DISTRIBUTION OF JURASSIC REEF TYPES: A MIRROR OF STRUCTURAL AND ENVIRONMENTAL CHANGES DURING BREAKUP OF PANGEA

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ABSTRACT

Jurassic reefs are composed of different biotic types (coral, siliceous sponge, microbial and mixed facies) and textural types (bafflestone meadows, framestones, debris reefs, mudmounds). They indicate water energy, depth, temperature, sedimentation rate, oxygen depletion and slope angle. The distribution of reefs hence reflects changes in shelf morphology, sea level, climate and oceanographic circulation in the course of the breakup of Pangea. Reefs diagnostic of steepened slopes (mixed coral-sponge reefs) mostly occur on the southern Tethyan shelf and in the Atlantic realm, whereas reefs diagnostic of homoclinal to moderately steepened ramps (coral-debris sands, extensive siliceous sponge facies) are largely restricted to the more stable northern shelf of the Tethys.

Temporal reef distribution on the southern Tethys shelf reflects increasing drowning of Triassic carbonate platforms during the Early and, particularly Mid Jurassic, and local uplift during the Late Jurassic. On the northern Tethyan shelf reefs generally expanded during the Mid and Late Jurassic. Rather than evolutionary radiation, this pattern mostly reflects increasing habitat availability caused by general sea level rise accompanying early drift. In the Atlantic realm reef distribution helps analyze the marine rifting pulse of the Late Jurassic.

High paleolatitude occurrences of coral reefs are indicative of a very equilibrated climate during the Late Jurassic, which reflects the buffer capacities of the wide sea cover. During the same epoch dysaerobic microbial crust reefs often grew at shallow depths in the western part of the northern Tethys shelf. Together with the frequent occurrence of Upper Jurassic bituminous deposits, this feature is interpreted as reflecting a strong reduction in oceanic circulation and weak upwelling on the northern Tethyan shelf. Both climatic leveling and sluggish circulation are interpreted as feedback effects of the continuous sea level rise which itself was caused by the increasing breakup of the northern hemisphere of Pangea.

RÉSUMÉ

Les récifs carbonatés du Jurassique sont composés de divers types biotiques (coralliens, éponges siliceuses, microbiens et faciès mixtes) et texturaux (prés de bafflestone, framestones, récifs formés de débris, monticules de boue ("mudmounds")). Ils indiquent le niveau énergétique, la profondeur, la température, le taux de sédimentation et la réduction en oxygène de l'eau, et l'inclinaison de la pente. La distribution des récifs reflète donc des changements dans la morphologie de la plate-forme, le niveau marin, le climat et la circulation des courants océanographiques durant la fragmentation de Pangea. Les récifs diagnostiques de pentes escarpées (récifs mixtes coralliens-à éponges) se retrouvent surtout sur la plate-forme méridionale de la Téthys et dans le domaine de l'Atlantique, tandis que les récifs diagnostiques de rampes monoclinales à modérément escarpées (sables composés de débris coralliens, faciès d'éponges siliceuses répandus) sont en grande partie restreints à la plate-forme septentrionale, plus stable, de la Téthys.

La distribution des récifs dans le temps sur la plate-forme méridionale de la Téthys reflète la noyade croissante des plate-formes carbonatées du Trias durant le Jurassique inférieur et, en particulier, durant le Jurassique moyen, et un soulèvement local durant le Jurassique supérieur. Sur la plate-forme téthienne septentrionale les récifs prirent en général de l'expansion durant le Jurassique moyen et supérieur. Plutôt qu'un rayonnement évolutionniste, cette distribution reflète surtout la disponibilité croissante de l'habitat causé par la hausse générale du niveau marin qui accompagna une dérive continentale précoce. Dans le domaine de l'Atlantique la distribution des récifs sert à l'analyse de la pulsion de distension marine du Jurassique supérieur.

L'existence de récifs coralliens sous des paléolatitudes élevées est une indication de conditions climatiques bien équilibrées durant le Jurassique supérieur, ce qui reflète la capacité tampon de la grande étendue marine. Durant la même époque des récifs formés d'incrustations microbiennes dysaérobiques se développèrent souvent dans des eaux peu profondes dans la partie occidentale de la portion septentrionale de la plate-forme téthienne. Avec la présence fréquente de dépôts bitumineux dans le Jurassique supérieur, ce dernier trait est interprété comme reflétant une forte réduction dans la circulation océanique et une faible remontée d'eau marine sur la plate-forme téthienne septentrionale. Tant la stabilisation du climat que la lente circulation océanique sont interprétées comme des effets du feed-back de la hausse continue du niveau marin qui à son tour fut produite par la fragmentation croissante de l'hémisphère nord de Pangea.

INTRODUCTION

The Jurassic was a transitional period in many aspects. Structurally it was the time of accelerated breakup of Pangea both in the Tethyan and in the North Atlantic realm. Climatically it was situated about halfway between icehouse scenarios of a late Paleozoic and super-greenhouse scenarios of a Mid to Late Cretaceous world. In terms of global sea level the sea was generally rising over most of the time, but neither started from very low nor reached levels as high as during the Mid Cretaceous. These changes are well reflected by the distribution and abundance of reef types which changed drastically in the course of the Jurassic. In the present paper it will be shown that reef patterns not only neatly mirror general structural reorganization and general sea level rise coming along with the breakup of Pangea, but are a valuable tool to identify less accessible changes such as climatic and oceanographic reorganizations.

During the Jurassic reefs occurred most widespread and most diversified in the final epoch of the period. That is why Jurassic reef types and the evaluation of basic factors controlling their occurrence and composition can be best calibrated by the Upper Jurassic examples. They will then be compared with reefs of the earlier parts of the period.

"Reefs" are treated here in a broad structural and compositional sense: Jurassic reefs may be buildups sensu Heckel (1974), where formation of positive structures was governed or accompanied by reefal organisms. If displaying a clear constructive fabric buildups may be termed bioherms. Buildups chiefly formed by calcareous crusts of presumed microbial origin are also considered here as reefs. Biostromes or meadows formed by reef biota, particularly corals and sponges, are reefs in a biological sense (e.g., Schuhmacher 1982). Bioconstructions or meadows dominated by bivalves are excluded in this study.

JURASSIC REEFS AS INDICATORS OF GENERAL ENVIRONMENTAL FACTORS

Compositionally, Jurassic reefs can be subdivided into the end members coral facies, siliceous sponge facies and microbial crust thrombolite facies (Fig. 1). The brief characterisation of reefs given here is based on detailed investigations of Upper Jurassic reefs from Portugal, Spain, France, Switzerland and Southern Germany, as well as on additional inspection of Lower, Middle and Upper Jurassic reefs from other localities (cf. Ellis et al. 1990, Keupp et al. 1990, Leinfelder 1992, 1993a, Leinfelder et al. 1993a,b, Werner et al. 1994; for further references see below).

COMPOSITIONAL REEF TYPES

Coral reef facies occur as low to high-diversity biostromes, often with a bafflestone fabric, open fabric bioherms with or without microbial crusts, debris piles containing only minor amounts of framework, debris-rich coral-microbial bindstones and true coral or coral-stromatoporoid framestones. The dominant constructional reef biota (constructional guild sensu
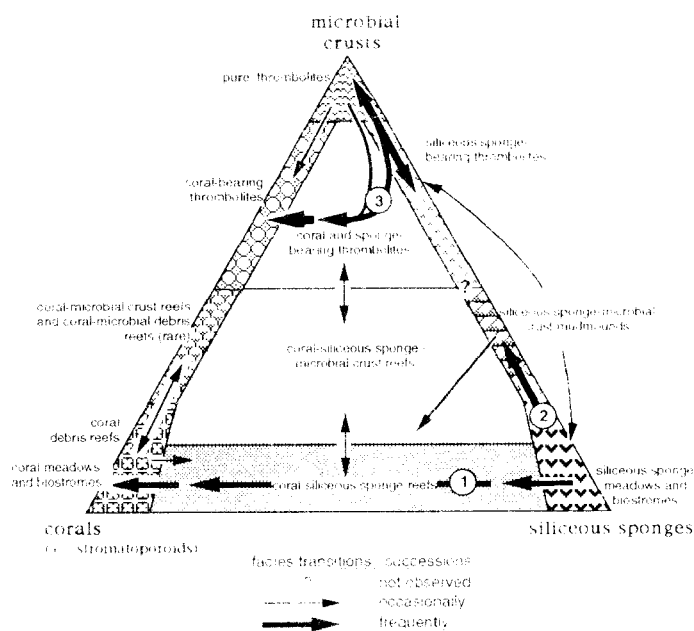

Figure 1. Jurassic reef types. Reef types can be plotted on a compositional triangle with the end members coral facies, siliceous sponge facies, and microbial facies. Arrows indicate frequent successions and facies transitions of reef types. The dominant transitional lines are labelled 1, 2, 3 (see text). The figure was calibrated by Upper Jurassic reef occurrences (cf. Leinfelder, 1993a), but is transferable to the entire Jurassic.

Fagerstrom, 1988) are corals, although stromatoporoids, chaetetids and other coralline sponges may occur in variable, partly large quantities. Rarely, the latter dominate the corals. Individual bushes of ramose and phaceloid corals, as well as encrusting coral colonies can attain sizes up to two metres, and hemispherical coral heads up to one metre, although the majority of coral colonies remained small. Not only low-diversity, but also medium, sometimes even high-diversity associations were dominated by a couple of distinct taxa, such as microsolenid, stylinid or isastreid massive corals, phaceloid *Calamophylliopsis* and *Thecosmilia*, or ramose forms of *Actinastrea*. The binder guild comprised microbial crusts, including a high percentage of micro-encrusters such as *Lithocodium, Bacinella, Tubiphytes*, solenoporoid red algae (in variable, mostly low quantities), bryozoans, encrusting foraminifera, occasionally oysters, as well as encrusting members of the constructional guild. Reef dwellers encompass many epibenthic bivalves (including diceratids) and gastropods (including nerineids), whereas brachiopods, except for encrusting thecideidinids, were not always abundant. Echinoderms were generally frequent. The destructional guild was dominated by lithophagous bivalves, but included boring sponges, polychaetes and microbes as well. Both biostromes and bioherms commonly are only up to several metres thick. Exceptionally bioherms, and particularly debris pile reef sands reached thicknesses up to several tens to hundreds of metres.

Siliceous sponge-dominated facies occur as sponge meadows and biostromes, and as sponge-microbial crust mudmounds. Siliceous sponges are mostly of the dictyid, lychniscid

and lithistid group and occur in dish, vase and tube shaped varieties. Mostly either dictyid sponges or a mixture of lithistid and lychniscid sponges dominated the associations. Also, the dominance of a single growth form is obvious in many occurrences. Siliceous sponges appeared in very variable proportion: some mounds only contain rare sponges, whereas in others, as well as in the majority of biostromes the sponges grew close to each other. Sponge sizes range from several centimetres up to two metres. Certain taxa of coralline sponges, particularly *Neuropora* can be frequent, although the majority of coralline sponges is missing. Microbial crusts occur in variable quantities and may become more abundant than sponges in the mound varieties. They include micro-encrusters such as *Tubiphytes* or the agglutinating polychaete *Terebella*, besides bryozoans and encrusting foraminifers. Brachiopods, including many encrusting thecideidinids besides the dominant terebratulids and rhynchonellids were more common than epibenthic or endobenthic bivalves and gastropods. Echinoderms may occur in considerable quantities, though they are less abundant than in the coral facies.

Sponge meadows and biostromes range from several centimetres up to several metres in thickness. Individual sponge-crust mudmounds range from decimetres up to tens of metres in thickness. Occasionally large buildups are composed of small stacked mounds.

Microbial crust facies form reefal bodies ranging from a few centimetres to several tens of metres in height. They may contain accessory siliceous sponges or corals, or both. The crusts mostly have a clotted, hence thrombolitic (Aitken, 1976, Riding, 1991), sometimes dense appearence. Macroscopically laminated crusts, i.e., stromatolites, occur very subordinately. In these thrombolitic reefs micro-encrusters may occur analogously to the crusts of the coral and siliceous sponge facies, although they are normally rare except for *Tubiphytes* and *Terebella*

Transitions between the three compositional reefal end members are frequent. Common are mixed coral-siliceous sponge types as well as compositional reef type successions which occur along three basic lines (Fig. 1): (1) A line poor in crusts is the transition from siliceous sponge meadows to mixed coral-siliceous sponge facies to coral facies; (2) An increase in crusts occurs along the transition from siliceous sponge meadows to muddy siliceous sponge-microbial crust facies which sometimes culminates in thrombolitic facies; and (3) A crust-rich line is the rapid transition from pure thrombolites to siliceous sponge-containing thrombolites to coral-rich thrombolites. This type of reef succession can be repetitive.

BASIC ENVIRONMENTAL DEMANDS OF JURASSIC REEF TYPES

General demands for all reef types

All mentioned reef types clearly grew in a normal salinity setting. This is indicated by the high diversity of many faunal associations as well as by abundant stenohaline elements such as a large variety of echinoderms, articulate brachiopods or associated ammonites (in the sponge facies). The occurrence of a variety of such stenohaline elements even in low-diversity

reefs proves that salinity was not the restricting factor. An exception is an Upper Jurassic *Amphiastrea* dominated low-diversity coral association discovered in Portugal which shows signs of reduced salinities (Leinfelder, 1986; Werner, 1986).

Very reduced background sedimentation, both terrigenous or allomicritic is an important prerequisite for reef growth. Dominance of epifauna, the frequent attack of boring bivalves and a high incrustation rate by oysters, thecideidinid brachiopods, serpulids, bryozoans, coralline sponges and microbial crusts show that most reefal coral and siliceous sponge associations occurred in a regime of low background sedimentation rates that caused stable substrates. Due to their slow growth capacity microbial crusts are strongly dependent on starved sedimentation. Hence their frequent occurrence is diagnostic for very low background sedimentation rates (Leinfelder et al., 1993b)(cf. Fig. 8). This is corroborated by the fact that many crust-rich reefs are restricted to correlatable horizons that exhibit features of starved sedimentation or sedimentary breaks, such as abundance of authigenic glauconite, autochthonous shell concentrations (including ammonite shell beds) or incipient hardground characteristics. In a sequence stratigraphic context these horizons are interpretable as transgressive phases, resulting from a regional lowering of background sedimentation (Leinfelder, 1993a, b; Leinfelder et al., 1993a, b). Particularly in deeper settings, occurrences of microbial crust reefs are of special interest to detect phases of strongly suppressed sedimentation, since other biologic indicators such as boring bivalves or encrusting coralline sponges are partly or entirely lacking in deeper settings.

Some Jurassic reefal associations were adapted to a certain degree of sedimentation and related soft bottom settings. For example, low diversity associations of siliceous sponges may indicate higher sedimentation rates, particularly if sponges are of the tube type. *Eudea clavata*, a coralline sponge partly closed its lower inhalant pores by a calcareous plug in order to prevent penetration of sediments and thus could cope with slightly elevated sedimentation rates (Krautter, 1994). Morphologies of corals, particularly general growth form and calical types, to some degree reflect adaption towards sedimentation (Hubbard, 1973; Hubbard and Pocock, 1972). Using these parameters and diversity patterns, some of the coral biostromes and small bioherms of Portugal seem to have been adapted to sedimentation in various degrees (Leinfelder 1986, 1994). Particularly, many low-diversity coral bafflestones occurring in mixed carbonate-terrigeneous or pure calcareous inner-ramp, lagoonal settings or within lagoons or rimmed shelves apparently were adapted to a soft, unstable substrate resulting from elevated background sedimentation. Some of the most widespread Upper Jurassic coral associations, bafflestones (meadows and bioherms) dominated by a thin-branched variety of *Calamophylliopsis* or by *Stylosmilia* are particularly characteristic of soft substrates and high sedimentation rates. Coral bushes often toppled even within a general low energy setting, indicating substrate instability. Characteristically, coral branches of these thin-branched phaceloid corals are often not bored or encrusted by microbial crusts.

The fact that very thick, mud-rich reef bodies, particularly siliceous sponge - microbial crust mudmounds commonly interfinger with sediment-starved horizons is not contradictory. The thickness of the reef body is either related to an elevated in-situ productivity of carbonate mud within the reef or, alternatively, a higher ability to fix episodically available allochthonous mud, whereas the general initiation and continuation of reef growth is dependent on a reduced background sedimentation regime over an extended period of time.

Environmental factors responsible for differences in reef composition

Water energy and water depth are the most obvious factors controlling the differences in composition and fabric of Jurassic reefs. The majority of Jurassic shallow water reefs are poorly preserved. These reefs are mostly represented by debris-rich coral sand facies. Most of them can be described as bioclastic piles containing only small patches of coral framework (Baria et al., 1982; Crevello and Harris, 1984; Leinfelder, 1992). Such debris-rich coral reefs mostly occur in association with autochthonous oolite sands and hence are characteristic of a shallow water, high energy setting.

The poor preservation of reef framework can be explained by the fact that the available Jurassic binding organisms, chiefly the microbial encrusters and, to a lesser extent the solenoporacean algae were less effective in debris fixation than modern melobesioid coralline algae. Only when steep reef margins enabled exportation of a major part of the reef debris could microbial crusts stabilize the remaining material. The resulting high energy reef limestones are rich in both debris and crusts which seem to be indicative of bypass margin situations (Leinfelder, 1992, see below).

Commonly the debris reef type is not recognized as 'true' reef because of the subordinate occurrence of reef framework. However, even modern and Pleistocene reefs do not show a lot of framework preservation (e.g., Shinn, 1988; Choi and Ginsburg, 1983; Ginsburg, 1992). This is despite the fact that modern reefs contain coralline algae, which are highly effective, energy-tolerant sediment binders. Much better studied Jurassic reefs are the more spectacular biostromes and bioherms with corals in life position. The general setting of such reefs and the fragility of mostly delicate coral bushes participating in, or dominating reef formation show that despite their shallow water origin, such reefs mostly are of the low energy type. Associated sediments show that coral framestones with coral colonies overgrowing each other are often also related to low energy settings. This is, for example, obvious for many of the widespread *Microsolena* dominated framestones. These framestones often include siliceous sponges or are developed on top of siliceous sponge reefs. On the other hand, the coral *Microsolena* itself is eurytopic in terms of water depth and water energy, so that framestones with or without *Microsolena* also occur locally in high energy settings, particularly forming patches within oolitic sands. Well preserved coral reefs, particularly with delicate bushy corals in life position, are therefore mostly indicative of low energy settings, both in protected

shallow water and in slightly deeper water. Together with low water energy, fairly rapid burial may be another prerequisite for preservation of reef framework (G.D. Stanley, Jr., pers. comm.).

Siliceous sponges become increasingly abundant towards deeper water. The first siliceous sponges to appear towards greater water depth are lithistid and lychniscid forms, which often occur with a relict coral fauna dominated by *Microsolena* (see above). Possibly below 50 to 60 metres siliceous sponges occur without reef-building corals. Dictyid sponges gradually dominate the other sponge groups towards deeper water. Based on semi-quantitative comparative paleoecological analysis, many other bathymetric faunal gradients can be established (Werner et al., 1994). The compositional change to deeper water settings occurs along a variety of mixed coral-siliceous sponge reef associations. The bathymetric change in faunal composition can be substantiated by the fact that pure siliceous sponge facies, mixed facies and pure coral facies occur as distinct facies progression within shallowing upward successions of Iberia (Leinfelder et al., 1993a).

Pure thrombolitic reefs occur below the siliceous sponge facies, but they may also be intercalated in almost any position within shallowing upward successions, so that their distribution is not governed by bathymetry alone. The wide distribution of the Iberian pure thrombolites, as well as of thrombolitic reefs containing additional reefal macrofauna must have been controlled by factors other than bathymetry. Thrombolite occurrences are restricted to distinct levels which mostly are very rich in authigenic glauconite as well as early diagenetic framboidal pyrite. Glauconite not only occurs within the thrombolites but particularly coats the outer surface of the structures and is enriched in lateral bedded intervals between the thrombolite buildups. Besides low sedimentation rate, authigenic glauconite also indicates slightly reducing conditions in the top part of bottom sediments (e.g., Cloud, 1955; Odin and Matter, 1981) and is therefore a strong indicator for generally lowered or frequently shifting oxygen concentrations at the sediment-water interface. The occurrence of the dysaerobic epibenthic flat clam *Aulacomyella* in these horizons demonstrates phases of oxygen depletion (Leinfelder et al., 1993a, b) and shows glauconite formation directly on the sea floor. Serpulids are often the only faunal element of thrombolites. Such annelids are known to be euryoxic (Schöttler and Bennet, 1991). *Tubiphytes*, a probable microbial-foraminiferal symbiotic association is another frequent participant in the formation of thrombolites (Crevello and Harris, 1984; Leinfelder et al., 1993b).

Microbial crusts *per se* are not diagnostic of reduced oxygenation since their only demand is reduced sedimentation. However, if pure thrombolitic reefs occur in normal marine settings where, depending on depth, coral or siliceous sponge association should be expected, then they are good indicators of reduced or fluctuating oxygenation. This interpretation is substantiated by the occurrence of the above mentioned indicators of oxygen depletion. Decrease of oxygen content in bottom waters is commonly due to productivity blooms in surface

waters caused by elevated nutrient input (e.g., Lohse et al., 1989; Lozan et al., 1990; cf. Sarnthein et al., 1987; Berger, 1991). Such nutrient input will damage both reefal corals and, probably, siliceous sponges. Restriction of reef building corals to high oxygen and low nutrient levels is well known (cf. Kühlmann, 1984; Hallock and Schlager, 1986). Although there are exceptions, most siliceous sponges seem also to be related to high oxygen/low nutrient levels (Reitner, Berlin, pers. comm.), so that their occurrence within thrombolites should reflect phases of improved oxygenation (see below).

Some transitional pathways between reef types also can be well explained by fluctuations in nutrient/oxygen content rather than by extraordinary, unlikely jumps in water depth (cf. Leinfelder et al., 1993b): In Portugal and, partly, in Spain pure thrombolites or thrombolites containing some siliceous sponges may rapidly grade into a crust-rich coral facies. Within one bioherm such transitions occur within centimetres or decimetres and may also be repetitive, forming cycles of microbial versus metazoan dominance. The sudden change from thrombolites to coral facies may be explained with episodically improving oxygenation of previously dysaerobic or poikiloaerobic (Oschmann, 1991) conditions.

The interaction between background sedimentation rate, water depth and fluctuations in the nutrient/oxygen levels largely controls the growth of Jurassic reefs (Fig. 2). Along the bathymetric gradient coral facies is followed by mixed facies, then by pure siliceous sponge facies. Given other stable factors, particularly stenohaline conditions, sedimentation rate controlled much of the faunal diversity as well as the occurrence of microbial crusts. Once sedimentation dropped below a critical threshold reefal facies appeared. Such reefs, which grew under moderate background sedimentation, represented low diversity meadows of adapted reef biota. Diversity increased and microbial crusts occurred once background

sedimentation rate approached zero. In the deeper water setting occasional oxygen depletion possibly stimulated crust formation during certain phases (crust-dominated parts within some bioherms). Reefal macrobiota became increasingly excluded if phases of impoverished oxygenation (probably coinciding with phases of increased nutrient levels) became increasingly frequent. This eventually led to the formation of thrombolites, which occasionally could even take over settings in fairly shallow water otherwise occupied by 'favourable time' reefal associations. Such shallower 'nasty time' thrombolitic reefs immediately disappeared once oxygenation improved or background sedimentation started again.

JURASSIC REEFS AS INDICATORS OF SHELF STRUCTURE

Jurassic reefs are often characteristic parts of carbonate or, sometimes, mixed carbonate-siliciclastic ramp systems as well as of rimmed carbonate shelves.

Ramp systems generally are not as clearly organized in facies belts as rimmed shelves, but partly show zones of facies mosaics (cf. Read, 1985; Burchette and Wright, 1992). Nevertheless, simple prograding ramp systems can be easily recognized by the development of large scale shallowing upward successions without apparent bathymetric breaks (cf. Gygi, 1986; Gygi and Persoz, 1986, 1987; Leinfelder et al., 1993a, Nose, Stuttgart, in prep.). This situation helps calibrate the characters of Jurassic ramp type reefs and helps in recognizing ramp settings in regions where insufficient preservation of successions prevents easy interpretation of shelf style.

Another general structural setting of Jurassic reefs, reef-rimmed shelves and isolated reefal buildups was on structural (including halokinetic) uplifts.

Sometimes ramps graded upwards into depositional rimmed shelves, with reefs occurring in front of, within and behind the shoal rim as well as in lagoonal positions. In most cases true rimmed shelves never formed and the development stopped in the interim stage of a 'proximally' (rather than distally) steepened ramp. As discussed below, in most cases such transformation seems to have been related to structural accentuation of slopes rather than exhaustive reefal carbonate production. Detection of such steepenings hence may allow recognition of synsedimentary tectonic activity.

Jurassic reef types can be used as an additional tool to identify the style of structural development. They help to differentiate between carbonate ramps and shelves (cf. Crevello and Harris, 1984), and allow reconstruction of their topography and hypsometry, since water energy, water depth and slope angles are reflected by the character of the reefs (Fig. 3):

Low energy, low-diversity coral meadows and small patch reefs dominated by phaceloid (mostly *Calamophylliopsis* and *Stylosmilia*) or ramose (e.g., *Actinastrea*) associations often occur in marly to silty sediments within proximal, siliciclastical influenced parts of inner ramps (Leinfelder, 1986; Werner, 1986), together with bivalve meadows and, rarely, coral-coralline sponge associations (Fürsich and Werner, 1991). The occasional occurrence of high-diversity meadows related to
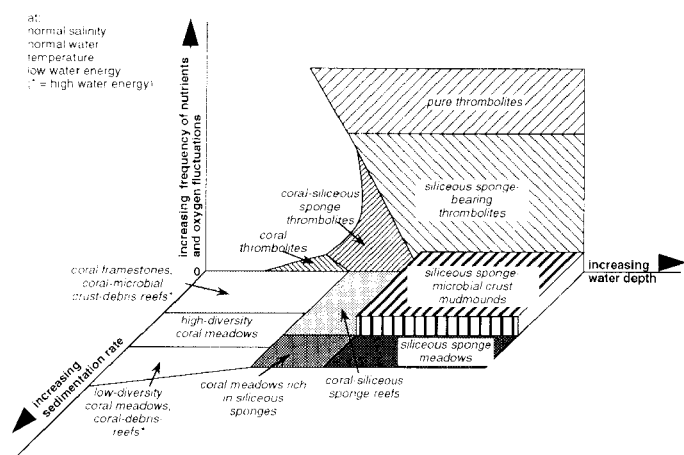

Figure 2. The triple factor model of Jurassic reefs (based on Upper Jurassic examples, cf. Leinfelder, 1993a). It is assumed that differences in background sedimentation rate, bathymetry and oxygen levels are the dominant factors determining the occurrence and character of Upper Jurassic reefs. Microbial crusts only occur when sedimentation is very low or ceases. Calcifying reefal metazoans will be increasingly excluded by fluctuating oxygen/nutrient levels, leading to microbial facies.
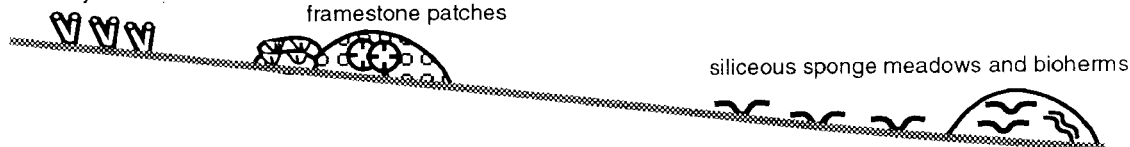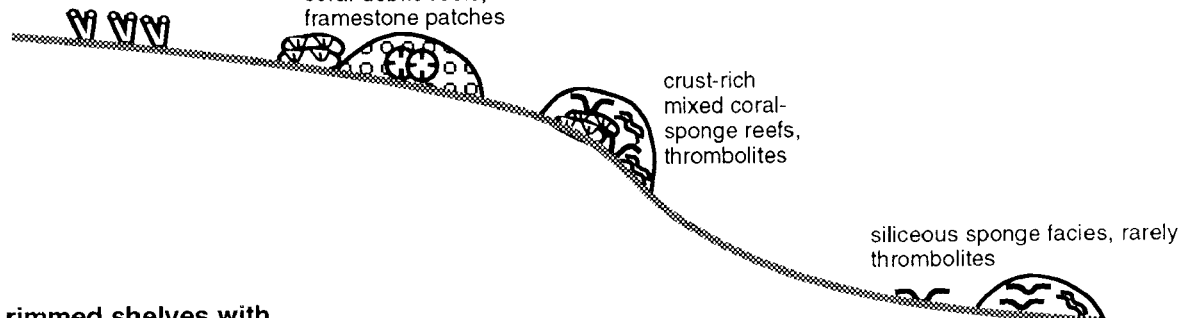
Figure 3. Jurassic reef types related to different shelf configurations. Extensive pure siliceous sponge facies is restricted to near level-bottom ramp situations (1). Mixed coral-sponge reefs are particularly diagnostic for the existence of steepened slopes (2, 3). Coral-debris sands are indicative of shallow ramp and shelf depositional margin situations (1-3), whereas crust-rich coral-debris reefs grew atop bypass margin situations (4). Jurassic reef distribution reflects that rimmed shelves with steepened slopes were particularly characteristic of the southern Tethys and North Atlantic realm, whereas ramp configurations prevailed on the northern Tethys margin.

phases of optimum conditions is not contradictory. Similar low diversity meadows also occur within pure carbonate successions and can be considered as diagnostic of proximal, protected parts of inner ramps or low energy, normal salinity settings within larger lagoons of rimmed shelves.

Medium to high-diversity coral bafflestones, coral framestones and, if constantly wave-agitated, debris pile reefs have a fairly wide structural distribution. They often occur in the distal part of inner carbonate ramps (sensu Burchette and Wright, 1992; = lower part of shallow carbonate ramps, after Tucker and Wright, 1990). Large debris pile reef sands including small patches of high-diversity coral framestones and bafflestones frequently border rimmed shelves with depositional margins. Lagoonal bafflestones are mostly of the low-diversity type (see above), whereas high-diversity bafflestones are particularly a feature of the upper slope of depositional margins, below the constantly agitated zone. Coral-microbial crust reef patches indicate very reduced background sedimentation. They either developed during times of generally starved sedimentation in slightly deeper settings on ramps or, if this be excluded by other criteria, are diagnostic of steepened parts of the upper depositional slope of rimmed shelves.

High energy, debris-rich coral reefs rich in microbial crusts are particularly indicative of shelf edge reefs with steep bypass margins. Often these reefs have a low preservation potential, but debris aprons of reefs shed into deeper basinal settings with large clasts of crust and debris facies are indicative of such shelf edge reefs atop bypass situations. Another possibility to detect major fossil bypass margins is when a shallow water carbonate shelf exhibits aggradational structure throughout its development despite the occurrence of sea level changes, because steep and deep margins will prevent any progradatation. Shelves with depositional margins often prograded, as did most ramp systems (Ellis et al., 1990; Leinfelder, 1994). In the Portuguese example bypass margins were clearly related to structural basement uplift (Leinfelder, 1992), whereas depositional margins particularly developed when structural uplift was accompanied by halokinetic modification (Leinfelder and Wilson, 1989; Ellis et al., 1990).

Isolated coral-dominated buildups such as the shallow water Barreiro or Monte Gordo buildups of central Portugal mostly show aggradational architecture accompanied by a mixture of catch-up, keep-up and give-up trends. This allows evaluation of relative sea level changes which may or may not be related to synsedimentary tectonics (Ellis et al., 1990; Leinfelder, 1993b).

Even in areas of high terrigeneous input shallow water coral reefs may occur. The case example of this aspect is the Upper Jurassic of the Lusitanian Basin, which underwent a severe rifting pulse during that time. The occurrence of coral reefs within siliciclastic ramps and large fan deltas, besides representing bathymetric dipsticks, allows interpretation of sheltering mechanisms which might give additional clues to basin configuration. It also helps detect episodes of relative tectonic quiescence characterized by reduced terrigeneous input, although the separation of the eustatic signal can be difficult (Leinfelder, 1994).

Mixed coral-siliceous sponge reefs are a frequent constituent in settings at the transition of the mid ramp to the inner ramp. Often they are associated with allochthonous slope sediments (Leinfelder et al., 1993a), showing that they are diagnostic of structural steepening of ramps. Similar reefs are also frequent in the lower part of the upper depositional slope of rimmed shelves, particularly if slopes angles were accentuated.

The pure siliceous sponge reef facies is a good indicator of mid-ramp settings (i.e., the parts between fair weather wave base and normal storm wave base, after Burchette and Wright, 1992). Only very rarely does the siliceous sponge facies occur in the middle and lower slope of depositional rimmed shelves. There elevated sedimentation rates mostly prevented the establishment of microbial crusts so that the sponge facies normally occurs only as autochthonous spiculites.

Large siliceous sponge mid ramp buildups also locally developed strong positive relief, so that they grew up to shallower water and hence became capped by mixed coral-siliceous sponge reefs and, later, by pure coral reefs. In other areas isolated coral buildups are capped by mixed coral-siliceous sponge facies, or siliceous sponge facies indicating drowning of the buildups, which might be related to tectonic movement.

In Portugal and Spain thrombolitic reefs are widespread in the lower part of the inner ramp and in mid-ramp settings. In these settings they were dependent on the exclusion of reefal macrobiota by phases of impoverished oxygenation. They also occur in outer ramp settings (cf. Ellis et al., 1985; Dromart, 1989, 1992; Jansa et al., 1988), where the exclusion of reef macrobiota might alternatively be related to lack of light or colder water temperatures (but see below). Microbialites of the intertidal and supratidal zone owe their existence to the fact that variable salinities prevented the growth of reef biota. These shallowest microbialites generally exhibit a stromatolitic rather than thrombolitic fabric. Since the development of thrombolites was particularly dependent on sediment starvation they are very rare in the lower part of depositional slopes of rimmed shelves. Besides their significance in detecting oxygen depletion, they are characteristic of episodes of very reduced sedimentation in mid and outer ramps and were sometimes clearly related to tectonic slope steepening. The occurrence of thrombolites and siliceous sponge facies in terrigeneous deposits allows detection of episodes of reduced terrigeneous input, which may be interpreted in terms of structural quiescence besides eustatic and climatic aspects (see below).

DISCUSSION: THE EARLY BREAKUP PHASE OF PANGEA REVIEWED BY REEF DISTRIBUTION

INFLUENCE OF EVOLUTION ON JURASSIC REEF OCCURRENCES

When comparing reef abundance of the Early, Mid and Late Jurassic it is quite obvious that both coral and siliceous sponge reef facies dramatically expanded in the course of the period. Before evaluating this trend in terms of environmental and structural change in the course of the breakup of Pangea, possible effects of evolution of reef biota must be considered.

The Jurassic was a time when major reef biota, particularly scleractinian corals, stromatoporoids, coralline sponges and siliceous sponges were generally present, although some perturbances took place, particularly at the start of the period. Scleractinian corals and siliceous sponges were the most important reef biota, and their occurrence will be discussed in more detail.

Actually extinction events of reef biota at the Permian/Triassic boundary, and several similar events during the Triassic and at the Triassic/Jurassic boundary were not that far behind. Scleractinian corals, possibly having been derived from non-calcifying 'sea anemones' rather than survivors of rugose corals (cf. Stanley, 1988), only slowly developed during most of the Triassic. They rapidly expanded during the Norian, which was possibly related to the (renewed) invention of algal symbiosis (Stanley, 1988; see also Cowen, 1988) after another minor extinction event during the Carnian. However this expansion was mostly due to the success of only a few genera, such as the distichophylliids of the Upper Triassic reefs. After a setback of corals at the base of the Jurassic, corals rapidly diversified during the Early and, particularly, Mid Jurassic (Stanley, 1981, 1988; Beauvais, 1984). Early Jurassic coral reefs (mostly biostromes) are normally not older than Pliensbachian, although some earlier occurrences do exist (Great Britain, Beauvais, 1976; Morocco, Beauvais, 1986). Those corals are relics of the few surviving Late Triassic taxa and are often considered as nonzooxanthellate (e.g., Beauvais, 1984, 1985). They occur together with a large number of coralline sponges (including sphinctozoans) and therefore resemble Middle Triassic buildups. Possibly they lived in a somewhat deeper neritic environment (Roniewicz and Morycowa, 1989). Nevertheless, rare coral buildups termed reefs from the Sinemurian are known (American Cordillera, Poulton, 1988; Stanley 1993a, b; Stanley and McRoberts, 1993). Elmi (1987) mentioned a Hettangian coral reef from France, but detailed data are not yet available. Even in Toarcian coral associations faunal diversities apparently were not very high, which is partially related to the reduced availability of coral taxa (59 genera, after Beauvais, 1984). Given suitable habitats, reef growth was nevertheless possible. Most probably the extreme rarity of earliest Liassic reefs was caused by the restricted availability of framebuilders after Triassic/Jurassic extinction events as well as by the prevalence of unsuitable, siliciclastic dominated settings.

Middle Jurassic coral reefs are particularly of Bajocian/Bathonian age, although Callovian occurrences are known (cf. Beauvais, 1984). Despite the fact that Middle Jurassic coral reefs were not as widespread as Upper Jurassic coral faunas, coral taxa availability during the Mid Jurassic was already almost as high as during the Late Jurassic. The rarity of coral taxa during the Early Jurassic, with 59 genera, was followed by 92 genera from the Mid Jurassic and 128 genera during the Late Jurassic (Beauvais, 1984). Reefs were much rarer during the Callovian (e.g., Tunisia: Busson, 1965; Beauvais, 1985, Saudi Arabia: El Asa'ad 1989; India: Gregory, 1900). Callovian corals only comprise 39 genera

according to Beauvais (1980). This figure might, however be biased by the rarity of coral reefs during this time. It seems that the apparent setback in coral reefs then may have been an effect of poor habitat availability rather than a true extinction event. Beauvais (1980) states that a cooling event was responsible for an extinction pulse. The much greater expanse of coral reefs during the Late Jurassic (Figs. 4, 5) was only partly due to an adaptive radiation of Upper Jurassic corals. Most major coral groups existed already during the Early Jurassic. The only new family appearing in the Late Jurassic was the Guyniidae (Beauvais, 1984). However, at the genus and species level coral diversification was rapid, which seems to reflect positive responses to the increasing availability of habitats.
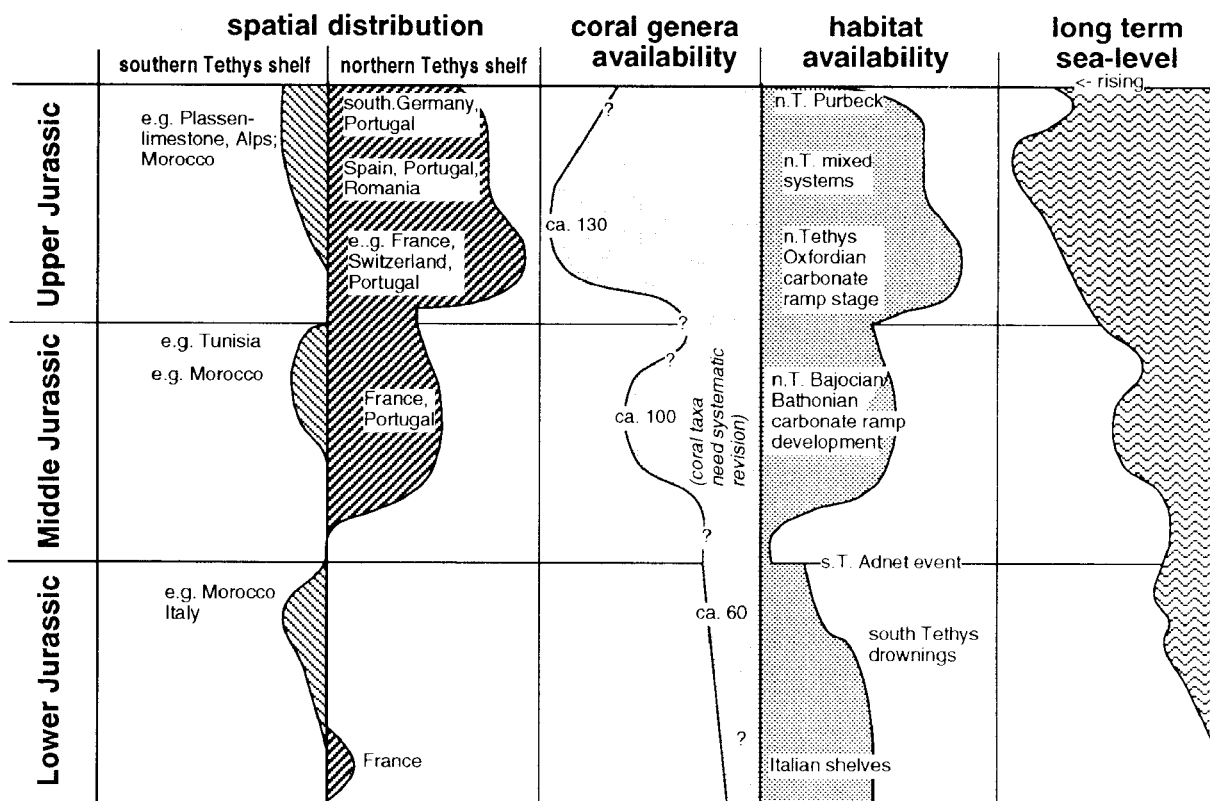
Phylogenetic considerations of Jurassic corals would be more reliable at the species level. However, Jurassic species partly are insufficiently defined and need taxonomic revision, so that at the present comparisons of species number are of little relevance (see also Beauvais, 1984). Although Jurassic genera also are not always substantiated and their actual number is a matter of debate (cf. Beauvais, 1980, 1984), it is believed that comparing genera numbers through time gives a reasonable qualitative outline of Jurassic coral phylogeny.

Less is known about siliceous sponges. They represent very conservative organisms which apparently had not changed much in their functional adaptions since the Paleozoic. Siliceous sponges have been more or less important members of reefs during most of the Earth's history. Phylogeny of both coralline and siliceous sponges is currently under discussion, since the classical hierarchical system is not satisfactory (Reitner, 1992; Mehl, 1992; Gruber, 1993). Probably the hexactinellids represent the most archaic group of sponges (Mehl, 1993). Although spiculitic rocks from the base of the Jurassic are known (e.g., Mostler, 1989), siliceous sponge facies with preserved sponge specimens occurred since the Sinemurian and particularly, Pliensbachian. Together with a large number of coralline sponges or in places corals, they participated in the formation of local small reef structures (see below). Siliceous sponge facies became more widespread during Mid Jurassic time, particularly during late Bajocian and early Bathonian time, and rapidly spread regionally during the Late Jurassic. Available data indicate that many dominant taxa existed during the entire Jurassic, or at least since the Mid Jurassic (e.g., Gruber, 1992; Mehl, 1992). Only the lychniscids first appeared during the Bajocian (Pisera, 1993) and became particulary widespread during Late Jurassic (Mehl and Reiswig, 1993). Besides this latter exception, it seems that the expansion of siliceous sponge facies through time was again only to a certain amount caused by evolutionary radiation. However this conclusion is hampered by the fact that for the majority of occurrences of Jurassic siliceous sponge facies no detailed taxonomic determinations of the sponges so far exist. In any case, siliceous sponges had the potential to form siliceous sponge reefs at any time during the Jurassic Period.

SHELF DEVELOPMENT DURING PANGEA BREAKUP

The plot of reef occurrences for the Early, Mid and Late epochs of the Jurassic (Figs. 4, 5) highlights the following:

Jurassic Coral Facies

	spatial distribution		coral genera availability	habitat availability	long term sea-level
	southern Tethys shelf	northern Tethys shelf			
Upper Jurassic	e.g. Plassen-limestone, Alps; Morocco	south.Germany, Portugal / Spain, Portugal, Romania / e..g. France, Switzerland, Portugal	ca. 130	n.T. Purbeck / n.T. mixed systems / n.Tethys Oxfordian carbonate ramp stage	<- rising
Middle Jurassic	e.g. Tunisia / e.g. Morocco	France, Portugal	ca. 100 (coral taxa need systematic revision)	n.T. Bajocian/Bathonian carbonate ramp development	
Lower Jurassic	e.g. Morocco Italy	France	ca. 60	s.T. Adnet event / south Tethys drownings / Italian shelves	

Jurassic Siliceous Sponge Facies

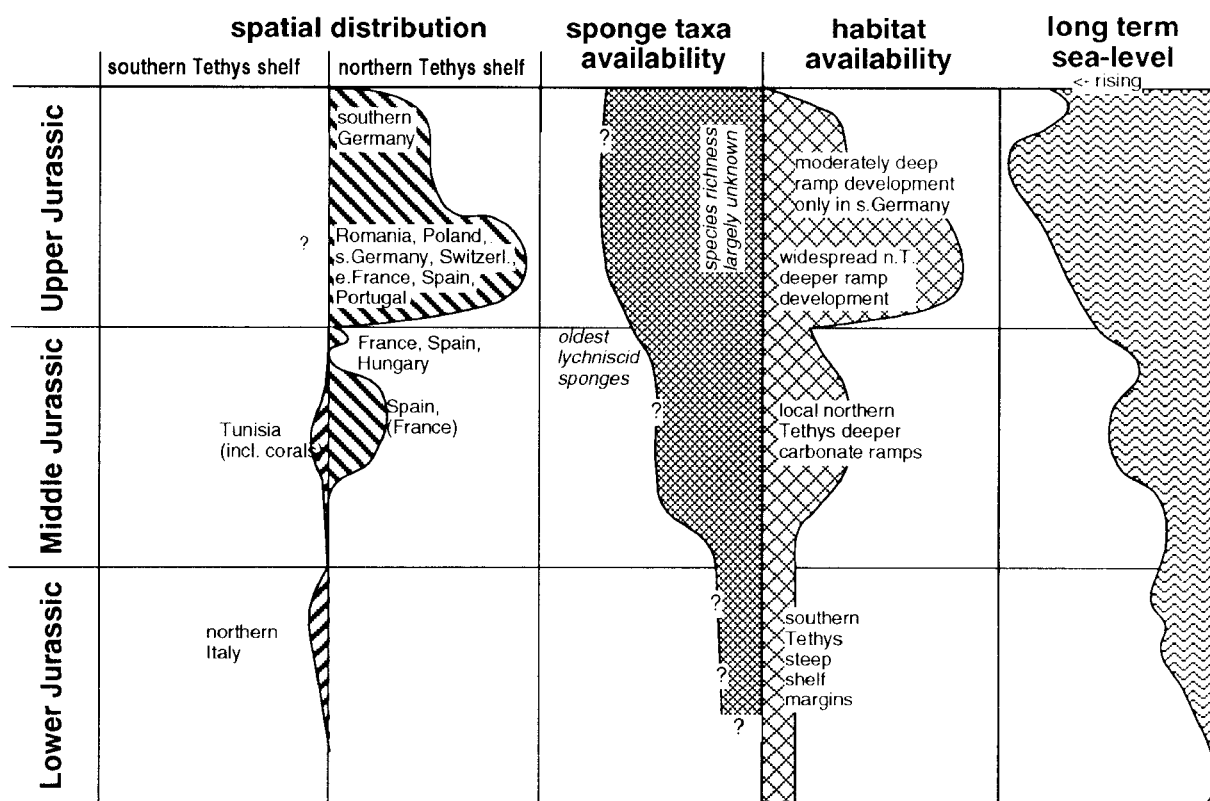|	spatial distribution		sponge taxa availability	habitat availability	long term sea-level
	southern Tethys shelf	northern Tethys shelf			
Upper Jurassic	?	southern Germany / Romania, Poland, s.Germany, Switzerl., e.France, Spain, Portugal	species richness largely unknown	moderately deep ramp development only in s.Germany / widespread n.T. deeper ramp development	<- rising
Middle Jurassic	Tunisia (incl. coral)	France, Spain, Hungary / Spain, (France)	oldest lychniscid sponges	local northern Tethys deeper carbonate ramps	
Lower Jurassic	northern Italy			southern Tethys steep shelf margins	

Figure 4. Distribution of Jurassic coral and siliceous sponge facies from southern and northern margins of the central Tethys. S.T. Adnet event: major drowning of platforms in southern Tethys. The comparison of reef occurrences with habitat availability, evolution of reef biota, and sea level change shows that the expanse of reefs reflects changes in shelf structure and sea level coming along with the breakup of Pangea. Compiled from various sources (cf. Fig. 5 and text for references).

Early Jurassic

///, coral reefs
\\\ siliceous sponge reefs
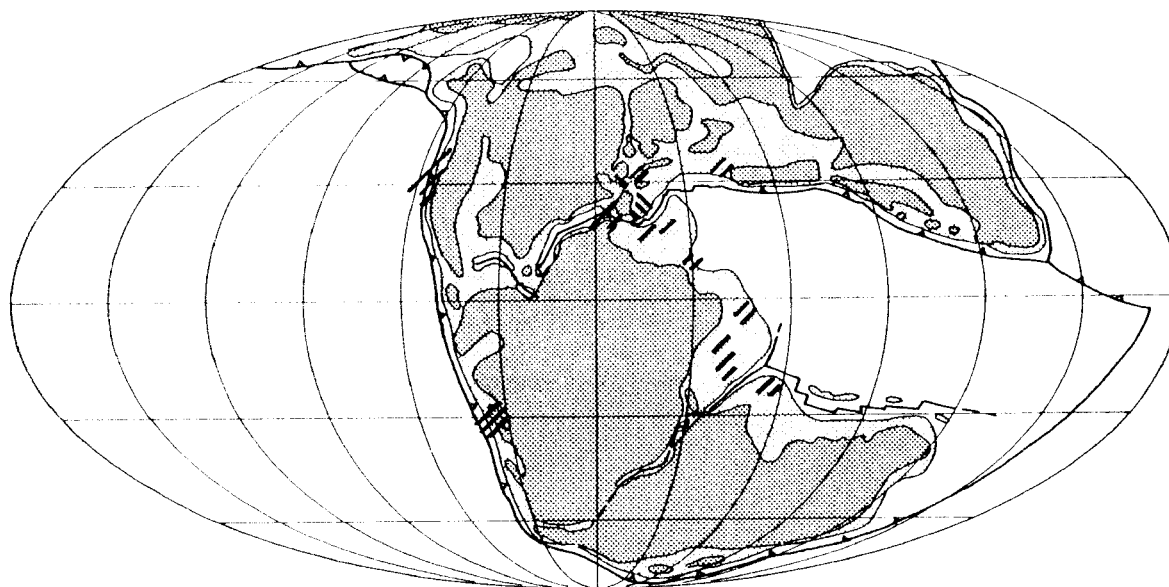• • thrombolite reefs
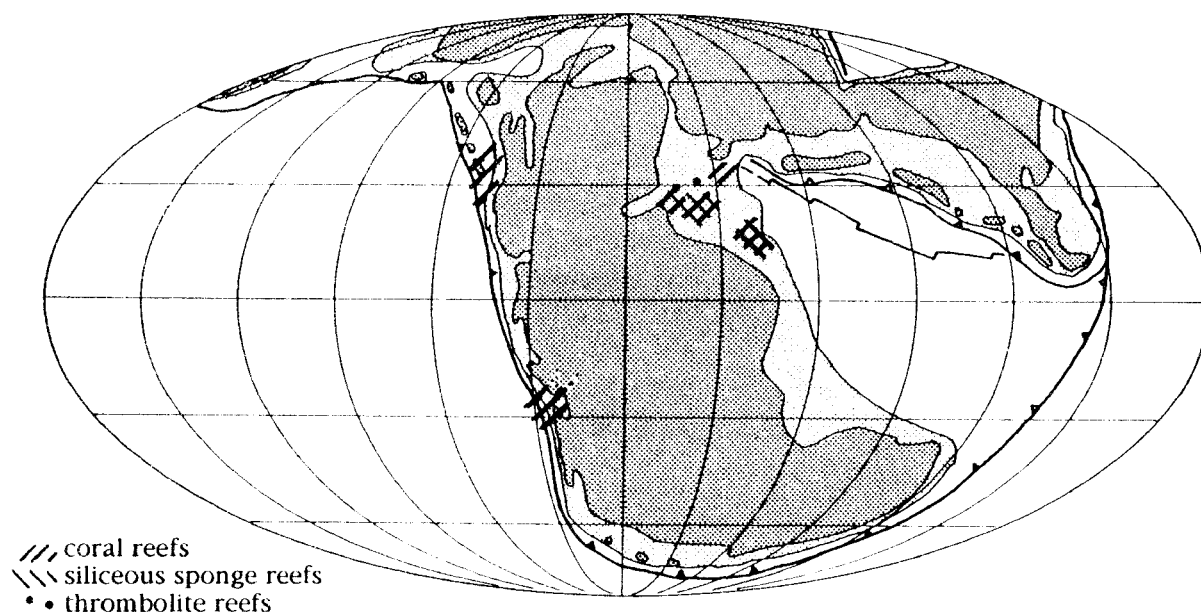
Mid-Jurassic

Figure 5. Simplified reef distribution maps for Early, Mid and Late Jurassic. Based on Beauvais (1973, 1977, 1979, 1980), Talent (1988), Flügel and Flügel-Kahler (1992) and other sources (see text). Paleogeographic maps are simplified from Scotese et al. (1993). See text for further explanation.

1. Most reefs occurred in the Tethyan realm and its bordering pericontinental and epicontinental seas, but some reefs grew far to the paleonorth and paleosouth. Outside the Tethys the Pacific coast of South America, exotic terranes now attached to the North American Cordillera, Japan and the Sakaline Islands also were sites of Jurassic reef formation.

2. Reefs occurred scattered on the southern shelf of the Tethys throughout the entire Jurassic. On the northern Tethyan shelf they were very rare during the Early Jurassic, locally frequent during the Mid Jurassic, but expanded rapidly at a regional scale during the Late Jurassic.

3. Siliceous sponge facies occurred very subordinately on the southern Tethyan shelf. On the northern Tethyan shelf, where it was lacking during the Early Jurassic, it occurred during the Mid Jurassic and rapidly expanded during the Late Jurassic.

This distribution closely mirrors the effects of the general Jurassic sea level rise and the type of structural development of the margins of the Tethys as well as of the Atlantic, all of
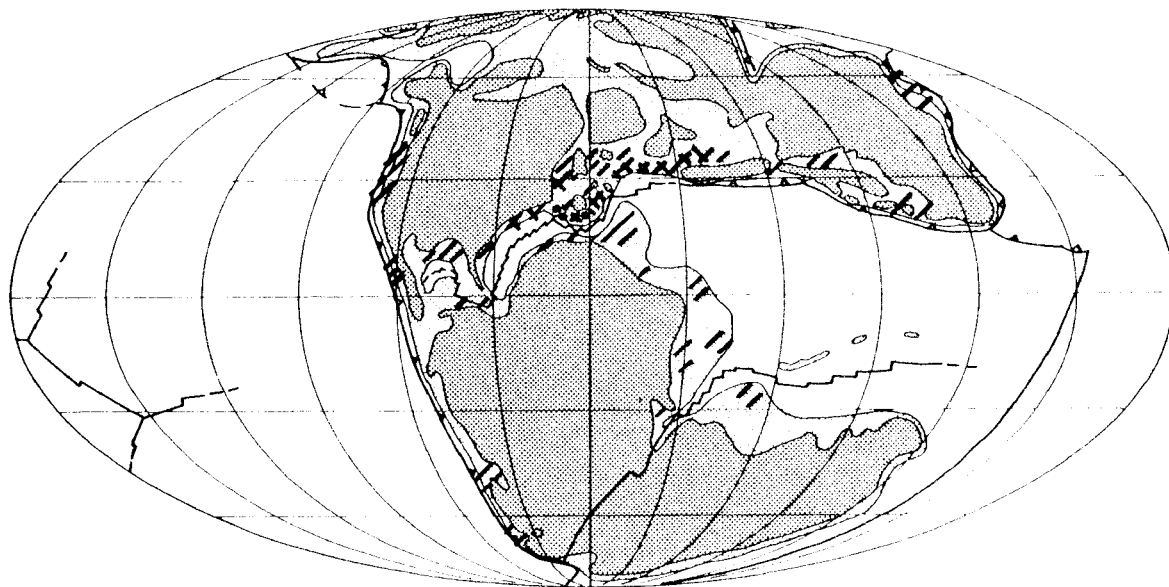
Late Jurassic

Figure 5. Continued.

which was governed by the initial breakup of Pangea. This will be discussed in greater detail in the following section.

Reef distribution on the southern Tethys shelf (Mediterranean region)

On the southern shelf of the Tethys the large shallow water carbonate platforms of the Triassic became increasingly fragmented and drowned in the course of the Jurassic (e.g., Bosellini, 1989; Cocozza and Gandin, 1990). Remaining shallow water platforms of the Jurassic were small and steep walled. This shelf style is well reflected by the distribution of Jurassic reef types on the southern Tethyan shelf. Medium to low angle deeper water slope settings were very rare, so that siliceous sponge reefs could hardly find suitable habitats. It was only during the Early Jurassic, i.e., at the beginning of platform breakup, that moderately inclined depositional slopes suitable for siliceous sponges existed: Lower Jurassic siliceous sponge facies is known from the Trento platform of northern Italy (Kolekmann, 1988; Beccarelli-Bauck, 1988; Schmidt and Schweigert, 1991) as well as from Morocco and adjacent areas (Dresnay, 1971; Dresnay et al., 1978; Wiedenmayer, 1980; Crevello and Harris, 1984; Warme et al., 1988; Hauptmann, 1990). However in these examples siliceous sponges are mostly either outnumbered by coralline sponges or directly pass into a coral-coralline sponge association, so that this reef facies appears characteristic of slope settings. Drowned platforms may be veneered with siliceous sponge spiculites, such as the transition of some Rhaeto Liassic shallow water platforms to the basinal 'Lias-Fleckenmergel' of the (dislocated) Northern Calcareous Alps (Mostler, 1989; Doben, 1991). During Mid and Upper Jurassic time no true siliceous sponge reefs are known, except for occurrences of Bajocian to Callovian

siliceous sponge associations in southern Hungary (Pisera, 1993), which most likely was part of the southern Tethys margin. On the other hand, Upper Jurassic reefs built by coralline sponges are known from Tunisia (Gautret and Cuif, 1989). This general rarity to total absence of pure siliceous sponge associations nicely mirrors the increasing steepening of carbonate platform flanks coming along with marine rifting of the southern Tethyan shelf.

Coral associations had somewhat less difficulty in finding suitable habitats on the southern Tethyan shelf, although shallow water areas became increasingly drowned. Favourable sites for coral reef growth were the edges of remaining steep walled platforms, so that sometimes crust-rich, high energy coral reefs developed which shed a great volume of debris into adjacent deeper water settings. However, shelf edge reefs were not as frequent as might be expected by the wide availability of shelf edges, which were mostly occupied by oolitic and bioclastic shoals. This clearly reflects the evolutionary restrictions outlined above. Low energy coral reefs from lagoonal settings are known as well. Lower Jurassic south Tethyan coral reefs existed in the Trento area of northern Italy (e.g., Beccarelli-Bauck, 1988; Schmidt and Schweigert, 1991), southern Spain (Turnsek et. al., 1975) and Morocco (e.g., Park, 1983; Hauptmann, 1990; Crevello, 1990). Increasing rate of drowning explains why Middle Jurassic southern Tethys coral facies was largely restricted to stable shelves in the direct vicinity of the Gondwana mainland (e.g., Morocco: Hauptmann, 1990; Tunisia: Busson, 1965; Saudi Arabia: El-Asa'ad, 1989; northwestern India: Gregory, 1900). Particularly in the European part of the southern Tethys no reefs occurred. Interestingly, Upper Jurassic coral reefs were again more common, which might be explained by the availability of volcanic islands

(Bosellini, 1989) and wrench movements lifting up some blocks which previously were in deeper structural position. Reefs now developed not only in the proximal shelves, e.g., in Saudi Arabia (Okla, 1986; Mitchell et al., 1988; El-Asa'ad, 1991), Israel (Picard and Hirsch, 1987), Tunisia (Busson, 1965) and Morocco (Adams, 1979; Auzende et al., 1984; Hüssner, 1985), but also on isolated platforms such as Greece (Decrouez et al., 1983), Yougoslavia (Turnsek et al., 1981; Strohmenger, 1988), northern and central Italy (Luciani, 1988; Sartorio, 1989), or parts of the (dislocated) Northern Calcareous Alps (Fenninger, 1967; Steiger and Wurm, 1980).

Only a couple of thrombolite reefs are known from the southern Tethys shelf, despite the fact that suitable steep margins were present (cf. Crevello and Harris, 1984; Dresnay et al., 1978). It remains unclear whether this reflects a bias in investigation or, more probably, is due to lack of dysaerobic environments favourable for development of pure thrombolitic reefs (see below).

Reef distribution on the northern Tethys shelf (Europe)

The northern Tethys shelf exhibited completely different structure during the Jurassic. Unlike the southern Tethyan shelf, it showed large scale ramp characteristics and was tectonically rather stable, although in the outer shelf differential structure may be recognized (Elmi, 1990). In the course of the Jurassic the Germano-Gallian epicontinental shelf sea was transformed into a marginal north Tethys shelf sea by the disappearance of the Vindelician High and the uplift of the London-Brabant-Rhenish-Bohemian massif. During the Early Jurassic high terrigeneous influx prevented reef growth in most areas; during Mid, and particularly Late Jurassic globally rising sea level, together with shelf subsidence, increasingly turned the northern shelves and their bordering epicontinental seas into a carbonate-dominated province and hence made it prone to reef development. The change to carbonate dominance might have been facilitated by an explosion of calcareous nannoplankton (e.g., Weissert, 1993), although actual detection of nannoplankton relics is exceptional in Late Jurassic reef settings.

On the northern Tethyan shelf siliceous sponge facies is not known from the Early Jurassic, although presumed water depths should have been favourable. Principal restricting factors were probably elevated terrigeneous influx and, possibly, elevated nutrient levels. During the Bajocian and Bathonian siliceous sponge facies rapidly colonized extensive areas in Spain (Deusch et al., 1991; Friebe, 1991) and also occurred locally in the eastern Paris Basin (Palmer and Fürsich, 1981). Siliceous sponges occur very rarely in the Middle Jurassic of southern Germany (Franz and Müller, 1988), without, however, forming siliceous sponge facies. During the Late Jurassic reefs dominated by siliceous sponges covered the largest areas in a belt extending from Romania (Draganescu, 1976) to Poland (Trammer, 1982, 1988), southern Germany (e.g., Wagenplast, 1972; Gwinner, 1976; Meyer and Schmidt-Kaler, 1989; Keupp et al., 1990; Leinfelder, 1993a), northern Switzerland (Gygi, 1986), eastern France (Gaillard, 1983), eastern Spain (Deusch et al., 1991) and southern Portugal (Ramalho, 1988; Leinfelder et al., 1993a).

Pure siliceous sponge facies clearly was restricted to carbonate-dominated ramp systems, preferably of very low angle characteristics. The latter is particularly true for the extensive development of biostromal facies, as that occurred during the Bajocian/Bathonian, and particularly Oxfordian of eastern Spain. Slope angles of the south German ramp must have been lower than one percent, given the fact that extensive biohermal and biostromal Oxfordian to Tithonian siliceous sponge facies occurred over a radial shelf transsect at least 200 kilometres broad (cf. Meyer and Schmidt-Kaler, 1989).

Generally the south German siliceous sponge dominated reefs were buildups that grew on a near level-bottom homoclinal ramp in a mid-ramp setting. Siliceous sponge meadow facies was widespread only during certain time intervals. Contrasting with the south German occurrences, the Spanish siliceous sponge facies is dominated by sponge meadow facies rather than crust-rich biohermal mud mound facies (Deusch et al., 1991; Krautter, 1991, in prep.). In the eastern Algarve of southern Portugal siliceous sponge facies occurs mostly as siliceous sponge bearing thrombolites, although meadow and mudmound facies occasionally occur as well. The sponge bearing thrombolites are in close association with pure thrombolites, mixed coral-siliceous sponge reefs and coral facies. This association of reef types is indicative of steepened ramp settings (cf. Leinfelder et al., 1993a).

It was the dominance of terrigeneous fine grained clastics which suppressed siliceous sponge facies during the Early Jurassic. Siliceous sponge associations occurred suddenly and extensively in the Mid Jurassic in mid-ramp areas dominated by carbonates (eastern Spain), whereas siliciclastic dominated areas such as Germany remained barren of sponge facies despite suitable water depths. This changed drastically when, during rapid sea level rise of the Oxfordian, accompanied by a tectonically quiescent phase, mid-ramp carbonate environments expanded enormously, giving rise to the European sponge belt development described above. Due to Kimmeridgian rifting in the Atlantic realm, many areas shallowed, or were taken over by siliciclastics at a high sedimentation rate despite ongoing sea level rise. As a consequence siliceous sponge facies disappeared in most areas, except for southern Germany, where it developed well into the Tithonian.

Coral facies was also widespread on the northern Tethyan shelf. One of the recently discovered Hettangian coral reefs of the world is from southeastern France (Elmi, 1987). In the course of the Mid Jurassic many parts of this shelf, with its epicontinental marginal seas turned into carbonate dominance due to rapidly rising sea level. Coinciding with the maximum peak of carbonate platform development, most Middle Jurassic coral reefs are of Bajocian to Bathonian age. Oolitic facies including coral reefs characterize major parts of the Bajocian/Bathonian in the Paris Basin (Hallam, 1975; Lathuilière, 1982; Geister and Lathuilière, 1991), northern Switzerland (Genser, 1966) and the southern Rhine Valley (Ernst, 1991). Middle Jurassic coral reefs also existed in the carbonate platform developments of southern Portugal (e.g., Rocha, 1976) and are known from Romania (Beauvais and

Draganescu, 1985). If of high energy character, these inner ramp coral reefs mostly represent the coral-debris sand type. Widespread are low energy bafflestones and framestones in protected or slightly deeper positions.

The same is true for most of the Upper Jurassic coral reefs developed widely on the northern Tethys shelf. Such reefs were widespread in southern Portugal (Rosendahl, 1985; Leinfelder et al., 1993a), northern and eastern Spain (Errenst, 1990a, b; Fezer 1988), southern France (Enay, 1965) and the Paris Basin (Geister and Lathuilière, 1991), and Switzerland (Bolliger and Burri, 1970). In France coral reefs grew very extensively on a very large, shallow ramp with almost negligible slope extending from the Paris Basin to the northern parts of the Swiss Jura Ranges, where the ramp rapidly steepened (cf. Geister and Lathuilière, 1991; Gygi and Persoz, 1986; Gygi, 1986, 1992). Coral reefs of the Paris Basin are particularly well developed in its eastern part. They occur in a variety of settings within intra-ramp banks, such as the Burgundy, Armoricain and Lorraine Platforms, chiefly of mid-Oxfordian age. These banks were separated by zones of slightly deeper water (Hilly and Haguenauer, 1979). The margins of the banks were characterized by ooid shoals containing coral reef patches rich in debris. Interior, lagoonal bank areas contain mud-rich, low energy reef knolls composed of branching and massive corals, as well as delicate to thick thickets of coral bafflestones. Also, crinoidal sand bars were widespread (Geister and Lathuilière, 1991).

In southern Germany coral reefs developed from Kimmeridgian time onwards in the marginal areas of the shelf, particularly in front of the Bohemian massif and, during the Kimmeridgian to Tithonian, on some of the major siliceous sponge mounds which grew up into shallow water. The Arnegg reef of southwestern Germany is an example for such reefs (Paulsen, 1964), although the top part is not preserved due to recent erosion. However the reef shed a large amount of debris along steep slopes into deeper areas. This debris is rich in encrusting organisms, particularly *Tubiphytes*, so that the former reef supposedly was of the crust-rich type. Another famous reefal sediment of upper Tithonian to Berriasian age occurs at Stramberg, Czechia in the foreland of the Carpathian mountains (Eliasova, 1981; Elias and Eliasova, 1984), though the reef itself is not preserved. However a huge mass of debris rich in crusts and *Tubiphytes* outcrops as an allochthonous block. Richness in calpionellids (Housa, 1987) and ammonites shows that the reef debris apron reached rather deep areas which, together with the enormous amount of debris is evidence of steep reef margins. The reef debris apron itself is penetrated by neptunian dykes which, during the Berriasian were filled with marine sediments. Although structural relations are not completely clarified, the reef was most likely situated on the northern margin of the Tethys (Elias and Eliasova, 1984). The presumed occurrence of long, steep slopes both in the Arnegg and Stramberg examples is atypical for the rest of north Tethyan Upper Jurassic coral reefs, but more resembles reefs of the southern Tethyan shelf or Atlantic marginal basins. Steep slopes were due to the pronounced

upwards growth of a sponge reef in the Arnegg example, showing the capability of sponge reefs to transform an initially near level-bottom ramp into a rugged topography. In the Stramberg example the steepening probably reflects tectonic accentuation caused by compressional or transpressional movements. This is evidence that crustal shortening on the northern Tethyan shelf started earlier here than in the central and western parts of the Tethys (cf. Ziegler, 1988).

During the Late Jurassic, particularly the western part of the northern Tethys was the site of development of thrombolitic reefs. They occur in Spain and are frequent in southern Portugal, where they form buildups up to 30 metres in height (Ramalho, 1988; Leinfelder et al., 1993a, b). On the other hand, only patches of thrombolitic fabric occur in some of the south German Upper Jurassic sponge reefs. Besides being indicative of occasional oxygen depletion, the thrombolitic reefs mirror slope steepenings which particularly occurred in southern Portugal, where the shelf was developed as a steepened ramp. Besides these occurrences of medium deep to fairly shallow settings more deep water microbialites apparently existed in the Upper Jurassic of the western Tethys (Dromart et al., in press; cit. in Dromart, 1992).

Reef distribution in the North Atlantic realm

During the Jurassic Florida and offshore Nova Scotia may be interpreted as part of the northern Tethys, whereas the Newfoundland and Grand Banks areas were part of the North Atlantic realm. Along the North American east coast siliceous sponge facies of this epoch occurred occasionally, although mixed coral-siliceous sponge reefs were more common (cf. Eliuk, 1978; Jansa et al., 1983; Crevello and Harris, 1982; Baria et al., 1982). Due to Upper Jurassic rifting and tectonic accentuation of slopes, both large scale coral reefs and mixed coral-siliceous sponge reefs occurred in the Newfoundland and Grand Banks area as parts of very large carbonate platform systems (Eliuk, 1978; Jansa, 1986; Pratt and Jansa, 1988; Meyer, 1989; Ellis et al., 1990). Microbial limestones are known from the Lower and Upper Jurassic of Portugal (Elmi et al. 1988, Leinfelder et al., 1993a, b) and off eastern Canada (Dromart, 1992; Jansa et al., 1988).

Exposed at today's surface is only the Lusitanian Basin of west-central Portugal, which provides the case example for Atlantic marginal basins. In the large carbonate ramp systems of the Bajocian/Bathonian local coral facies (Ruget-Perrot, 1961) and siliceous sponge facies (Klingel, Stuttgart, in prep.) existed as well, but is was only during the Late Jurassic that extensive coral reef development took place. However, except for some basinal spiculites no pure siliceous sponge facies existed. This may be explained by the almost absence of stable, carbonate-dominated, low angle slopes in settings of low sedimentation rate. Steepened slopes were widespread. This is partly reflected by the frequent occurrence of crust rich mixed coral-siliceous sponge facies which found their habitats in the upper part of depositional slopes of isolated carbonate platforms. However, in most locations of the Lusitanian Basin

thrombolitic development was the result of regional sediment starvation, possibly only facilitated by the existence of moderately steepened slopes. The synsedimentary rift activity led to the co-occurrence of isolated carbonate shelves with both bypass and depositional margins as well as of low angle ramps. This is reflected by the distribution of coral reef types which span the entire range of types discussed above (cf. Leinfelder, 1986, 1992, 1994; Leinfelder and Wilson, 1989; Leinfelder et al., 1993b, Werner, 1986; Werner et al., 1994; Fürsich and Werner, 1991; Ellis et al., 1990).

Coral reef types indicative of shallow ramps, hence coral-debris sand facies and low energy bafflestones and framestones frequently grew during the Mid and Late Jurassic in marginal seas connected with the North Atlantic realm, particularly in northern Germany (Bertling, 1993) and southern England (Arkell, 1935; Wilson, 1968; Ali, 1983; Beauvais, 1979).

CLIMATIC AND OCEANOGRAPHIC CHANGES DURING PANGEA BREAKUP REFLECTED BY REEF DISTRIBUTION

Little is known about the temperature and oceanographic demands of siliceous sponges. Modern siliceous sponge associations mostly occur in very deep settings where water is generally cold (cf. Reid, 1968) or, if shallower, are restricted to subpolar areas (East Canadian Arctic Islands: VanWagoner et al., 1989; Greenland Sea: Henrich et al., 1992) or cold currents (Western Canadian shelf: Conway et al., 1991). On the other hand, Jurassic siliceous sponges mostly grew in low paleolatitudes. Additionally, accompanying benthic fauna such as brachiopods, gastropods and bivalves, as well as sedimentary features indicate that they mostly grew at greater depths than reef building Jurassic corals, but certainly shallower than most modern deep sea occurrences. Hence Jurassic siliceous sponge facies cannot be compared with modern siliceous sponge associations and cannot directly be evaluated for temperature reconstructions. It must be assumed by their dependence on moderately deep, carbonate dominated settings and by associated organisms that Jurassic sponges preferred warm water. This is corroborated by temperature measurements based on oxygen isotopes (Fritz, 1965).

The distribution of reef building coral facies was clearly related to warm, shallow water as it is today. Together with coral reefs, indicators of high temperatures such as dasycladacean algae, caliche crusts and evaporites are frequent and are evidence of a warm, tropical to subtropical to semiarid climate. Associated high energy sediments and green algae show that reefs were shallow. Actually most Jurassic coral reefs mentioned above occurred in low paleolatitudes, that is, in the southern part of the North Atlantic realm, along the margins of the European-Circum-Mediterranean part of the Tethys, but also in Crimea, Caucasus, Karakorum, Madagascar, East Africa, Middle and Far East (for additional references on Middle and Upper Jurassic coral reefs see Beauvais, 1973, 1977, 1984; Talent, 1988 and Flügel and Flügel-Kahler, 1992).

For low to medium latitudes a hot Jurassic climate is unequivocally accepted by all authors. However, general paleoclimatologic reconstructions for the entire Jurassic globe differ largely from each other, particularly for the Late Jurassic epoch. Paleoclimatologic modelling by Moore and co-workers (Moore et al., 1992a, b; Ross et al., 1992) yielded very steep latitudinal Late Jurassic temperature gradients with very cold high latitude regions characterized by sea ice (Fig. 6). By contrast, Valdes and Sellwood (1992) modelled a much more equilibrated climate, with fairly warm temperatures even in high latitudes, supporting qualitative considerations, e.g., by Hallam (1985, 1993). Looking at the distribution of coral reefs during the Early Jurassic, one reef was discovered far to the paleonorth in northwestern Canada (Poulton, 1988). However, this is probably situated on an exotic terrane of unclear original position and hence cannot be evaluated for climatic reconstruction. Other Lower and Middle Jurassic reefs occurred in northern Chile (Prinz, 1986, 1991) in a medium paleolatitude, no exceptional position. However the global reef distribution of the Late Jurassic shows that well developed coral reefs, mixed coral-siliceous sponge reefs and siliceous sponge reefs existed in Patagonia and the Neuquén basin of Argentina (Ramos, 1978; Leggareta, 1991). The Neuquén basin is a back arc basin and hence preserved in almost autochthonous position. To date no detailed description of the reef fauna exists, so that discussion on diversity patterns of these reefs is not possible. The same is true for coral facies from high to very high northern paleolatitudes. According to Beauvais (1977, 1984), Upper Jurassic hermatypic coral reef facies exist in northern Scotland and southern Greenland. Coral reefs also grew on the Sakhaline Islands (Krasnov and Savitsky, 1973). Whether these occurrences represent true reefs or rather isolated associations of colonial corals remains unclear, since details are not available. However the fact that coral taxa known from low latitude reefs occur at high latitudes is a strong argument for an equilibrated, balanced climate at least during the Late Jurassic, a fact recognized by Beauvais (1973). Also, ammonoid faunas of this epoch show a lot of mixing and exchange from different biogeographic provinces (e.g., Enay, 1972; Enay and Mangold, 1982), and new finds indicate that provincialism was much less than previously thought (cf. Zeiss, 1971; Schweigert, 1993, 1994). Good possibilities of faunal exchange existed, which was enabled both by extensive seaway connections and by minor climatic differences. It must be assumed that the equilibrated, maritime Late Jurassic climate over most areas of the globe was due to the high sea level, which strongly buffered temperature differences (Leinfelder, 1993a; Leinfelder and Seyfried, 1993).

The distribution of reefs not only is a good means to reconstruct qualitative temperature distribution, but also helps reconstruct oceanographic states. Jurassic coral reefs, as today's, are interpreted as reflecting rather oligotrophic, fully oxygenated environments, although the occurrence of coral meadows in very proximal, strongly terrigeneously influenced settings might indicate that some or all Jurassic corals were more tolerant to slightly elevated nutrient values than modern corals. Evaluation of nutrient/oxygen dependance of Jurassic siliceous sponge facies is not unequivocal. The success of
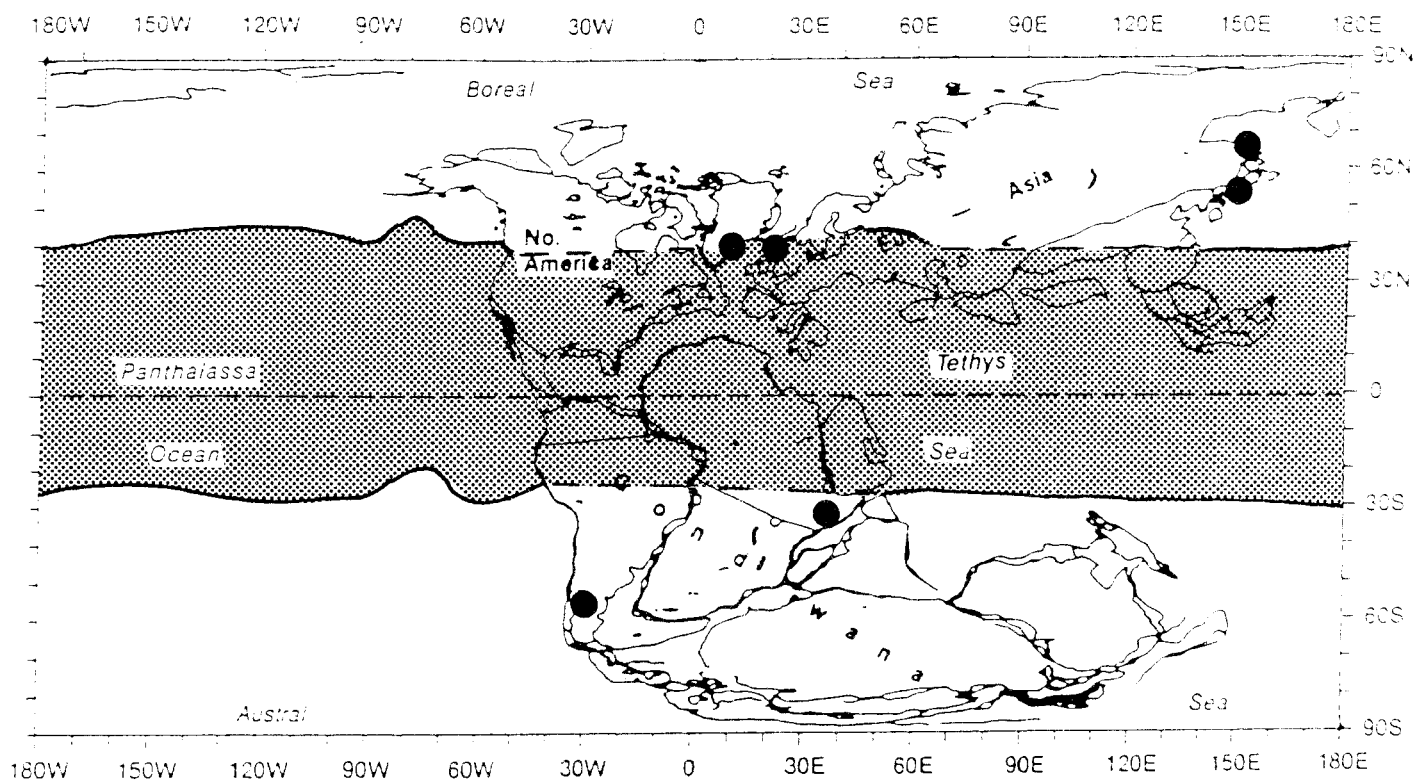
Figure 6. The paleoclimatologic simulation for the Late Jurassic from Moore et al. (1992a), using a four-fold pre-industrial carbon dioxide level. Dotted area indicates postulated water temperatures above 20°C (Dec.-Jan.-Feb for northern hemisphere, June-July-Aug. for southern hemisphere). Paleogeographic reconstruction based on Rowley (1992). Note that despite a supposed strong greenhouse effect, postulated sea-water temperatures are not compatible with Upper Jurassic high latitude coral reef occurrences (indicated by black dots), which rather indicate a more equilibrated climate.

some modern siliceous sponge associations seems to be due to settings characterized by a nutrient input higher than in adjacent areas, such as occurrences on a seamount in the Greenland Sea, where a downwelling current accounts for periodically elevated nutrient availability (Henrich et al., 1992). Despite higher nutrient input these areas are well oxygenated. Modern soft sponges often occupy nutrient-rich waters which may be depleted of oxygen, such as off river mouths (Sara and Vacelet, 1973) or in polluted coral reefs (Kühlmann, 1988; Schuhmacher, 1991). They even occur in strongly dysaerobic environments of the Black Sea (Baçesco, 1963). On the other hand, the majority of modern siliceous sponges seems to occur in very oligotrophic settings (Reitner, Berlin, pers. comm.).

Possibly a couple of Jurassic siliceous sponges, particularly larger specimens occurring isolated within thrombolites, were adapted to elevated nutrient and/or reduced oxygen levels. It also cannot be completely ruled out that Upper Jurassic siliceous sponge associations as a whole could have tolerated somewhat higher nutrient levels than the coral facies. As to oxygen levels, thrombolitic reefs are interpreted here as reflecting occasional oxygen depletion, which itself is related to elevated nutrient input, thermostratification of oceans or shelf seas, or both. However brachiopods and the majority of siliceous sponges which can be found together as additional elements within some thrombolites certainly lived during times of improved oxygen conditions. The same is true for corals which partly occur in considerable quantities within

crust-dominated, thrombolitic bioherms of Portugal and Spain (Leinfelder et al., 1993b). This means that pure thrombolites of moderate depth indicate extended phases of oxygen depletion, whereas macrofauna-containing thrombolites, as well as successions of pure thrombolites and reefal macrofauna associations are indicative of shifting oxygen levels.

Occurrences of thrombolites in deep water could be simply due to the exclusion of macro-organisms by darkness and water temperature. However it is striking that deep water thrombolites occurred in Early and Late Jurassic, but apparently not during Mid Jurassic, although favourable sediment-starved settings and episodes were frequent during this epoch. Hence, even deep water thrombolites may be related to episodes of generally oscillating oxygen depletion. Together with the frequent occurrence of black shales in the bordering seas of the Atlantic rift (e.g., Toarcian of the Germano-Gallian and North German Basins, Riegraf et al., 1984; see also Ziegler, 1988, Pl. 28-30), the exclusive occurrence of thrombolites in deep water settings during the Early Jurassic reflects widespread oxygen depletion in this area. Rather than having been dominantly caused by global change, Early Jurassic oxygen depletion seems to have been an effect of the narrowness of the new Atlantic rift and the moderate water exchange possibilities of epicontinental shelf seas which were surrounded by large basement blocks.

The lack of thrombolites from the Mid Jurassic matches the backdraw of black shales during most of the epoch. This may reflect better general ventilation of the widening seaways between Europe, North America and Africa respectively.

The general sea level rise, with its peak in the end-Kimmeridgian, not only leveled temperatures on Earth by thermal buffer capacities of the wide sea cover, but during the Late Jurassic apparently also led to frequent thermostratification as a result of such climatic leveling, which strongly reduced atmospheric and oceanic circulation. This can be deduced not only by the very frequent and widespread occurrence of deeper water black shales and bituminous facies both in the north Tethyan and North Atlantic realm, but particularly by the frequent occurrence of thrombolites of moderate water depths in the western part of the European northern Tethys shelf. Black shales and bituminous facies occurred particularly on the eastern Atlantic margin and its adjacent epicontinental seas (cf. compilation by Ziegler, 1988, Pl. 26-30; see also Brown, 1984, Oschmann, 1988); in the Helvetic zone of the northern margin of the Tethys (Schneider, 1962; Selg and Wagenplast, 1990; Geyer and Gwinner, 1991) and possibly in the northern Penninic basin, although sediments there became subsequently metamorphosed (Weissert, Zürich, pers. comm., Wörner, Mainz, pers. comm.). Quite in contrast, waters were well aerated both on the southern circum-Mediterranean margin of the Tethys as well on the eastern margin of the Atlantic (cf. Ziegler, 1988, Pl. 26-30; Jansa, 1993; Weissert, 1993). From this the following qualitative circulation pattern can be deduced for the Late Jurassic: A weak Tethyan water circulation mostly driven by evaporation was aerating equatorial areas. Oxygen was rapidly consumed due to the warm water temperature and partial thermostratification. Facilitated by a low-intensity trade wind belt, a weak upwelling system, which possibly did not affect deeper waters brought up dysaerobic waters onto the northwestern Tethys shelf (Fig. 7, cf. Leinfelder, 1993a; also for further discussion).

DIFFERENT SCALING OF ENVIRONMENTAL CHANGES: THE EFFECTS OF SEA LEVEL CHANGES OF DIFFERENT ORDERS

As was discussed above, the distribution of Jurassic reef types through time and space allows recognition of global to regional environmental changes coming along with sea level rise, particularly the leveling of temperature gradients and partial oxygen depletion of seas due to reduced water circulation. Such Jurassic environmental changes occurred at various scales.

A general trend of sea level rise throughout the entire Jurassic (Fig. 4; cf. Hallam, 1988; Haq et al., 1988) is related to the continuous breakup of the northern hemisphere of Pangea, which resulted in the onset of sea floor spreading in the central Atlantic and western Tethys (cf. Ziegler, 1988). General climatic equilibration and reduction of oceanic circulation clearly reached its peak during absolute Jurassic sea level high, during Oxfordian and Kimmeridgian time, when coral reefs expanded over a large area of the globe and both black shales and thrombolites were most frequent.

Major episodes of carbonate dominance were partly related to intra-Jurassic first to second order sea level rise. Particularly, the carbonate-dominated phases of the Bajocian/Bathonian and mid to late Oxfordian can be correlated with such transgressive episodes (Fig. 9). On the other hand, tectonic structures frequently overprinted this effect. In the Callovian to lower Oxfordian the many transpressional movements in the

western Tethys, as well as final crustal segmentation in the southern North Atlantic and western Tethys resulted in accelerated input of terrigeneous clastics. Strong rifting pulses in the North Atlantic realm similarly caused the dominance of siliciclastics in many areas during Kimmeridgian time.

Particularly during the Late Jurassic, global to regional environmental changes coming along with third order sea level changes are obvious. In Portugal thrombolite occurrences diagnostic of dysaerobic environments often are correlatable across major parts of the basin, or even between both Portuguese basins. Particularly, one horizon of mid-Kimmeridgian age (hypselocyclum to divisum chron) shows thrombolite development not only in southern and central Portugal, but also in eastern Spain. Furthermore, it correlates with a horizon exhibiting a peculiar, to date not well studied siliceous sponge-brachiopod reef type in southeastern Germany reflecting a very special, though to date unknown environmental situation, and with a coral reef level in western-most France whose thrombolitic character was only recently discovered (Hantzperque and Leinfelder, in prep.). In sequence stratigraphic terms this horizon, as well as other horizons bearing crust-rich reefs can be interpreted as maximum flooding surfaces or condensed sections. In southern Germany the lateral expanse of siliceous sponge facies is also related to such flooding events. Both expanse peaks and marker horizons correlate well with the latest version of the Vail Group curve (Ponsot and Vail, 1991a, b) (Fig. 8). The restriction of thrombolites in moderate water depth to such third order horizons indicates that third order sea level rises caused additional climatic leveling and related reduction in ocean circulation, allowing dysaerobic bottom waters to rise onto the moderately shallow shelf (Leinfelder, 1993a, b; Leinfelder et al., 1993a) (Fig. 9). Since in Iberia many third order sequence boundaries coincide with tectonic pulses, Leinfelder (1993a) speculated that Late Jurassic sea level changes were driven by regional intra-plate stress rather than being of glacioeustatic origin.

Environmental changes during third order sea level rises did not occur uniformly but themselves show a cyclic pattern. Successions of dysaerobic thrombolite facies and oxygen-dependent coral or siliceous sponge facies of Iberia can be repetitive (Fig. 9). Also, oxygen-dependent macrofauna occur scattered or in distinct levels within dysaerobic thrombolites. This shows that shifts in oxygenation occurred at higher orders as well, possibly down to a Milankovitch or even seasonal cyclicity. Again, this may be interpreted as climatic feedback of sea level oscillations (Leinfelder et al., 1993b).

CONCLUSIONS

The distribution of Jurassic reef types through time and space helps to interpret changes in shelf morphology, sea level position, climate and oceanographic circulation, all of which came along with the increasing breakup of Pangea:

* Lower Jurassic reefs are scarce, whereas more reefs grew during the Mid Jurassic and became very abundant during the Late Jurassic. Since the availability of corals and siliceous sponges was generally high, this pattern shows that the expansion of reefs through Jurassic time was particularly caused by
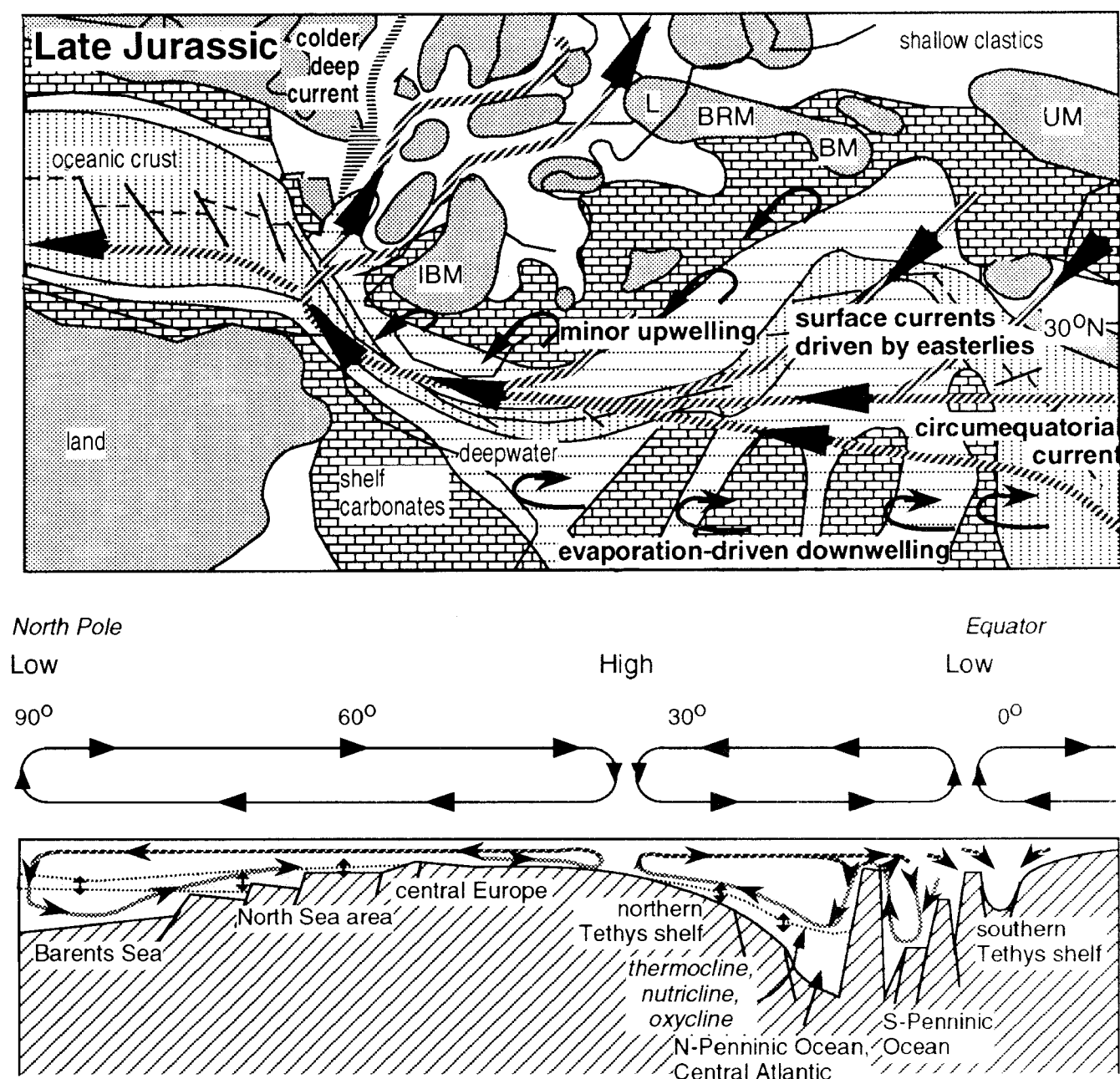
Late Jurassic colder deep current

shallow clastics

oceanic crust

L BRM

BM

UM

IBM

minor upwelling

surface currents 30°N driven by easterlies

land

circumequatorial current

deepwater

shelf carbonates

evaporation-driven downwelling

North Pole

Low 90°

High 60° 30°

Equator

Low 0°

Barents Sea

North Sea area

central Europe

northern Tethys shelf

thermocline, nutricline, oxycline

N-Penninic Ocean, Central Atlantic

southern Tethys shelf

S-Penninic Ocean

Figure 7. Possible circulation pattern in the Tethyan and North Atlantic realm during the Oxfordian and Kimmeridgian. It can be assumed that due to the equilibrated climate ocean circulation was sluggish and partly driven by evaporation. Probably oceans and shelf seas were partly stratified (circulation partly modified after Oschmann, 1988, 1990; Jansa, 1986; Leinfelder 1992, 1994). Top: Circulation map (palaeogeography and distribution of sediments after Ziegler, 1988). IBM Iberian Massif; L. BRM, BM London, Brabant and Bohemian Massif. UM Ukrainian Massif). Bottom: Section showing hydrospheric - atmospheric circulation for a Late Jurassic summer.

an increase of suitable habitats rather than by evolutionary radiation. The extinction phase of the Triassic/Jurassic boundary certainly restricted coral taxa availability during the Early Jurassic. Corals may have survived on a few formerly Pacific terranes of the American Cordillera, from which they recolonized the reef habitats of the world (Stanley and McRoberts, 1993). The existence of a Hettangian coral reef in southern France (Elmi, 1987) shows that, provided suitable habitats had existed, corals would have had the potential ability to grow over much wider areas of the globe already during the earliest Jurassic.

On the northern Tethyan shelf the main factor influencing the increase of reefs during the Jurassic was the generally rising sea level, which during the Mid Jurassic transformed some of, and during the Late Jurassic the major part of the shelf from a terrigeneous into a carbonate-dominated setting. The above trend is different at the southern margin of the Tethys, where during the Early Jurassic quite a number of reefs existed, while during the Mid Jurassic they were rare, and became more frequent again during the Late Jurassic. The dominant influence on reef occurrence on the south Tethyan shelf was tectonic development. Partial drowning during the Early
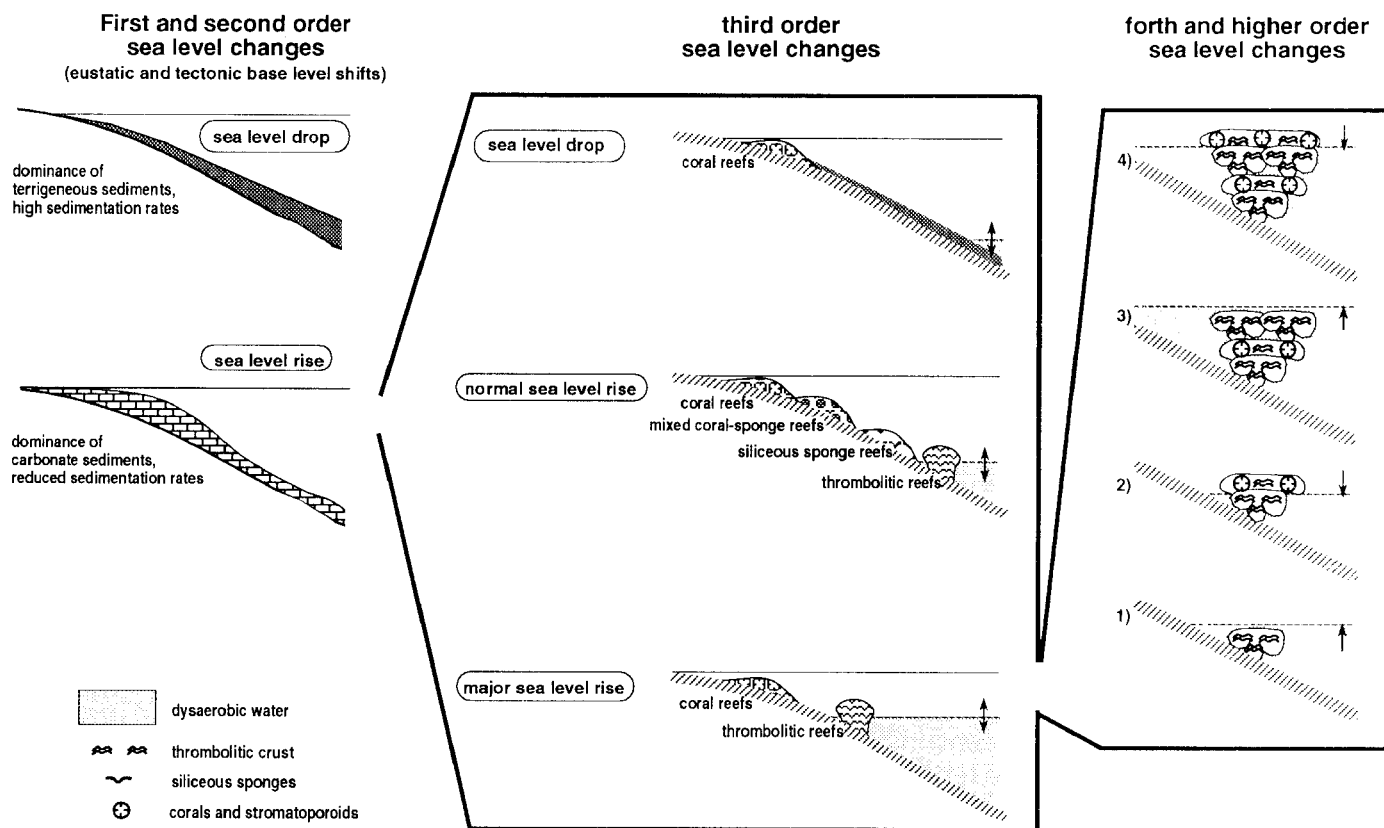
First and second order sea level changes
(eustatic and tectonic base level shifts)

third order sea level changes

forth and higher order sea level changes

sea level drop

dominance of terrigeneous sediments, high sedimentation rates

sea level drop

coral reefs

4)

sea level rise

dominance of carbonate sediments, reduced sedimentation rates

normal sea level rise

coral reefs
mixed coral-sponge reefs
siliceous sponge reefs
thrombolitic reefs

3)

2)

1)

dysaerobic water

thrombolitic crust

siliceous sponges

corals and stromatoporoids

major sea level rise

coral reefs
thrombolitic reefs

Figure 9. Sequence stratigraphic models to explain Jurassic reef occurrences (mostly based on the Upper Jurassic Iberian examples. cf. Leinfelder et al., 1993a, b). Both first to second order sea level rises and tectonic quiescence were responsible for dominance of carbonate deposition. Minor third order sea level rises allowed reefs to develop over a wide bathymetric range due to reduction in background sedimenation rate.

During the Late Jurassic with its equilibrated climate major third order sea level rises resulted in additional climatic feedbacks. During rise the climate became more humid, water circulation slowed down and the zone of dysaerobic bottom water strongly shallowed, giving way to the occurrence of oxygen-controlled thrombolites in fairly shallow water. Higher order oscillations were particularly responsible for fluctuations in oxygen content giving rise to successions of aerobic and dysaerobic reef associations (metazoan-bearing thrombolites).

framework reefs, particularly coral bafflestones and many coral framestones commonly grew in low energy environments, but may occur both on ramps and within lagoons of rimmed shelves. More refined assignments of these types to distinct environmental and structural settings may be possible after establishing standard coral associations (cf. Leinfelder, 1986, 1992; Werner, 1986; Fürsich and Werner, 1991, Werner et al., 1994).

* The global distribution of Upper Jurassic coral reefs shows that the majority of reefs, as expected, grew in low latitudes, but others were present in high latitudes. This pattern contradicts some recent paleoclimatologic computer simulations, which assume steep climatic gradients and very cold water temperatures with sea ice coverage or glaciation in high latitudes. Instead, Upper Jurassic reef distribution reflects a maritime greenhouse effect caused by the high sea level of that time.

* Crust-rich reefs are either restricted to, or more extensively developed in distinct horizons showing features of starved sedimentation. This is a good tool to detect third and higher order sea level changes which, given the climatic equilibration and tectonic activity of the Jurassic, should be caused by intraplate stress rather than glacioeustatic cycles.

* Successions of oxygen-depleted thrombolitic and oxygen-dependent coral- or sponge-rich facies closely mirror climatic and oceanographic changes occurring during sea level rise. Such 'maritime greenhouse events' occurred at various scales and were particularly frequent during the Kimmeridgian. This was a time of rapidly rising sea level, but due to tectonic perturbances carbonate production was strongly decreased relative to that of the Oxfordian or Tithonian. The frequency of such climatic excursions during the Kimmeridgian may point to the general importance of carbonate depositional systems as important climatic buffers. This should be a strong warning of destruction of more present day reefs by deforestation and the subsequent increased runoff of terrigeneous material or other forms of pollution. Naturally the given picture is simplified because of the general complexity of reefs and their controlling factors. Nevertheless, it is hoped that the Jurassic example of reef distribution not only helps understanding structural and environmental changes in the course of the breakup of Pangea, but may also serve as an example for the understanding of other times of major structural and/or climatic reorganizations such as the Devonian and the present day.
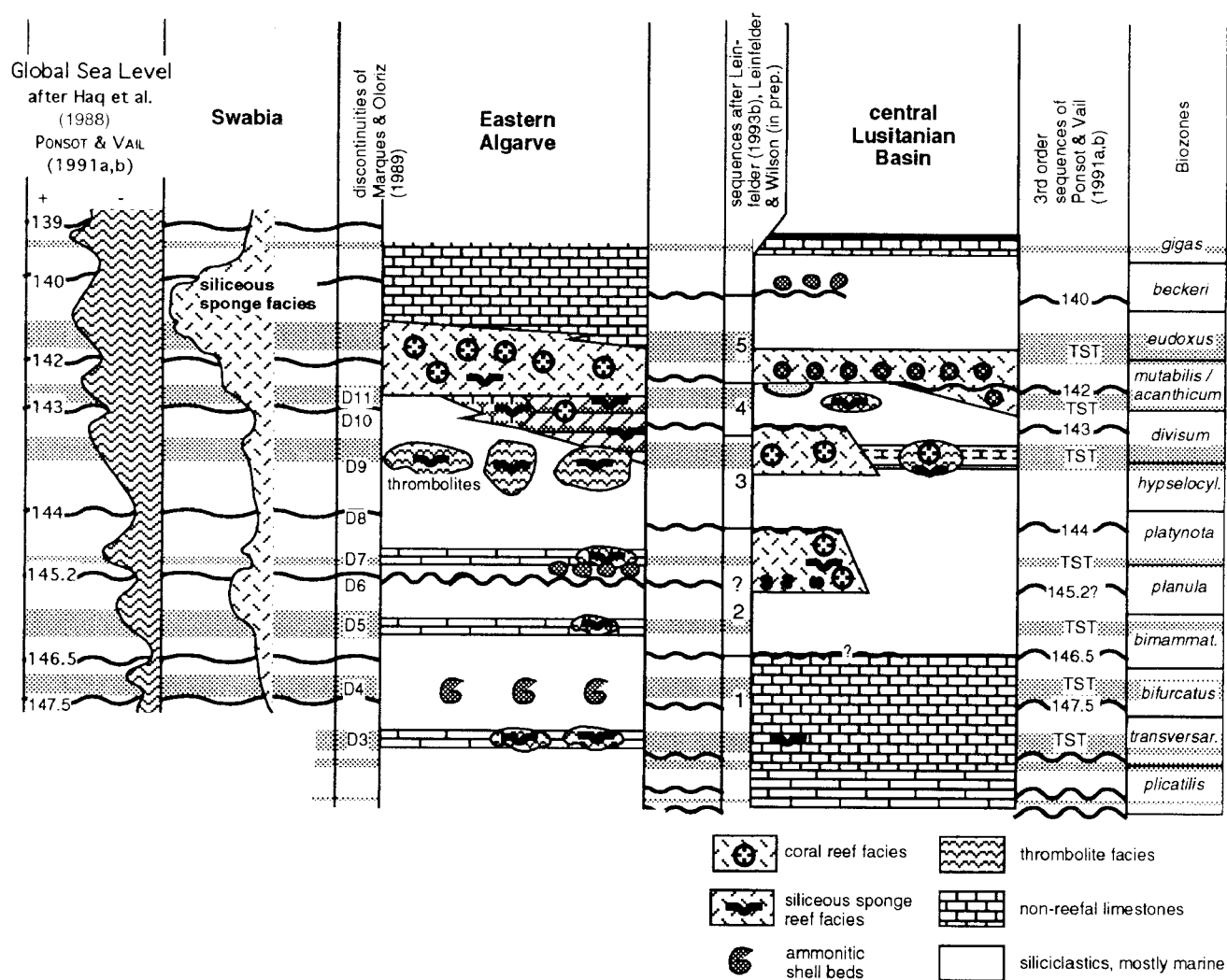
Figure 8. Sequence stratigraphic correlation for the Upper Jurassic successions of the central Lusitanian Basin, the Eastern Algarve Basin (both Portugal) and Swabia (SW-Germany) with the sea level curve of Haq et al. (1988), modified by Ponsot and Vail (1991a, b). Stippled horizontal bars are Ponsot and Vail-type transgressive systems tracts. Occurrence or lateral expanse of reefs is largely related to third order sea level rises. Particularly obvious is the occurrence of thrombolites and siliceous sponge facies within the marl-dominated Kimmeridgian upper hypselocyclum to divisum zone in all three areas. Marls or siliciclastic sands are without signature. Simplified after Leinfelder (1993a).

Jurassic kept some platforms shallow and available for coral reef growth, increasing drowning removed most of them during Mid Jurassic and transpressional movements uplifted some blocks during the Late Jurassic.

* Pure siliceous sponge facies is mostly indicative of mid ramp settings. Extensive biostrome and bioherm development occurs only on low angle ramps. This is why the siliceous sponge facies is almost exclusively restricted to the northern Tethyan shelf. However biohermal growth can modify the topography of ramps and influence the style of subsequent reefs. On the southern Tethyan shelf siliceous sponge facies is largely restricted to isolated occurrences of Early Jurassic age, when tectonic structuration was not yet accentuated everywhere.

* Occurrences of microbial thrombolites are diagnostic of starved sedimentation and thus help in recognizing sea level rises and/or steepened slopes. Their co-occurrence with dysaerobic epibenthic macrofauna, Chondrites horizons and abundant authigenic glauconite, together with the almost total absence of macrobiota within the micobial reefs makes them a valuable tool for recognizing oxygen depletion. Distribution of dysaerobic thrombolites greatly helps reconstruct paleooceanic circulation and paleoclimate.

* Jurassic coral reef facies occurred in very different types, some of which are diagnostic of the style of shelf morphology. Reefs shedding a lot of debris are characteristic of steepened slopes, which are mostly due to tectonic accentuation. Reefs rich in both debris and microbial crusts are indicative of bypass margins. Both types occur most commonly along the southern Tethyan shelf and in Atlantic marginal basins. On the northern Tethyan shelf they similarly indicate the existence of local or regional steep slopes.

Unstabilized coral reef sands associated with autochthonous oolite bars are the most frequent high energy reefal facies type on low angle ramps and consequently are widespread on the northern Tethyan shelf. Well preserved

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