity of the reef architecture which is consistent with an interpretation as a strongly microbially bound, debris-rich high-energy reef belt with little *in situ* preservation and the development of a spur-and-groove system (Leinfelder, 1992, 1994a; Figs. 17, 19).

Stop 3: Northern Part of Ota Platform, along Road N1 north of Ota.

This road cross-cuts through the northern part of the Ota Platform. At the western entrance the onlapping of the Amaral Formation (here largely oolitic) on the Ota Platform is partially visible (facultative Stop). The excursion will visit a small road cut section in the lagoonal zone of the Ota Platform, showing floatstones to micritic rudstones rich in large nerineids. These nerineids have been partially silicified which in the Ota Limestone is a frequent phenomenon towards the top of the succession, being associated with subaerial exposure. The section also shows the typical bioclastic wackestones with occasional lituolid foraminifera, rare dasyclads (e.g. *Clypeina jurassica*) and frequent indistinct coated mud grains as well as occasional loferite horizons. Contrasting the well developed loferitic cycles in the peritidal zone of the Ota Platform (not visited due to time constraints), these thin and isolated horizons pinch out rapidly and have been interpreted as the top parts of indistinct mud-ridge developments (Leinfelder, 1994a).

Stops 4-5: Castanheira Fan and its reefs

Largely coeval with the Ota Platform development is the siliciclastic Castanheira Fan which entered the basin trough a gap in the basement uplift (see Fig. 3c).

Stop 4: Castanheira Fan

This outcrop shows the character of the massive debrites of the Castanheira conglomerate, a typical conglomeratic-fanglomeratic fan delta sensu Nemec & Steel (1988). The east-derived material contains all sorts of basement material in pebble and cobble sizes, such as granites, slates, amphibolites, gneisses and especially phyllites. Carbonate pebbles from older material (presumably lower and middle Jurassic) may also appear. The material is extremely rich in detrital feldspar being largely derived from transported granites. The freshness of the feldspar indicates rapid transport and deposition in a marine environment. The most impressive feature of this outcrop is a horizon with elongated, up to 8 m long blocks of soft marl being transported in the rigid plug of at least 20 m thick debrites. The largest of these blocks is positioned in rotated, upright position. No distinct bedding planes are visible between the individual debrites which thus are strongly amalgamated.

Stringers of this material can be occasionally found in coeval fine-grained basinal Abadia marls as grainflow and turbidite deposits.

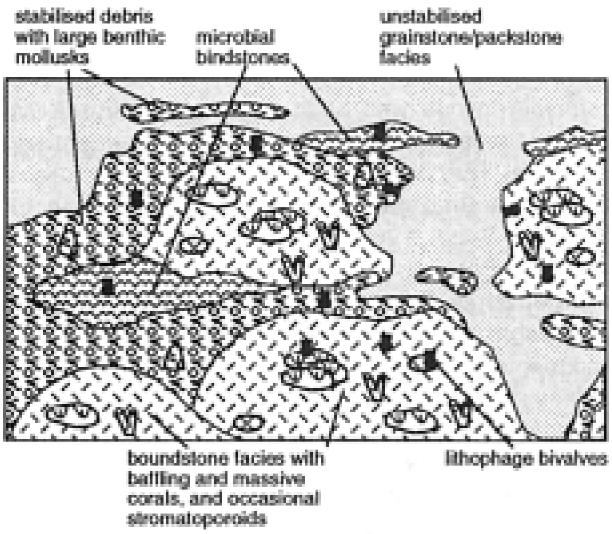

Fig. 18 - Summary sketch diagram illustrating the interfingering of facies types in the southern part of the reef zone. A scale bar is not given, as the variations shown may occur across widths ranging from one to ten metres (from Leinfelder, 1992, 1994a, modified).

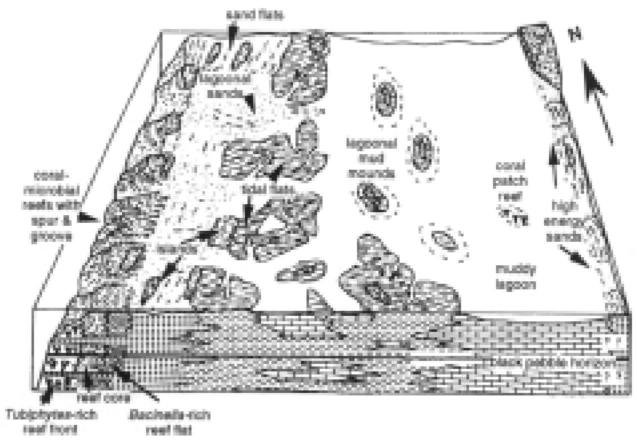

Fig. 19 - The depositional model for the exposed part of the Ota Limestone. The aggradational shallow-water platform is rimmed by a high-energy coral-microbolite-debris reef and exhibits well developed facies belts. In the inner platform autocyclic shifts of sediments led to small-scale shallowing up successions). Sediment relics indicate that a grainstone shoal complex and local, ephemeral islands rimmed the inner platform margin (from Leinfelder, 1994a).

The hilltop above this outcrop is characterised by the palaeokarsted relic of the Castanheira Reef (will not be visited, see Leinfelder, 1994a). The bus will proceed several hundreds of meters on the road towards the west to demonstrate the existence of large allochthonous reef boulders in higher parts of the fan which are evidence of collapse events of the Castanheira Reef (Figs. 3b, 20, 21).

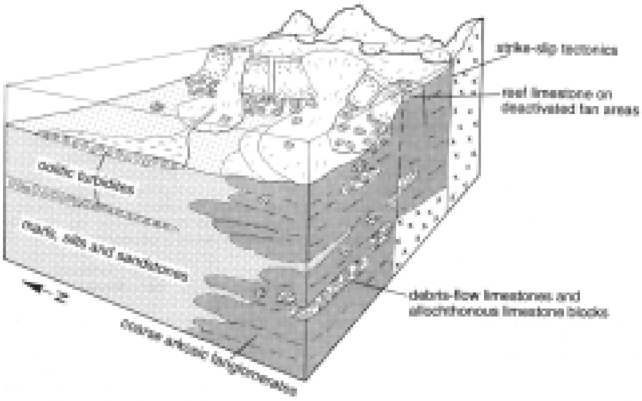

Fig. 20 - Generalised depositional model for the mixed carbonate--siliciclastic Castanheira slope-type fan delta. Deposition of autochthonous carbonates was particularly related to two phases of relative sea level rise, but could nevertheless only take over in some autocyclically or allocyclically deactivated fan areas. Collapse events were related to local tectonic activity and drops in relative sea level (from Leinfelder, 1994a).

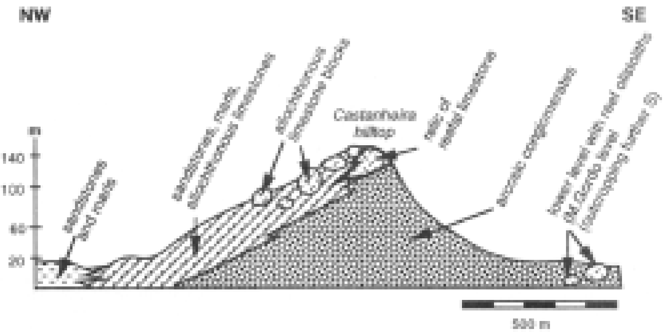

Fig. 21 - Structure and facies succession around the Castanheira hill (Castanheira fan). Allochthonous limestone blocks are not to scae (from Leinfelder, 1994a).

Stop 5: Monte Gordo Pinnacle Reef above Vila Franca de Xira

The Monte Gordo reef is another reef developed at the margin of the Castanheira Fan. Field mapping suggests that it is older than the Castanheira Reef. The reef has been examined by climbing through the inacessible quarry which is not possible with the excursion group. A short Stop at the base of the reef reveals gigantic allochthonous reef blocks in the surroundings of the reef and quarried material used for building which shows the basal reef facies: rudstones with large mollusks and corals which are very rich in detrital quartz and feldspar as well as vadose silt (Fig. 22). The short drive to the top shows again arcosic conglomeratic fan material. The second substop is at the top of the hill (viewpoint) which allows an overview of the Arruda Subbasin during clear days. Sandstone blocks transported during road works are from closeby sites and represent the capping sandstones of the reef. Some of the blocks show reworked reef pebbles.

A short walk down to the reef allows to examine the top facies of the reef with baffling corals and other reef fauna. Palaeokarst overprinted by modern subaerial exposure phenomena makes inspection partially difficult.

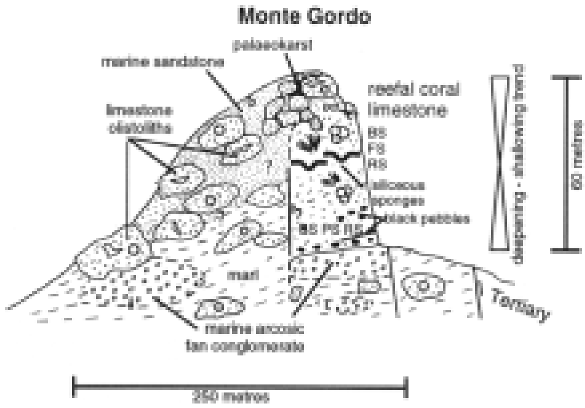

Fig. 22 - Geological structure and facies succession of the Monte Gordo reefal limestone (Vila Franca). Allochthonous blocks are not to scale (from Leinfelder, 1994a).

Stops 6 to 7 (with substops): Reefs and Carbonate Platforms within and on top of the Abadia Slope System around Arruda dos Vinhos

The fertile broad valley of Arruda dos Vinhos is situated within the Abadia Beds which may be inspected at outcrop in the town of Arruda dos Vinhos. Several decameters below the top of this prograding, fine siliciclastic to marly slope system containing ammonites is the Serra Isabel level with very specialised reef development. The Abadia marls are overlain by the Amaral Carbonate Platform which forms the top part of the valley flanks to the north and a pronounced, well outcropping and partially quarried level to the south (Fig. 3a).

Stop 6a, b: Serra Isabel Level at Casal das Lapas and Serra Isabel

The Serra Isabel level is a horizon in the upper part of the Abadia Beds which can be partially mapped. It is not a horizon with continuous facies but rather a condensed level with a predisposition to occasional microbolite reef and/or coral reef development. Fig. 23 shows the prominent features, such as telescoping of infauna-dominated to epifaunal development. Epifauna includes a great taxonomic variety of relatively small corals and coralline sponges, echinoid spines, *Millericrinus* stems and roots, oysters and small brachiopods. Besides faunal telescoping, other condensation features include enrichment of ironhydroxide nodules which partially are bored or encrusted by oysters, and microbial crusts, ammonite and belemnite richness which otherwise are completely rare in the Abadia Beds, and the occurrence of small patch reefs. A patch reef at Casal das Lapas (Upper Serra Isabel Level) shows a distinct deeper water association of corals, being rich in broad cup-shaped solitary and thin platy corals (*Microsolena-Trocharea* association; Nose, 1995, 1999). The most peculiar feature of the Serra Isabel level is the occurrence of pure thrombolitic microbolite reef patches and biostromes (e.g. at Stop 6b where they frequently develop around crinoid roots or at Stop 6a where they occur in intimate association with *Tubiphytes*, and occasional hextactinosan siliceous sponges). Pure microbolites may attain sizes up to 8 m and lateral extensions of several hundred meters (e.g. Schmid, 1996). The level also shows signs of oxygen depletion at least in the top part of sediments, such as framboidal pyrites and secondary gypsum which gives rise to the conclusion that oxygen levels were shifting during this transgression owing to partially very sluggish water circulation. This explains the close relation of a medium to even high-diversity epibenthic fauna with environments where all life was excluded except microbial development (Leinfelder *et al.*, 1993b, 1996; see Fig. 23). Interestingly, the Serra Isabel level which could be dated as transition from the hypselocyclum to divisum chron is not unique, but pure and partly large thrombolites also developed coevally in the Algarve and mixed reefs with partly repetitive transitions from pure thrombolite to coral-microbolite occurred at the same time in eastern Spain and southern France (Leinfelder *et al.*, 1996; Leinfelder, 2001). The Amaral formation in this area (e.g. Casais Verdelho) is developed only as thin marly coral microbolite patches and meadows. Despite elevated terrigenous influx, the coral fauna is charcterized by a moderate to high diversity. Notwithstanding the fact that beyond a certain level terrigenous sedimentation is detrimental to coral growth, seasonally or slightly elevated influx of terrigenous material often coupled with an increase in particulate organic nutrients might even improve the diversity and hence the growth conditions of Upper Jurassic scleractinians (e.g. *Thamnasteria-Ovalastrea*-association; cf. Nose, 1995; Leinfelder *et al.*, 1996).

Stop 7: Amaral Formation around Arruda dos Vinhos (several substops possible)

Substop 7a: Returning from Stop 6, the Amaral Formation at Serra Isabel hilltop can be briefly inspected, showing in-place bafflestone structures (*Ovalastrea, Calamophylliopsis*) and massive corals (e.g. *Acanthogyra, Synastrea*) in a mostly bioclastic groundmass with many other faunal elements (e.g. echinoids, bivalves). In the region of Serra Isabel hilltop and adjacent peak Moinho do Casal Novo, the Amaral formation is clearly subdivided into two reefal subunits interrupted by allochthonous coarse-grained debris facies (bioclastic rudstones) grading laterally into marly sandstones. This bioclastic and/or siliciclastic interval can be traced over large parts of the subbasin and is correlative with a regressive phase during relative sea level drop (Nose,

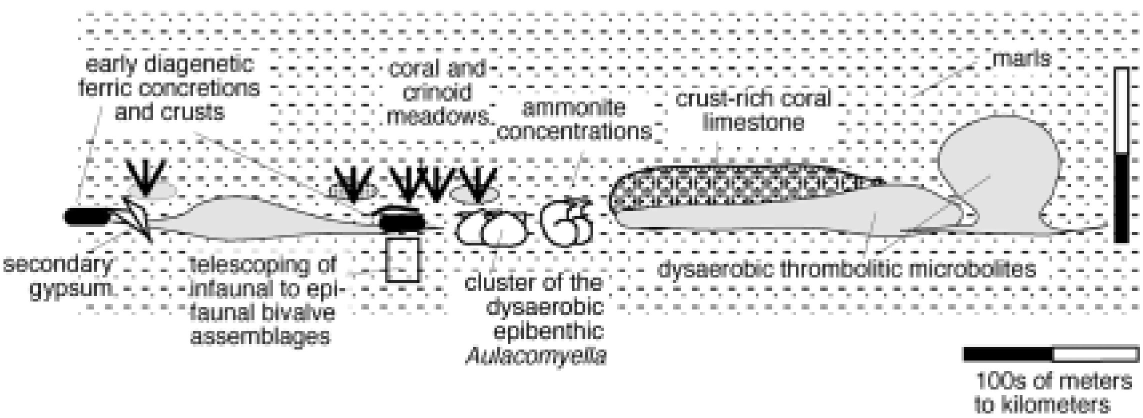

Fig. 23 - Lateral variability of the Serra Isabel level from the Arruda subbasin. The level is a condensed level, partly with telescoped successions of dysaerobic and oxygenated reef facies (from Leinfelder, 2001).

1995; Leinfelder & Wilson, 1998). Contrasting the upper coraliferous level, the lower reefal subunit reveals a marked discontinous development with microbial crust--rich coral patches and biostromes (Nose, 1995). Here, at Serra Isabel hilltop, the lower reefal level is not even developed with bioclast-bearing sandstones forming the base of the Amaral formation. The base of the upper reefal unit is characterized by a diverse coral fauna (e.g. *Synastrea subagaricites, Thamnasteria lobata, Ovalastrea* sp.) with marl lenses enriched in echinoid spines (*Rhabdocidaris* sp., *Pseudocidaris* sp.). In the upper part of this subunit, coral bafflestones interfinger with oncolitic wackestones/packstones (Fig. 24).

The way back to the bus may be taken climbing across the Lower Amaral outcrop (Corálico) to inspect oolite facies of the Upper Amaral (Oólito), including occasional oyster patch reefs.

Substop 7b: Trancoso Quarries, south of Arruda dos Vinhos: Depending on the accessability and working progress, a selection of this giant quarry assemblage will be inspected. The Trancoso site is described by Nose (1990, 1995). Trancoso locality shows a somewhat unique development within the Amaral formation, especially in terms of thickness as well as lateral and vertical facies variability of the coraliferous-oolitic limestones of the upper Abadia and Amaral formations. Reef development starts with deeper water biostromal thrombolites lacking reef building metazoans intercalated in the upper Abadia formation. Remarkably, this unit differs from the under- and overlying units in terms of dip and strike. It can be assumed that the thrombolitic limestones developed along a southward dipping clinoform in the Abadia slope system (cf. Leinfelder & Wilson, 1989). Up-section the uppermost Abadia marls show patchy development of large *Ovalastrea* bafflestones before reefal carbonates occur again (Amaral formation). The Amaral formation around Trancoso quarries reveals a complex facies pattern of pure *Terebella-Tubiphytes* thrombolites, massive coral-coralline sponge microbolites and coral framestones as well as lagoonal bioclastic-oncolitic wackestones/floatstones (Fig. 24). Locally, in areas with elevated deposition of calacareous mud, small branching coral mudmounds (?*Dendrarea*) developed, lacking microbolites.

Among the features to be inspected are establishment of coral facies in the topmost marly beds of the Abadia formation, small- and large-scale coral reefs rich in microbial crusts in the Lower Amaral, bioclastic coral facies, accompanying oncolitic and bioclastic facies, early dissolution features, oolitic, partly cross-bedded development of the Upper Amaral, lateral transitions from coral facies to oolite facies, and medium-diversity coral-microbolite reefs in marly settings in the top part of the Amaral facies.

Substop 7c: Moinho da Chã, east of Sobral de Monte Agraço: Similar to the development at Serra Isabel hilltop/Moinho do Casal Novo, the Amaral formation at Moinho do Chã is characterized by two levels of reef growth interrupted by oolitic sandstones of varying thickness (4-7 m where the lower reefal level is not developed, reduced thickness in areas where it is present; see Fig. 24). The sandstones show large scale cross bedding (megaripples) associated with mud drapes and small ripple structures indicative for nearshore tide

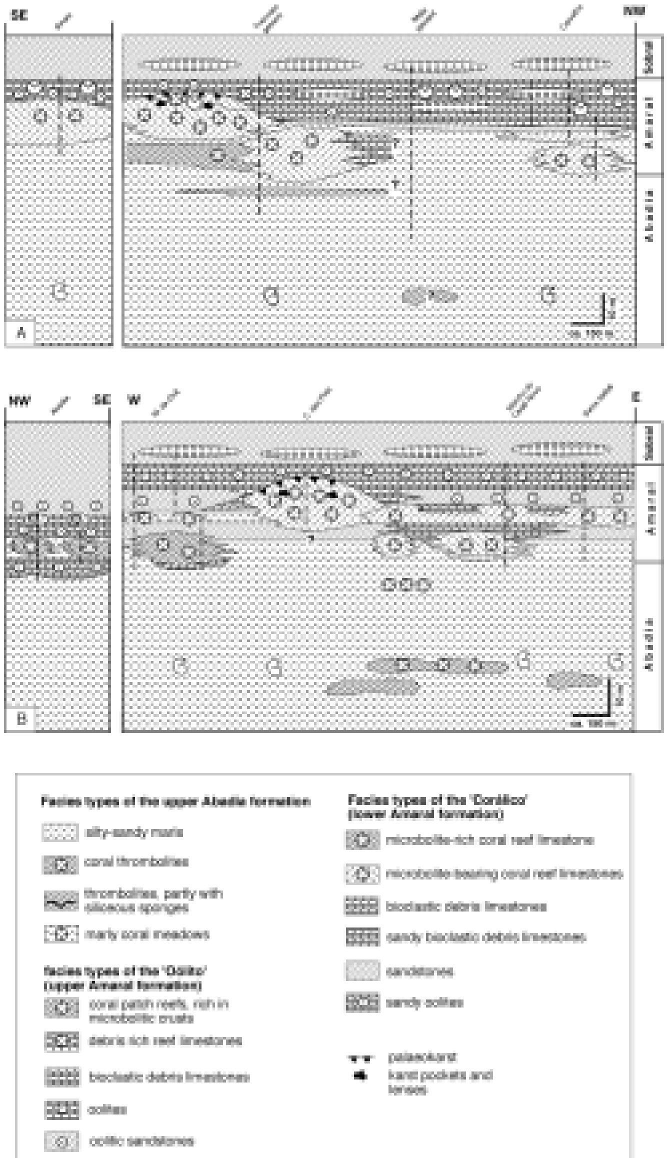

Fig. 24 - Facies development and lithological correlation of the Amaral formation in selected regions in the Arruda subbasin (from Nose, 1995).

influenced channels and sandy floodplain and overbank deposits (Nose, 1995). The lower reefal unit is built by discontinous massive coral microbolites with a dominance of branching phaceloid and ramose coral morphotypes (e.g. *Thamnasteria*). This interval wedges out towards the south but can be followed several hundred meters towards the north. The upper reef-bearing horizon is strongly influenced by fine siliciclastics allowing only for the development of small (4 m thick, 7-9 meters in lateral extension) coral patch reefs rich in microbolitic crusts (Fig. 24). Coral fauna is again mainly composed of branching morphotypes (*Convexastrea-Dendrohelia* association; Nose, 1995). Up-section the upper Amaral formation is characterized by trough cross-bedded oolitic sandstones and rare cross-bedded ooid packstones/grainstones resembling nearshore ooid bar systems in association with mainly siliciclastic distributary channels and troughs. Locally small oyster reefs (*Praeexogyra, Nanogyra*) are developed.

Stop 8: Alrota Coral Patch Reef, Tithonian

The ‚lagoonal-type' facies of the Tithonian marine embayment of the Arruda subbasin (Fig. 25) shows coral patch reefs at various places (Fig. 26). Depending on time constraints, a coral bafflestone patch reef composed of ramose corals (mostly *Actinastrea*) with additional oysters and small coralline sponges will be inspected at the entrance to the village Alrota, southwest of Arruda dos Vinhos. The Alrota area and its surroundings has been famous for corals since the last century (e.g. Koby, 1904/05; Geyer, 1995); see Leinfelder (1986) for details.

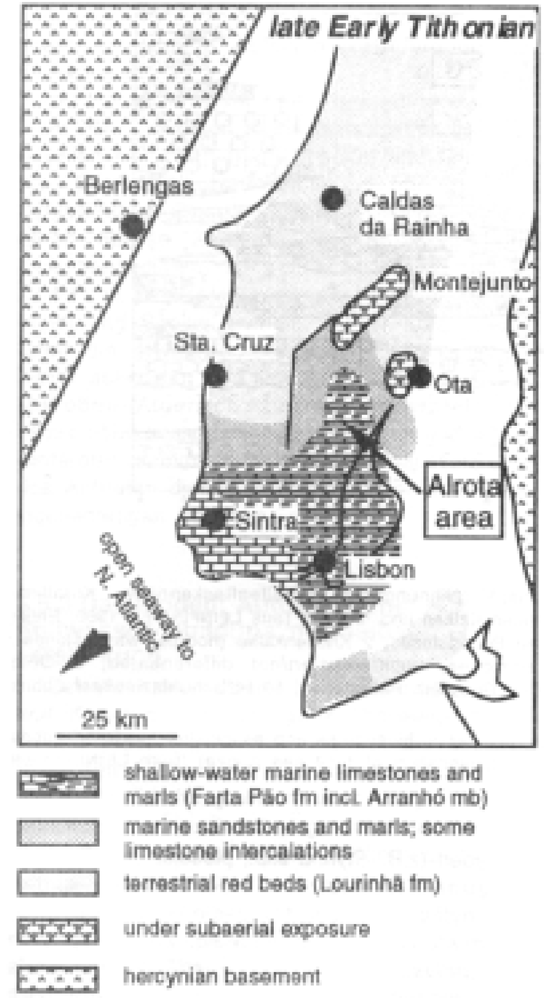

Fig. 25 - Palaeogeographic map of the middle part of the Lusitanian Basin for the late Early Tithonian (simplified from Leinfelder, 1987a).

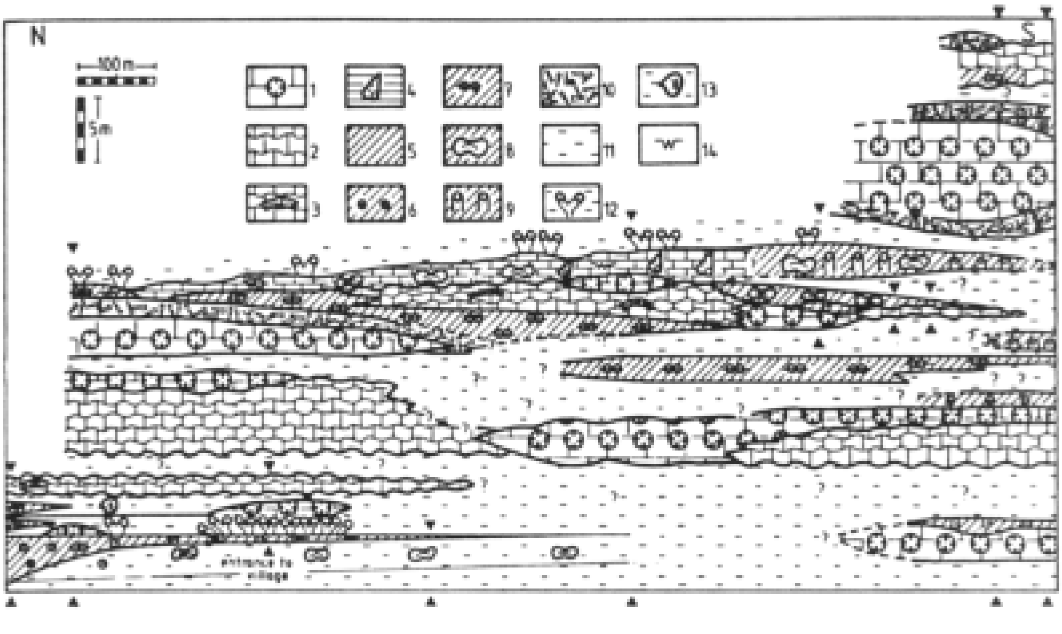

Fig. 26 - Arrangement of facies types in the Alrota area: Coral patch reefs, biostromes and associated bioclastic debris strongly interdigitates with lagoonal marly limestones and marls. 1 coral boundstones, 2 nodular bioclastic wackestones, 3 Trichites limestones, 4 nerineid packstones, 5 Pack/Grainstones, not differentiated, 6 Ooid Grainstones, 7 Cortoid Pack/Grainstones, 8 Oncoid Packstones, 9 Solenoporoid-*Marinella-Lithocodium* Packstones, 10 reefal debris facies (from Leinfelder, 1986).

The Alrota reef and similar reefs occur within a shallow-water marl-limestone succession characterized by nodular *Thalassinoides* limestones and infaunal to semiinfaunal bivalve associations. The Alrota reef association is a good example for the adaptational strategies of scleractinian corals related to elevated sedimentation rates as described for their modern counterparts by Hubbard & Pocock (1972) (Figs. 27, 28).

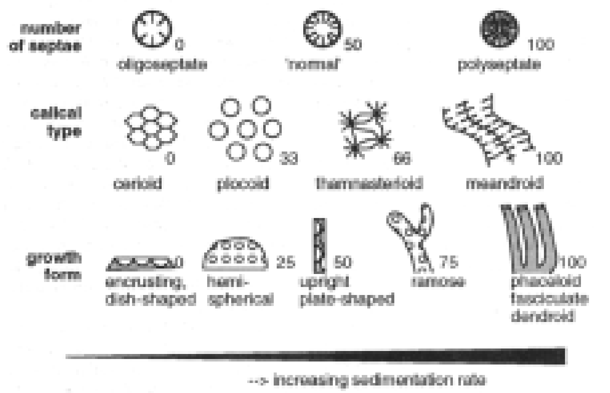

Fig. 27 - Morphologic criteria for estimating potential adaptation of corals to sedimentation. Values for a given species have to be added, giving the potential sedimentation adaptation index SAI. Minimum value is 0 (no morphological hard part adaptation in oligoseptate cerioid encrusting corals), maximum theoretical value is 275 (polyseptate meandroid ramose corals). Phaceloid, dendroid and solitary corals get the calical type value 33 (because adaptation is comparable with plocoid calical types), so that polyseptate phaceloid or solitary corals have a SAI of 233. SAI calculation give hints to adaptation or non-adaptation towards increased background sedimentation, but it has to be kept in mind that morphology of corals is also dependant on other factors. Moreover, some adaptations of corals towards sedimentation (e.g. secretion of mucus) does not leave traces in the morphology of hardparts. When using SAI, calculations must be performed for entire coral associations rather than one species only, with the lowest values obtained being critical for interpretation (see Fig. 168). Calculations should be accompanied by determination of encruster rate.

Second Day (Stops 9 to 14)

Stop 9: Beach of Santa Cruz:

The main beach of Santa Cruz allows to gain a good insight into the development of the western part of the Lusitanian Basin. A beach walk will show the outcropping salt diapir of Santa Cruz (Dagorda beds, latest Triassic to Lowermost Liassic; breakthrough during the Late Tertiary), the Abadia beds, a huge, west derived submarine canyon infill with material similar to the Castanheira Fan equivalent, and rapid grading into shallow-marine sandstones with hummocky cross-bedding to deltaic and terrestrial red beds (for details see Fürsich, 1981; Fig. 29). If time permits, a very impressive Kimmeridgian oyster reef composed of *Praeexogyra pustulosa* and *Nanogyra nana* developing over a meadow of infaunal *Isognomon* bivalves may be visited further south. This oyster reef is intercalated in a marginally marine succession probably representing the Amaral to lowermost Arranhó Beds of the Arruda subbasin. Stop 9 is optional.

Stop 10: The brackish water coral biostrome at Praia Azul:

The succession to the North and South of Praia Azul has been intensely studied by Fürsich (1981) and Fürsich & Werner (1986). Its siliciclastic development represents parts of a fluvial-deltaic succession and around Praia Azul may be rich in bivalve dominated faunal levels interpreted as mostly brachyhaline by faunal and sedimentological analysis as well as by stable isotope data (Yin *et al.*, 1995). Occasional accessory corals have been known, being considered as short term flooding with fully marine waters. However, a new finding of an about 40 m large and 80 cm high coral biostrome south of Praia Azul must be considered a true brackish water

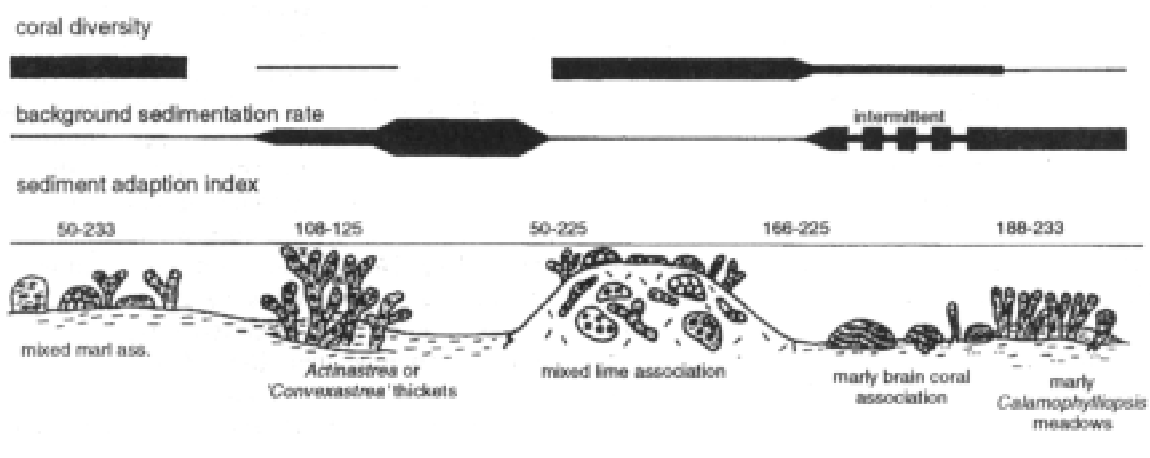

Fig. 28 - Estimation of sedimentation rate based on diversity of coral associations and functional morphology of corals using the SAI index: The example of the Alrota patch reefs (Tithonian) (from Leinfelder, 1994a).

reef, owing to its faunal associaton with oysters and its sedimentological and isotope context (Leinfelder & Werner, 2004).

Stop 11 a,b: Reefal coral biostromes and coral-rich oyster reefs at Consolação

The coastal section of Consolação starts at the Fort of Consolação (about 5 km south of Peniche) and ends at Praia da Lourinhã. It shows a complete section from the Lower to the Upper Kimmeridgian (?Lower Tithonian) (Fig. 30). The basal 200 m (from Fort of Consolação to Praia de S. Bernardino) represent a regressive siliciclastic sequence which is dominated by clay- to silt-rich sediments (silt, silty biomicrite, sandy marly limestones). They are deposited in generally calm and protected shallow water environments (nearshore shelf, prodelta, marine or brackish bays and lagoons) (Werner, 1986). Rarely sandy and conglomeratic sediments characterising shoals, delta front and coastal ridges developed. This lower part of the Consolação section corresponds to the Abadia and Amaral Formation of the Arruda subbasin and to the Alcobaça Formation of the region of Caldas and Alcobaça. The middle and upper part of the section (200 m to ca. 750 m) is characterized by reddish and greenish silty floodplain deposits, intercalated sandy channel fills as well as, rarely, fine-

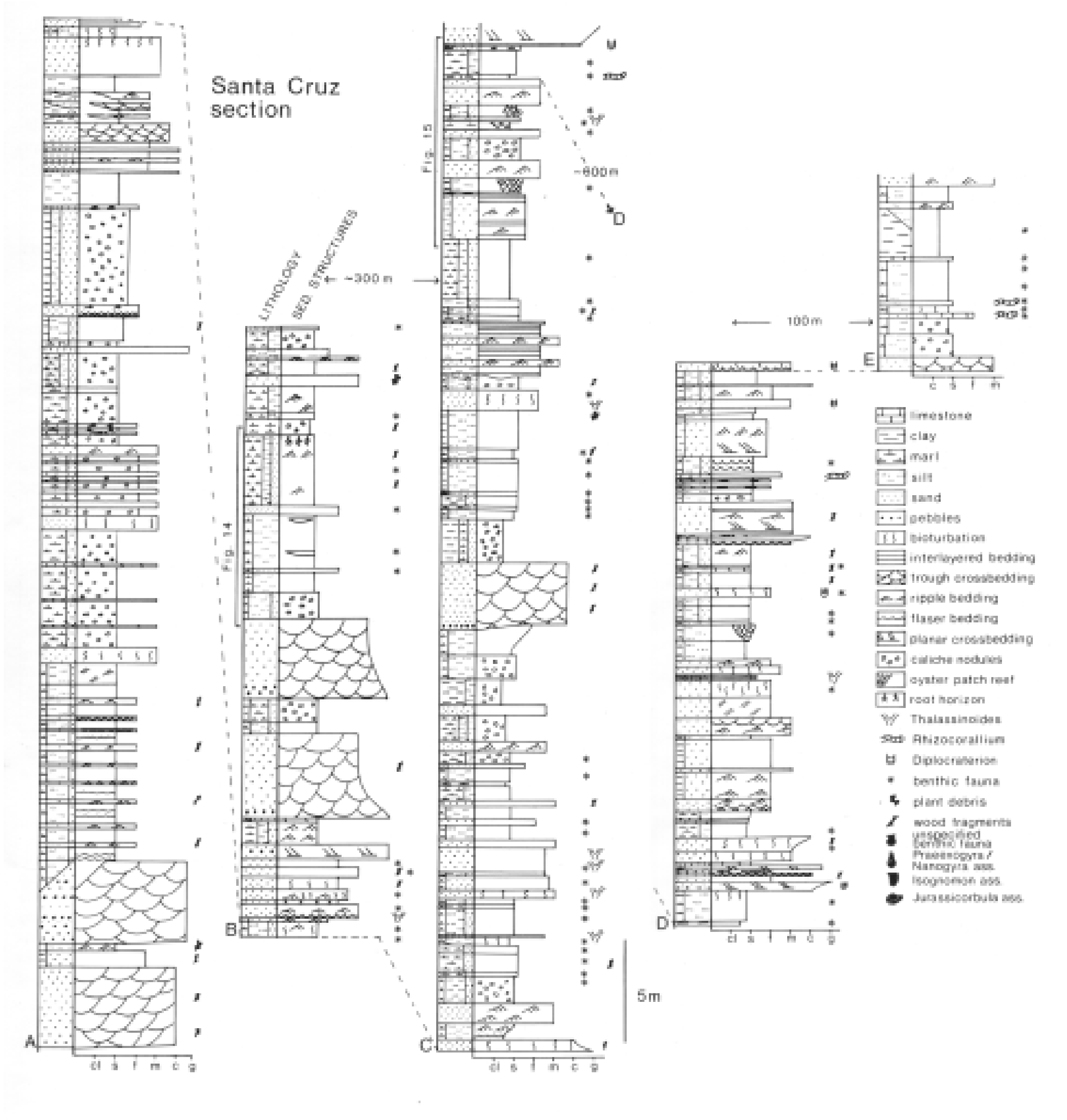

Fig. 29 - Sections through parts of the Upper Jurassic at Santa Cruz, Estremadura (from Fürsich, 1981).

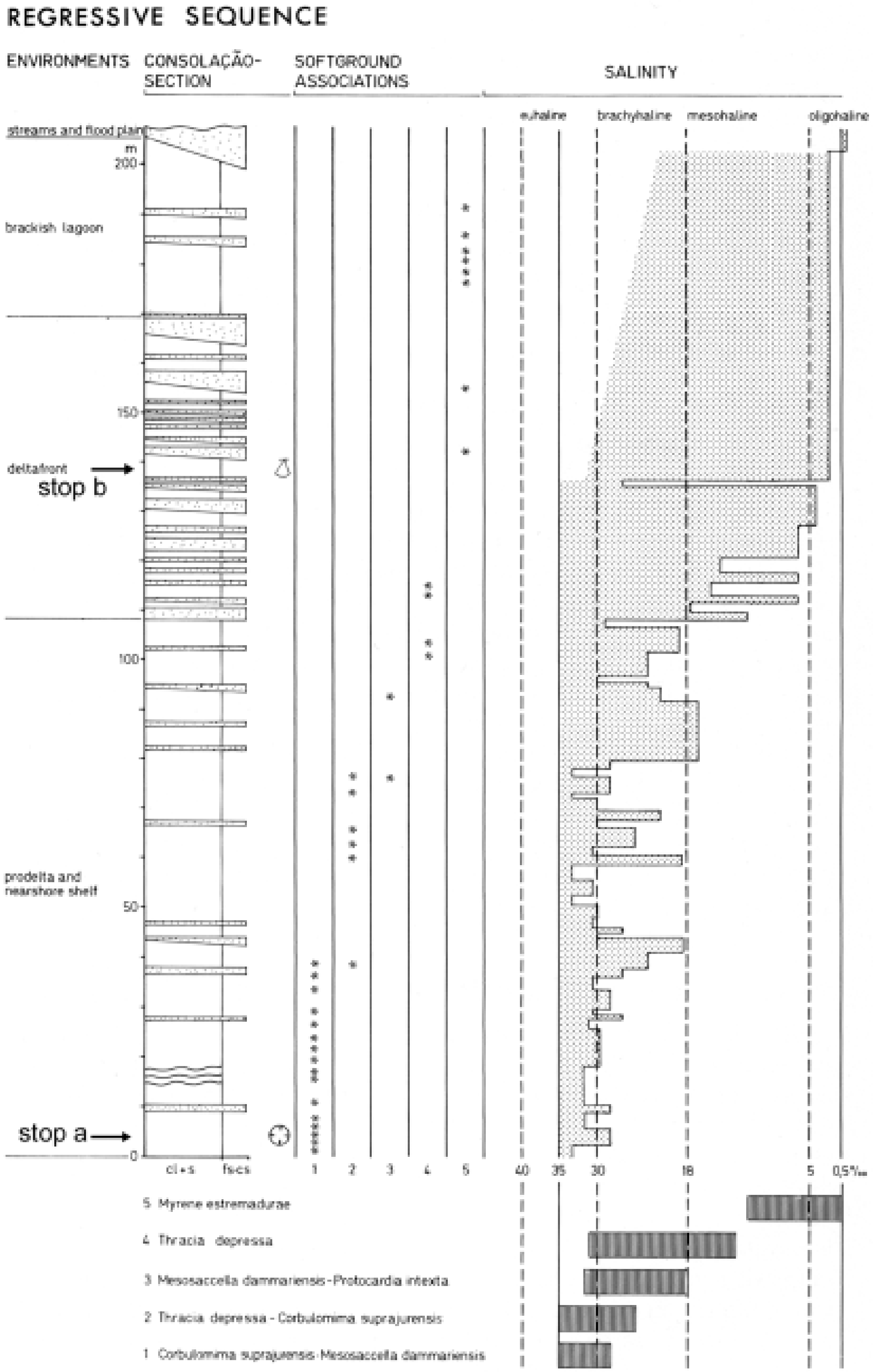

Fig. 30 - Schematic section of the regressive sequence at Consolação. Regression coincides with a general decrease of salinity, mainly traced by the replacement of endobenthic associations. The complex salinity curve was reconstructed using also epibenthic associations, microfauna, trace fossils, and sediments. Excursion Stops indicated by arrows. (modified from Werner, 1986; Fürsich & Werner, 1986).

-grained coastal lake and marsh sediments. A short brackish water intercalation between 580 and 630 m is interpreted to be equivalent to the Arranhó Formation (former Pteroceriano facies) of Santa Cruz and the Arruda subbasin.

Substop 11a: *Calamophylliospsis* coral biostrome: The lower part of the section is partly rich in epibenthic, semi-infaunal and endobenthic faunas (e.g. molluscs and corals). The composition and diversity of the various associations are largely controlled by sedimentation rate, substrate stability and salinity (cf. Werner, 1986; Fürsich & Werner, 1986; see Fig. 31). Due to the high sedimentation rate and the reduced stability of the silty to marly sediment, coral associations are developed only as biostromes with relatively small coral colonies. During the excursion a coral biostrome which is dominated by the branching phaceloid coral *Calamophylliopsis flabellata* can be seen below the Fort of Consolação. This coral could cope with sediment input by predominantly upward growth of the single branches. The rareness of small encrusters on the coral branches (e.g. bryozoans, serpulids) indicate a fast infilling of the lower coral parts by the silty, slightly calcareous sediment. Where *Calamophylliopsis* colonies are developed, less dense few additional massive corals (*Actinastrea furcata*, *Stylina* sp., *Ovalastrea caryophylloides*) and rare epibyssate bivalves (e.g. *Alaperna polita*) occur. The biostrome development was terminated by the increase of silty sedimentation which caused the installation of a typical softground association characterised by infaunal bivalves (e.g. *Corbulomima suprajurensis*, *Protocardia* sp.).

Substop 11b: *Praeexogyra* oyster reef: Oyster reefs are generally restricted today to brackish environments. This is also true for most of the known Jurassic oyster reefs. At 136 m of the Consolação section, a *Praeexogyra pustulosa* reef with small up to 80 cm high patches is exposed to an area of 90 m^2. Reef growth begins in the upper part of silty to fine-sandy marls with single shells of *Praeexogyra* and the epibyssate bivalve *Pteria credneriana.* These serve as base for the dense ca. 10 cm thick *Praeexogyra* shell layer and biostrome. In the lower part of the reef, few small corals (the massive cerioid *Cyathophora cesaredensis* and *Ovalastrea michelini*; the solitary *Axosmilia* ssp.) grow on oysters and are itself overgrown by oysters. Together with other rare faunal elements (the algae grazing trochid gastropod *Metriomphalus funatus*, the bivalves *Nanogyra nana* and *Alaperna polita*, echinoderme spines, bryozoans) the corals seem to represent short euhaline episodes within a generally stronger brackish (mesohaline to brachyhaline) environment. This is supported by palaeoecological analysis and isotope data (Werner, 1986; Fürsich & Werner, 1986; Yin *et al.*, 1995).

Stop 12, 13: Caldas-Bolhos-Unit at Caldas da Rainha diapiric structure

The probably Lower Kimmeridgian Caldas-Bolhos Carbonate Platform as the middle part of the Alcobaça beds developed coeval with the siliciclastic development at the coast of Consolação. Fig. 32 shows the model of development and facies distribution and explains the lack or strong reduction of siliciclastic contamination by synsedimentary tectonics associated with salt pillow movement. Platform development and thickness varies

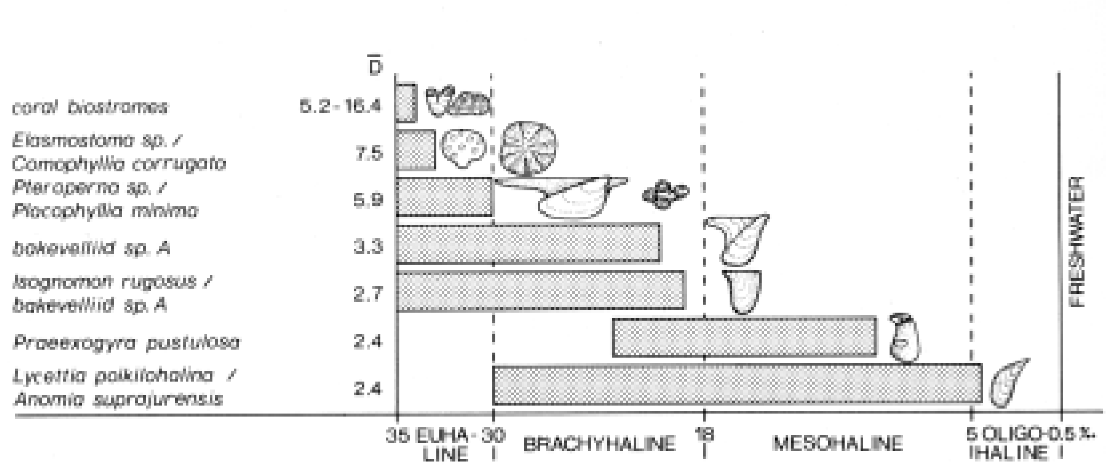

Fig. 31 - Salinity zonation of epifaunal and semi-infaunal firm substrate associations within the Upper Jurassic of Portugal. D: mean values of evenness (from Fürsich & Werner, 1986).

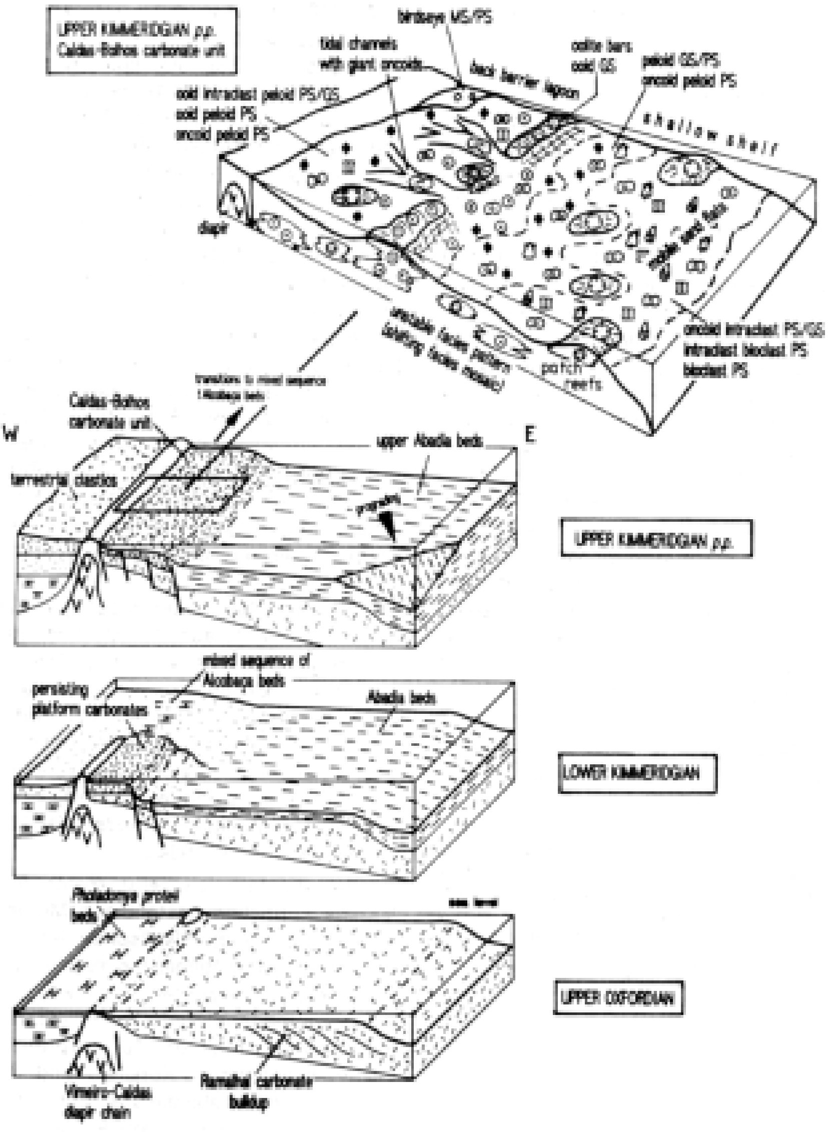

Fig. 32 - Depositional models for the Ramalhal - Vimeiro - Caldas da Rainha region, for different time intervals. At the end of the Late Oxfordian the Ramalhal buildup, with the exception of the Vimeiro area, becomes drowned and overlain by Kimmeridgian Abadia deeper water facies. West-derived siliciclastics largely get screened-off by a subaerial, salt-pillow and/or tectonic uplift. Due to improving protection and, possibly, sea level rise, shallow water carbonates (Caldas-Bolhos unit) expanded northwards to the Caldas area during the early Late (='mid') Kimmeridgian, but were coeval with shallow-water to terrestrial siliciclastic sedimentation further north and west. The facies model for the Caldas - Bolhos carbonate unit is mainly based on the sequences near Dagorda and Cesaredas. The unit represents shallow-ramp-type carbonates, characterised by a facies mosaic superimposing a weak facies zonation (from Leinfelder, 1994a).

greatly around the diapiric structure and may show siliciclastic gaps (Guéry, 1984; Leinfelder, 1994a).

Stop 12: Cesaredas Section:

The Cesaredas Section crosscuts the southern part of the Caldas-Bolhos unit and represents a succession of shallow-ramp, muddy-peloidal to grainy carbonates with levels of biostromal coral bafflestones, storm deposits and occasional ooid grainstones. The succession is rich in oncoids, with giant, decimetre-sized *Bacinella*-rich, fenestral oncoids filling tidal channels (Leinfelder, 1994a). The Stop will particularly focus on these oncoids which show features for *in situ* development (Fig. 33, 34).

Stop 13: Eastern flank of Caldas-da-Rainha diapiric structure:

Depending on time and restraints owing to highway construction, a final Stop or substops will be in coral facies with coralline sponges, oncoids, microencrusters, *Marinella* and many other features near São Mamede and Dagorda, at the eastern part of the Caldas-Bolhos Unit. The excursion will end with a view at the dinosaur tracks at Sobral de Lagoa before traveling to Coimbra.

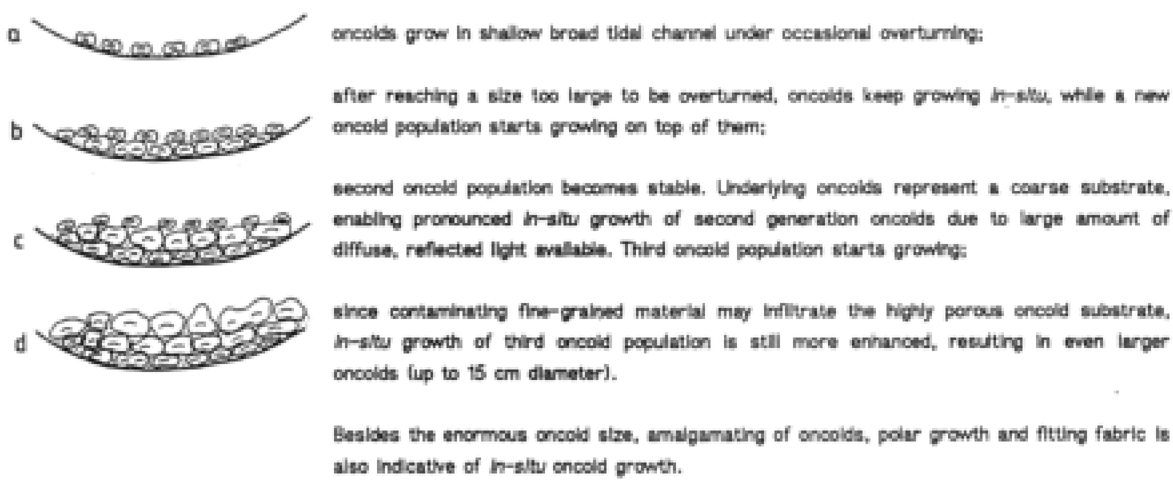

Fig. 33 - Model for the in-situ growth of the giant oncoids from the Cesaredas area (from Leinfelder, 1994a).

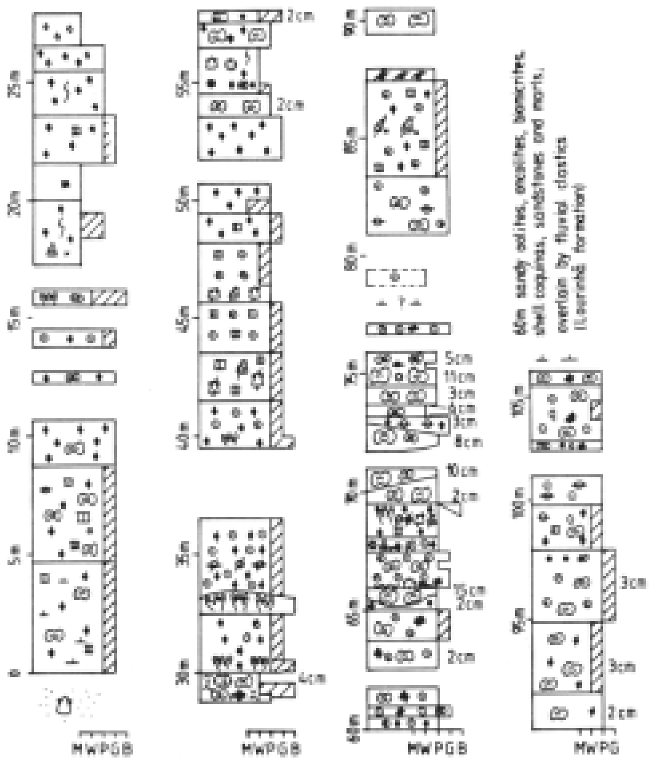

Fig. 34 - Section 'Cesaredas', middle? Kimmeridgian of the Caldas - Bolhos region. Centimetre indications refer to maximum oncoid size (for oncoids > 2 cm) (from Leinfelder, 1994a).

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