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ENVIRONMENTS AND FAUNAL PATTERNS IN THE KACHCHH RIFT BASIN, WESTERN INDIA, DURING THE JURASSIC

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Abstract. Marine Jurassic sediments (Bajocian-Tithonian) of the Kachchh Basin were deposited in a ramp setting. Except during the Middle and Late Bathonian, when a carbonate regime became established, the fill of the basin consists predominantly of siliciclastics. The sediments represent environments that range from coastal plains (rivers and associated flood plains with caliche nodules), deltas, brackish water lagoons, nearshore sand and iron-oolite bars of the inner ramp, generally situated above fair-weather wave-base, to the middle ramp influenced by storm-waves and by storm-generated currents, and finally to the outer ramp which is characterised by low energy, fine-grained sediments. Changes in relative sea level produced a cyclic sedimentation pattern. The rich benthic fauna of macroinvertebrates is dominated by bivalves, followed by brachiopods, gastropods, corals, serpulids, and sponges. The analysis of 370 statistical samples and more than 27,000 specimens produced more than 40 benthic associations and assemblages. They show a relationship to several environmental parameters, two of which, salinity and climate, are briefly discussed. The spatial distribution of the facies and biota is outlined for two time slices, the Bathonian and the Callovian-Oxfordian, respectively.

Riassunto. I sedimenti marini giurassici (Bajociano-Tithoniano) del Bacino di Kachchh furono deposti in un ambiente di rampa. Eccetto che durante il Bathoniano medio e superiore, quando si stabilì un regime carbonatico, il riempimento del bacino consiste predominantemente di materiale silicoclastico. I sedimenti rappresentano ambienti che vanno dalle pianure costiere (fiumi e relative piane d'inondazione con noduli a caliche), delta, lagune d'acqua salmastra, barre di sabbia litorale e ooliti ferrosi della rampa interna, generalmente situati sopra la base d'onda di bel tempo, alla rampa media (influenzata dalle onde di tempesta e dalle correnti generate da tempesta), ed infine alla rampa esterna, che è caratterizzata da sedimenti a grana fine, di bassa energia. I cambiamenti nel livello marino relativo hanno prodotto una sedimentazione ad andamento ciclico. La ricca fauna bentonica dei macroinvertebrati è dominata dai bivalvi, seguiti da brachiopodi, gasteropodi, coralli, serpulidi e spugne. L'analisi di 370 campioni statistici ed oltre 27000 esemplari ha prodotto più di 40 associazioni e raggruppamenti bentonici. Essi mostrano una relazione con molti parametri ambientali, due dei quali, salinità e clima, vengono brevemente discussi. Viene delineata la distribuzione areale delle facies e dei biota per due porzioni temporali, rispettivamente il Bathoniano ed il Calloviano-Oxfordiano.

Introduction

The rift basin of Kachchh originated at the western margin of the Indian Plate in the Triassic (e.g. Biswas 1982). After a phase that was characterised by non-marine sediments (alluvial fans, fluvial systems), the sea inundated the basin sometime in the early Middle Jurassic, when it became an appendix of the so-called Malgassy Gulf, a southern extension of the Tethyan Ocean. The precise timing of the transgression is still not clear; the oldest ammonite, a *Leptosphinctes*, is from the Late Bajocian (Singh et al. 1982). However, the bed containing this ammonite is underlain by about 250 m of sediments of partly marine, partly fluvial origin so that the earliest marine influence may date even from the Aalenian (Fürsich et al. 2001).

The Jurassic sedimentary fill consists mainly of siliciclastics (except for a carbonate interlude in the central and western areas of the basin during the Middle and Late Bathonian) and records a general deepening culminating in the Middle Oxfordian Schilli Subzone (Krishna et al. 2000). This was followed by regression which result-

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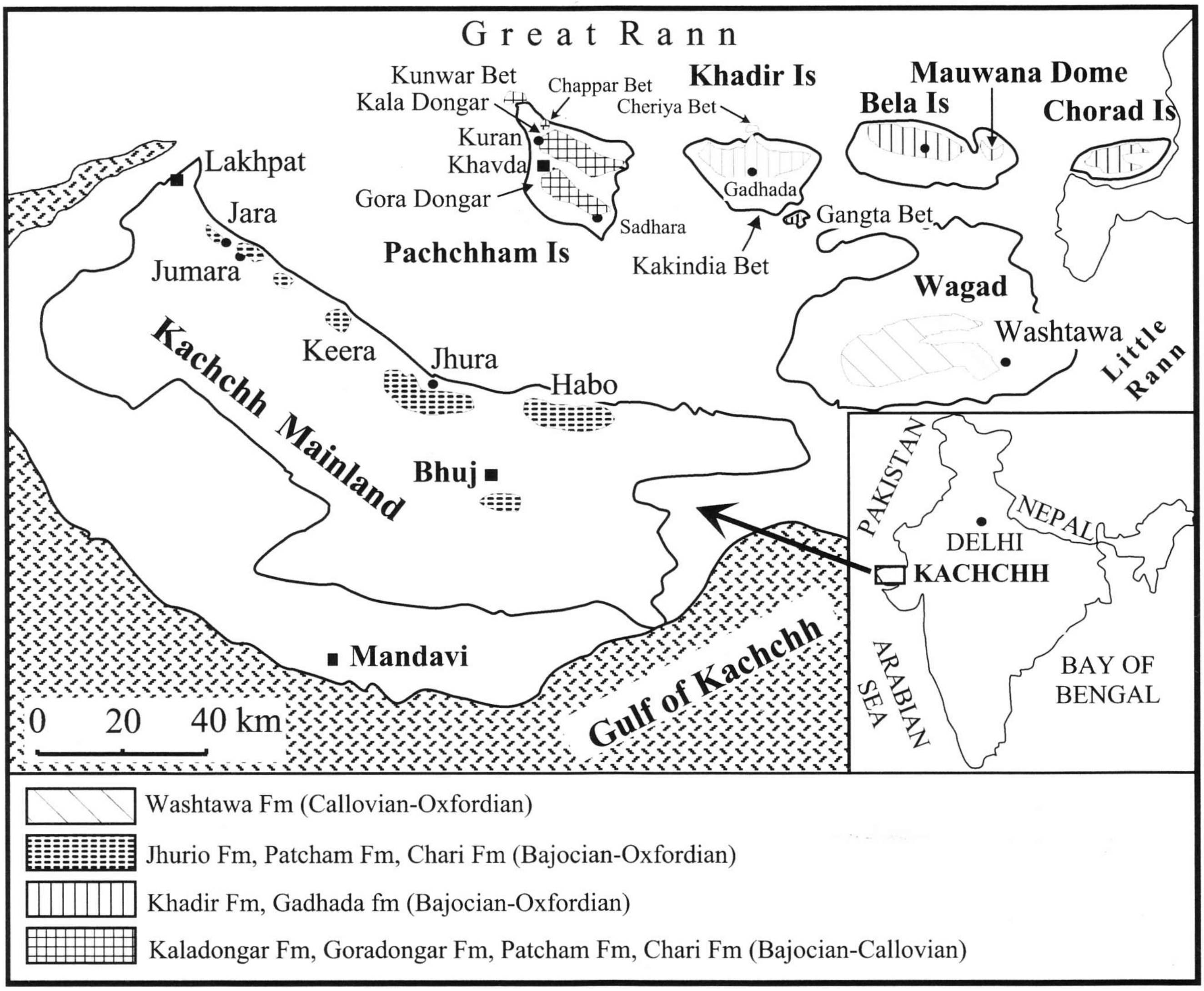

Fig. 1 - Generalised geological map of Kachchh with localities mentioned in the text.

ed in the deposition of marginal marine to non-marine sediments by the late Early Cretaceous in most parts of the basin. However, this overall trend was not uniform, but composed of numerous smaller cycles of different hierarchies (e.g. Fürsich & Oschmann 1993; Krishna et al. 2000).

The marine Jurassic sediments of the basin are well-known for their rich faunas, both benthic macroinvertebrates, ammonites, and microfaunas. Good exposures, the facies mosaic and the rich benthic faunas are ideal prerequisites for an integrated basin analysis. First results towards this goal have already been published (Fürsich et al. 1991, 1992, 1994a, b, 2001, in press; Fürsich & Oschmann 1993; Fürsich & Pandey 2003). The present paper gives a short outline of the main environments of the basin and of the palaeoecology of the benthic macroinvertebrates, focussing on their relationship with some of the main palaeoenvironmental parameters. A locality map is given in Fig. 1, an outline of the lithostratigraphy in Fig. 2.

Environments

Within the Jurassic of the Kachchh Basin, five distinct facies associations can be identified, namely alluvial fan conglomerates, coastal plain sediments, deposits of a siliciclastic and of a carbonate ramp, and mixed carbonate-siliciclastic deposits. In the following, the major facies types are briefly summed up. A somewhat more extensive account is given by Fürsich et al. (in press). A detailed description of the facies pattern is in preparation.

Alluvial fans and coastal plains

The non-marine sediments occur at the base of the basin fill and at the margins of the basin. At present-day they are exposed on the islands within the Great Rann of Kachchh (Fig. 1). They consist of conglomerates representing alluvial fans, of fining-upward crossbedded sandstones and arkoses with erosional bases that represent fluvial channels, and of reddish silts with thin intercalations of fine-grained sandstone. The latter are flood

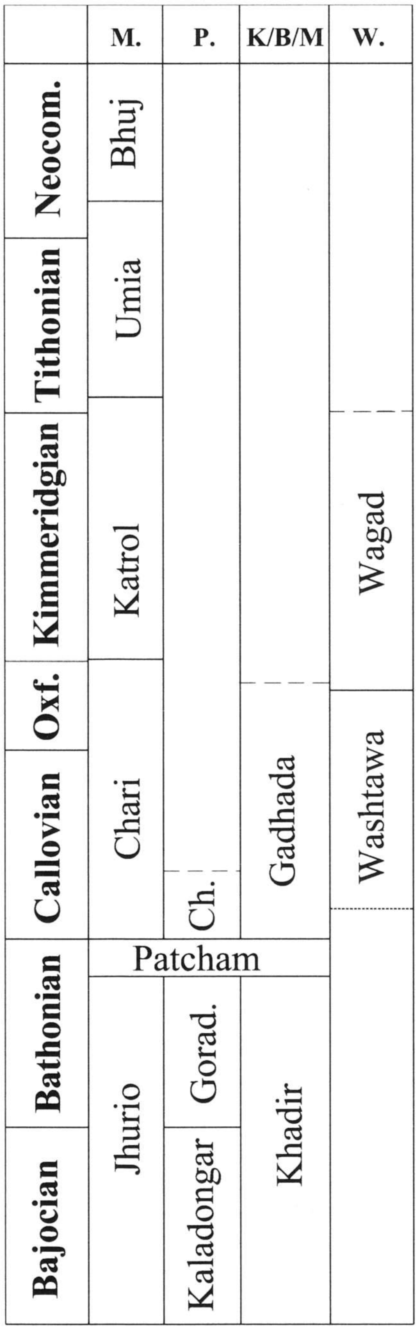

Fig. 2 - Outline of the lithostratigraphy of Jurassic rocks of the Kachchh Basin. The lithostratigraphic units are partly those of Biswas (1980), partly they are traditional terms introduced by Waagen (1875). For more detailed information see Fürsich et al. (2001). M: Kachchh Mainland; P: Pachchham Island; K/B/W: Khadir Island, Bela Island, and Mouwana Dome.

plain deposits, an interpretation which is supported by the occurrence of caliche nodules in a coastal plain setting. Intercalations of grey, highly carbonaceous marly silt are interpreted as lake deposits on the flood plain. The fluvial channel fills occasionally contain large wood pieces, in some cases even wood logs. Rootlets occur in ripple-laminated fine-grained sandstones, interpreted as levee deposits, near the top of the channel fills. Macroinvertebrate fossils are absent, but remains of camarosauromorph dinosaurs have been discovered in flood plain deposits on Khadir Island (Moser et al. submitted).

Siliciclastic ramp

Siliciclastic ramp deposits represent a range of environments. Strongly bioturbated silty to sandy sediments containing a low diversity molluscan fauna (see below) are indicative of brackish water conditions and correspond to protected bays and lagoons. Thick, large-scale cross-bedded sandstones of the western islands are most likely deltaic sand bodies. Towards the west (e.g. on the Habo Dome), these delta front sandstones grade into bioturbated silt and silty sandstone of prodelta origin.

Several metres thick, well sorted, fine- to coarse-grained sandstones (e.g. the Upper Callovian Athleta Sandstone of the Jara Dome; Fürsich et al. 2001) extend over tens of kilometres. They are interpreted as sheet sands that are of deltaic origin, but were subsequently spread across the middle ramp during destructive delta phase or transgressive events.

Argillaceous silt with thin intercalations of sandstones that exhibit an erosional base and hummocky crossbedding was deposited on the storm-wave influenced ramp, whereas bioturbated argillaceous silt with intercalations of graded, parallel-laminated, sharp-based, fine-grained sandstones with tool marks and flute casts are evidence of deposition by storm-generated currents below storm wave-base.

Indistinctly laminated to bioturbated argillaceous silt to silty clay with bands of ferruginous concretions represent the deepest environment in the Kachchh basin, beyond the influence of storms. These outer ramp deposits, widespread in the Callovian Chari Formation of Kachchh Mainland, generally reflect low energy conditions.

Protected bays with bioturbated iron-oolitic silt were widespread during late sea level highstand in the Late Callovian. They record low energy environments. In the Lower Callovian part of the Chari Formation at the Keera Dome and in the Jhurio Formation (Bajocian-Bathonian) of the Jhura Dome, several metres-thick crossbedded grainstones composed of Fe-ooids and ferruginized bioclasts originated as high energy shoals. They formed above fair weather wave base when the Fe-ooids, produced during late sea level highstand, were reworked during the subsequent transgression. In the Bathonian Goradongar Yellow Flagstone Member (Jhurio Formation) of Jhura Dome, thin lenticular bodies of Fe-oolitic grainstones, intercalated between carbonates, are interpreted as channels, in which Fe-oolitic sediment was transported from shoals into deeper parts of the ramp.

During the Oxfordian, large parts of the basin experienced sediment starvation due to a large rise in relative sea level (for details see Krishna et al. 2000). As a result, highly condensed sediments with ferruginous crusts, ferruginous ooids, hardgrounds, erosion surfaces, intraformational conglomerates and shell concentrations, the Lower to lower Middle Oxfordian Dhosa Oolite Member of the Chari Formation, were deposited on the Kachchh Mainland beyond the influence of storm waves but subject to currents (Singh 1989; Fürsich et al. 1992, 2001). The remaining Middle Oxfordian, the Upper Oxfordian, and the lowermost Lower Kimmeridgian are represented by a cm-thick ferruginous crust and by stratigraphic gaps. In contrast, from areas closer to the shore (e.g. Wagad Dome) a rich ammonite fauna has been recorded from these intervals (e.g. Krishna et al. 1998, 2000).

Carbonate ramp

Within the basin, carbonate sediments are largely restricted to the Middle and Upper Bathonian. A fair-weather wave-influenced ramp is documented by the Raimalrho Limestone Member of the Patcham Formation of the Pachchham Island. Thickly bedded, large-scale crossbedded grain- and packstones with scour and fill structures and shell lenticles indicate constant reworking by waves. Further offshore (e.g. at the Habo Dome), these carbonates change into graded grainstones with sharp, erosional bases, hummocky crossbedding, and occasional amalgamation of successive beds. These features are indicative of proximal storm deposits (e.g. Aigner 1985).

Still further offshore (e.g. at the Jhura Dome) thin, graded and laminated grainstones are intercalated between bioturbated, bioclastic marl. The environment was the storm-flow influenced middle ramp. Increasingly thinner and more fine-grained tempestites in combination with an autochthonous fauna of sponges correspond to the deepest part of the ramp exposed on Kachchh Mainland.

Mixed carbonate-siliciclastic environments

Mixed carbonate-siliciclastic sediments are widespread in the Kachchh Basin. They either represent environments of the carbonate ramp where the autochthonous carbonate component was diluted by silt and sand from a terrigenous source [e.g. the Bathonian Goradongar Yellow Flagstone Member (Goradongar Formation) of the Jhura Dome and the Pachchham Island], or else transgressive lag deposits. In the latter, lowstand deposits that usually consist of siliciclastic material were reworked during subsequent transgression. Due to low input of new terrigenous material during early transgression, skeletal-derived carbonate particles are important constituents of the sediment. The resulting rock ranges from calcareous sandstone to gravelly or pebbly rudstones, the pebbles usually consisting of quartz and granite/gneiss. They probably indicate marine reworking of fluvial sediments. A characteristic example is the Upper Bajocian *Leptosphinctes* Pebbly Rudstone at the top of the Kaladongar Formation of Pachchham Island (Fürsich et al. 2001).

Faunal patterns

Benthic macroinvertebrates are common in Jurassic marine sediments of the basin. In nearshore areas they tend to occur concentrated in shell beds and shells lenses. Usually they have been reworked and transported, although apparently not for large distances. In more offshore areas most shells occur scattered or as winnowed pavements. Deep burrowing bivalves commonly occur in position of growth and the preservation quality is generally high. In some cases, even epifaunal taxa such as brachiopods are preserved in life position suggesting low energy environments and lack of disturbance by predators or scavengers. Such autochthonous to parautochthonous faunas are the relicts of former benthic communities, termed here associations. In addition, shell concentrations formed during early transgression (transgressive lags) are widespread in the Callovian Chari Formation (Fürsich & Oschmann 1993), in the Oxfordian of the Wagad Dome (e.g. the so-called Bharodia Astarte Bands), and in the upper part of the Katrol Formation and the overlying Umia Formation (Kimmeridgian to Neocomian) (Fürsich & Pandey 2003). They are usually heavily time-averaged, mixed, and sorted, and therefore represent distorted community relicts, termed assemblages in the following (for terminology see Fürsich 1984).

Benthic associations

A quantitative data base consisting of more than 27,000 specimens and 370 samples was used to define more than 40 associations and several assemblages with the help of a Q-mode cluster analysis (Fürsich et al. in press; Table 1). Table 1 shows that most associations are dominated by bivalves and only few by other groups such as corals, sponges, gastropods or anellids. As can be also seen from Table 1, most associations come from the Callovian part of the basin fill. This is partly a collection bias, because the Middle Jurassic has been much more heavily sampled, partly it is a preservational bias, because in the largely sandy sediments of the Kimmeridgian-Tithonian of the mainland the preservation potential of shelly benthic macroinvertebrates is much lower than in the argillaceous silts of the Callovian Chari Formation. Nevertheless, the occurrence, within a confined time-interval, of numerous distinct associations in very similar substrate (argillaceous silt) and in what appears to have been similar environments (outer ramp) suggests that the distribution pattern of the benthic fauna was governed by very subtle differences in environmental parameters. The reason for this may be that in offshore mid to outer ramp environments (i.e. the equivalents of the middle shelf), the comparatively high environmental stability and low stress conditions led to a much narrower subdivision of the niches of the ecospace compared to shallower, frequently disturbed environments (e.g. Sanders 1968).

association	dominant group(s)	stratigraphic occurrence
Bositra buchi	bivalves	Bath.-Callov
Bositra buchi – Praesaccella juriana	bivalves	Callovian
Praesaccella juriana – Nicaniella pisiformis	bivalves	Callovian
Cingentolium partitum – Corbulomima macneilli	bivalves	Callovian
Cingentolium partitum	bivalves	Callovian
Nuculoma wynnei – Palaeonucula cuneiformis	bivalves	Callovian
Grammatodon jurianus – Corbulomima macneilli	bivalves	Callovian
Trigonia distincta	bivalves	Callovian
Nicaniella extensa	bivalves	Callovian
Dacryomya lacryma	bivalves	Callovian
Dentalium sp. – Palaeonucula cuneiformis	scaphopods/bivalves	Callovian
Nicaniella khadirensis	bivalves	Callovian
Indocorbula basseae	bivalves/gastropods	Callovian
Neocrassina subdepressa	bivalves	Callovian
Highly diverse softground	bivalves	Callovian
Eomiodon baroni-Protocardia lycetti	bivalves	Bajocian
Eomiodon baroni – Placunopsis socialis	bivalves	Bajocian
Indocorbula lyrata	bivalves	Bajoc.-Bath.
Indocorbula lyrata – Protocardia grandidieri	bivalves	?Aal.-Bajoc.
Thracia viceliacensis	bivalves	Callovian
Pseudolimea duplicata	bivalves	Callovian
Nanogyra nana – Palaeonucula cuneiformis	bivalves	Callovian
Nanogyra nana	bivalves	Callovian
Actinostreon erucum – Nanogyra nana	bivalves	Callovian
Gryphaea alimena	bivalves	Callovian
Nanogyra nana – Gryphaea alimena – Plicatula peregrina	bivalves	Callovian
Nanogyra nana – Ataphrus labadeyi – Ceratomyopsis striata	bivalves/gastropods	Callovian
Eligmus rollandi	bivalves/brachiopods	Bathonian
Bakevellia waltoni	bivalves	Bathonian
Modiolus imbricatus	bivalves	Bath.-Callov
Amphiastraea piriformis	corals/bivalves/gastropods	Callovian
Microsolena amorpha – Montlivaltia frustriformis	corals/brachiopods	Bathonian
Camptonectes auritus	bivalves	Callovian
Lophrothyris euryptycha	brachiopods	Callov.-Oxf.
Kutchithyris hypsogonia	brachiopods	Callovian
Rhynchonelloidella brevicostata	brachiopods	Callovian
Kutchithyris breviplicata	brachiopods	Callovian
Cycloserpula	annelids/brachiopods	Callovian
Platychonia schlotheimi	sponges	Bathonian
assemblages		
Somalirhynchia africana	brachiopods/bivalves	Callovian
Kallirhynchia versabilis	brachiopods	?Bajocian
Crinoid	crinoids/annelids	Callovian
Tetraserpula	annelids/brachiopods	Callovian
Bucardiomya lirata	bivalves	Callovian
Sphaera rogeri	bivalves	Callovian
Amphiastraea	corals	Tithonian
Gryphaea	bivalves	Tithonian
Indotrigonia – Pisotrigonia	bivalves	Tithonian
Trigonioid – *Herzogina*	bivalves	Neocomian
Seebachia	bivalves	Oxf.-Kimm.
Megacucullaea – Seebachia	bivalves	Tithonian

Tab. 1 - List of the benthic macro-invertebrate associations and assemblages recognised in the Jurassic of the Kachchh Basin.

On the whole, the environmental spectrum within the basin was fairly wide. Consequently, many environmental parameters differed strongly, say, between coastal and outer ramp settings and exerted a major influence on the distribution of the fauna. To illustrate this point, the influence of two of these parameters, salinity and climate, in particular water temperature, on the benthic fauna is briefly discussed in the following.

Environmental control of the benthic macrofauna

Salinity. Several of the associations listed in Table 1 are characterised by a low species diversity and are dominated by taxa, whose close relatives are known to have been able to tolerate brackish water conditions somewhere else in the Jurassic. They include the *Eomiodon baroni – Protocardia lycetti*, the *Eomiodon baroni – Placunopsis socialis*, the *Indocorbula lyrata*, and the *Indocorbula lyrata – Protocardia grandidieri* associations. The latter consists only of the two name-giving taxa occurring in grey marly silt in the ?Bajocian/Bathonian Khadir Formation of Mouwana Dome. More than 98% of the individuals are articulated (Fig. 3B). Size sorting or selective dissolution of shells can be excluded, as a wide range of sizes are present, although adults clearly dominate, and the originally aragonitic shells have been replaced by calcite, but are otherwise well preserved. The fact that the strata below and above the Indocorbula-Protocardia Bed are unfossiliferous and that three metres above the bed there occurs a well developed root horizon in a silty fine-grained sandstone (Fig. 3A), suggest lowered salinity values as the main stress fac-

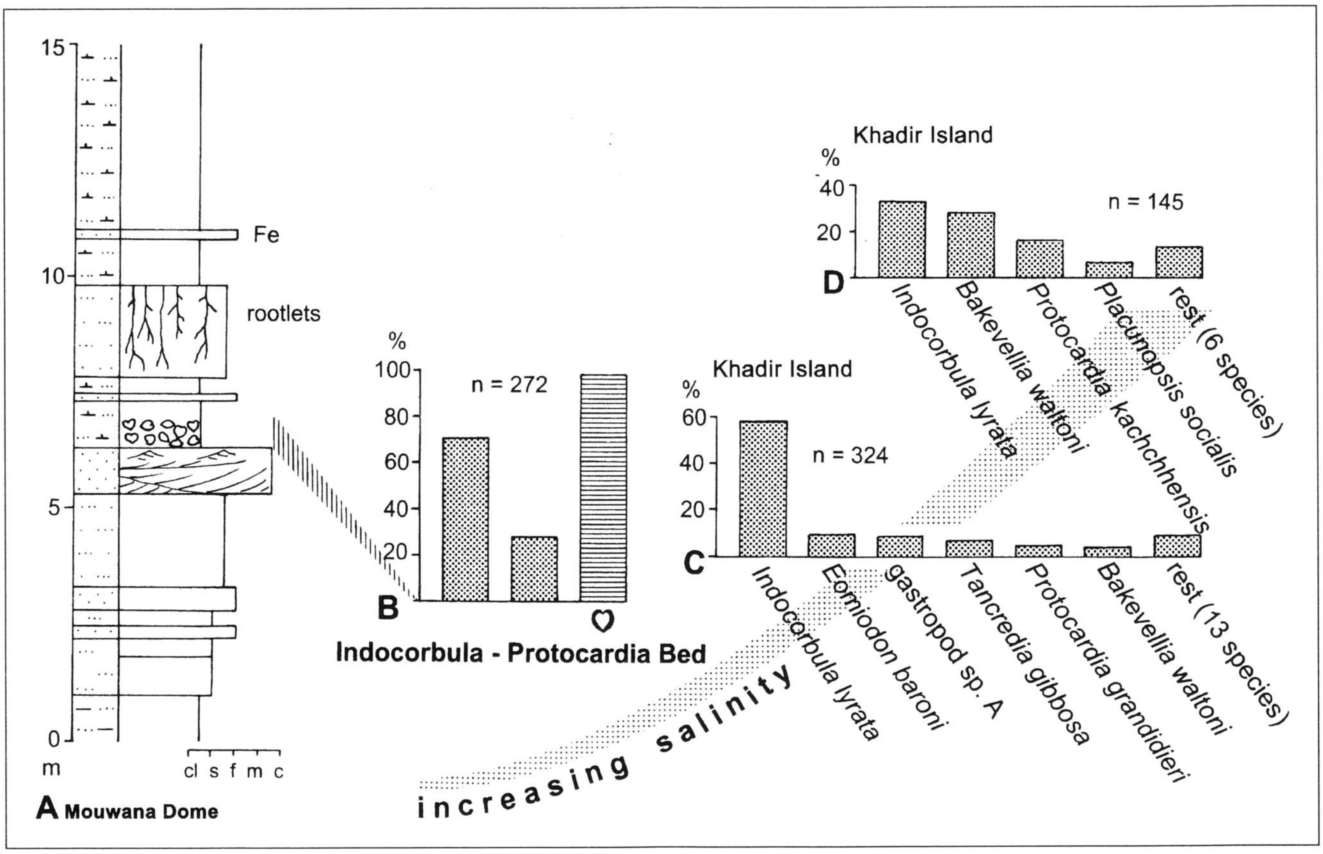

Fig. 3 - The *Indocorbula lyrata – Protocardia grandidieri* association from the Bathonian of Mouwana Dome (B) and related assemblages from the ?Bajocian of Khadir Island (C, D) are interpreted as having been strongly controlled by freshwater input. Given is the relative abundance of the species (n refers to the number of individuals). B-C-D is thought to reflect increasing salinity values, from oligohaline/lower mesohaline conditions (B) to brachyhaline conditions (C, D).

tor responsible for the low species diversity. Both taxa are well known members of salinity-controlled environments in the Middle Jurassic of Morocco (Mongin 1967) and Tunisia (Holzapfel 1998) and related species are dominant elements of many Middle and Upper Jurassic brackish water biota (e.g. Fürsich 1994). In the Kachchh Basin the two species were restricted to the ?Bajocian-Bathonian part of the sequence. They were no true brackish water endemics, but managed to thrive in a range of salinity regimes. Judging from its low diversity, the sample in Fig. 3B most likely corresponds to the lower mesohaline or even oligohaline regime, whereas in the other two samples (Fig. 3C-D), the salinity probably was in the brachyhaline range. Sample 3C is regarded as representing a somewhat lower salinity than sample D, despite its higher species richness, because it seems to be more time-averaged. The evenness is, however, still lower than that of sample 3D.

Climate (Table 2). Precise measurements of palaeotemperatures are only possible with the help of oxygen isotopes. This requires well preserved, diagenetically unaltered skeletal hardparts, a requirement not fulfilled by most benthic faunal elements within the basin. However, large-scale shifts in climatic conditions and hence also in temperatures can be deduced from the analysis of the benthic macrofauna in connection with changes in the facies pattern.

parameters	Late Bathonian	Callovian
observations:		
terrigenous input	low	high
sedimentary regime	carbonate	siliciclastic
faunal diversity	high	medium
characteristic faunal elements	diverse coral meadows *Eligmus*, Opinae (bivalves)	nuculid bivalves
inferences:		
water temperature	high	medium
nutrient supply	low	high
overall palaeoclimate	hot, semi-arid	warm, humid

Tab. 2 - Environmental change between the Late Bathonian and Early Callovian as inferred from the facies regimes and the benthic macrofauna.

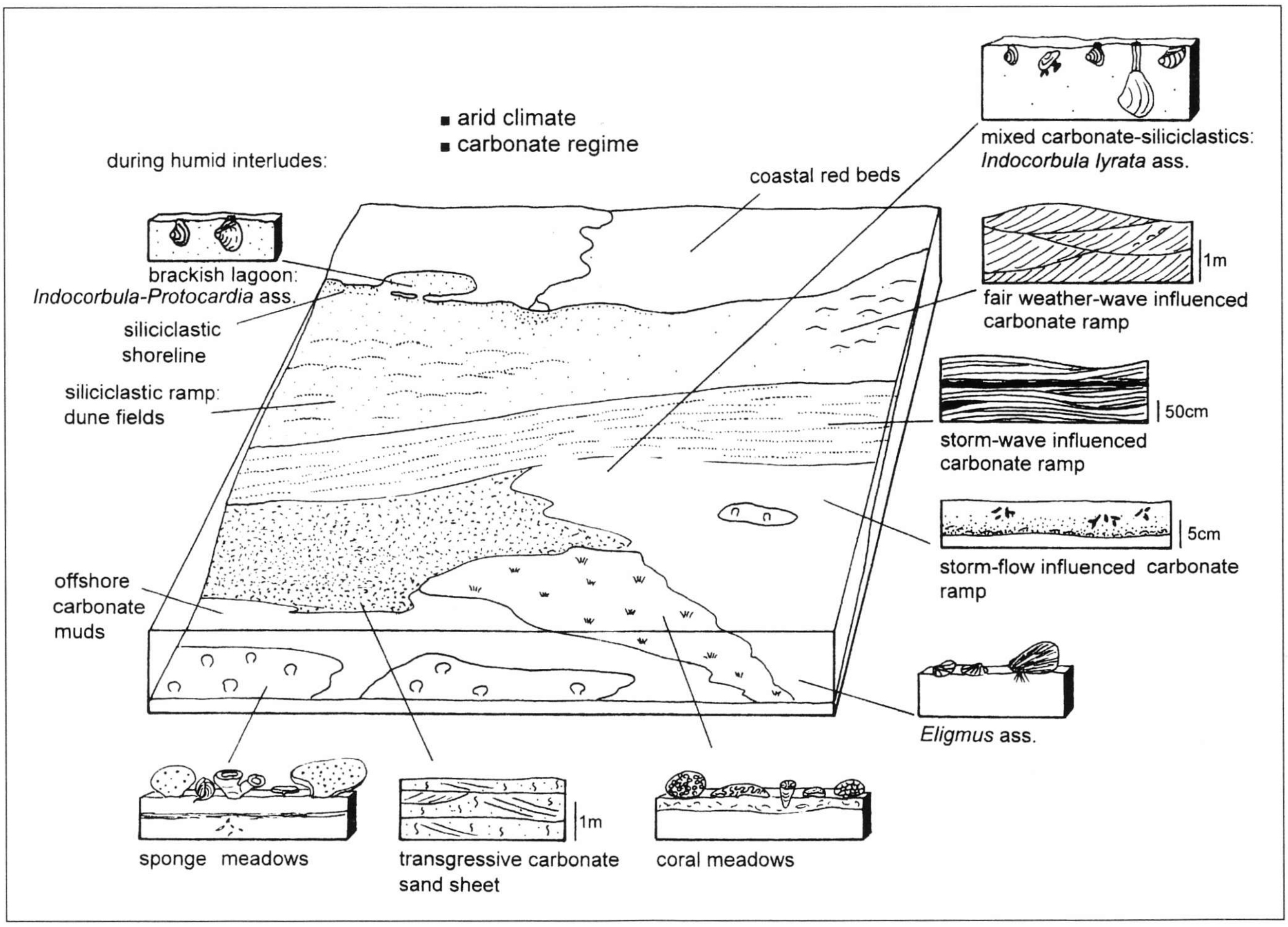

Fig. 4 - Bathonian palaeoenvironments and biota in the Kachchh Basin. Shown are characteristic facies and benthic associations, some of which are part of a carbonate ramp, others part of a siliciclastic ramp. Note that not all facies are contemporaneous. For example, the coral meadows and sponge meadows are separated in time by the transgressive carbonate sand sheet.

In terms of shifts in facies pattern, one of the most distinct changes within the basin is the change from a carbonate-dominated sedimentation regime in the Middle and Upper Bathonian (Jhurio Formation, Patcham Formation) to a siliciclastic regime in the Callovian (Chari Formation). This facies change is accompanied by a distinct change in the benthic macrofauna: at Jumara Dome, fine-grained carbonates with rare intercalations of distal tempestites of the middle to outer ramp contain high diversity coral meadows, the *Microsolena amorpha – Montlivaltia frustriformis* association (Fürsich et al. 1994b). Apart from more than 60 taxa of corals there occurs a rich fauna of bivalves, brachiopods, and gastropods. The overall species diversity is three to four times higher than that of average benthic associations occurring in older and younger beds. The good preservation of the fauna and limited biogenic alteration of shells (boring, encrustation, biogenic breakage) precludes time-averaging as the decisive factor for the high diversity. A characteristic faunal element of the coral meadows are bivalves of the subfamily Opinae. They are represented by five species of the genera *Coelopis*, *Trigonopis* and *Pachopis*, which do not occur elsewhere in the Jurassic of Kachchh. Similarly, the diversity of gastropods (more than 10 species) is quite unique, considering that in most associations from the Jurassic of Kachchh no or only 1-2 species of gastropods occur. In beds below the coral meadows the epibyssate bivalve *Eligmus rollandi* is a characteristic element. The bivalves mentioned above are characteristic elements of low-latitude carbonate environments in the Jurassic. Their occurrence, together with the high diversity coral meadows, in the Upper Bathonian of Kachchh points to tropical, high water temperatures in the basin at that time. This view is corroborated by the carbonate sediment. Apparently, the climate at that time was hot and at least semiarid, so that input of terrigenous siliciclastics from the hinterland was greatly reduced. Low run-off probably also resulted in a low nutrient supply and hence oligotrophic conditions. This view is supported by the high faunal diversity and by the presence of sponge meadows, consisting of "lithistid", hexactinellid and calcarean sponges (Mehl & Fürsich 1997). These sponge meadows, occurring in fine-grained carbonate sediments, are the

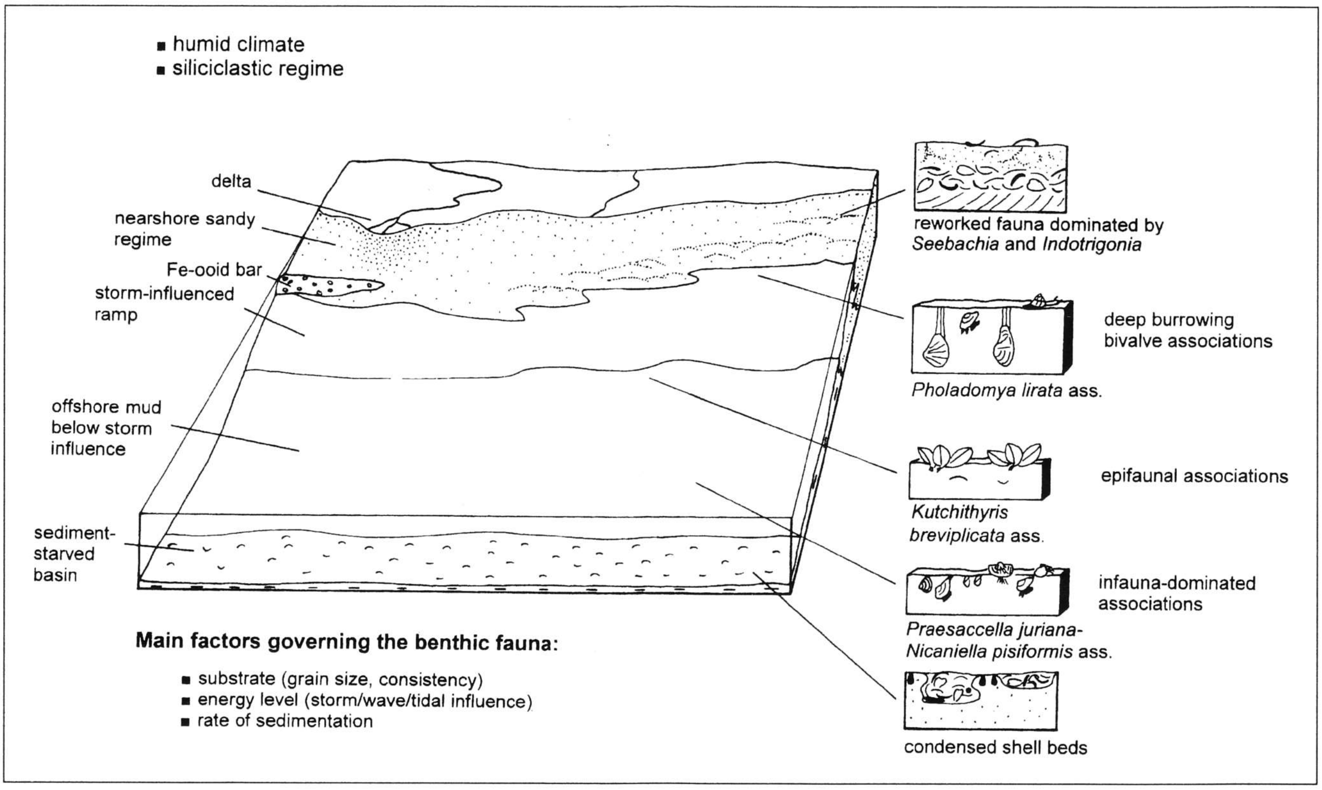

Fig. 5 - Callovian to Oxfordian palaeoenvironments and biota in the Kachchh Basin. Shown are characteristic facies and benthic associations, which are part of a siliciclastic ramp. Note that not all facies are contemporaneous. For example, the condensed shells beds are a result of a major rise in relative sea level during the Oxfordian.

characteristic biofacies of the Upper Bathonian Patcham Formation of the Jumara and Jhura domes. In contrast to the classical Upper Jurassic microbial-sponge reefs on the northern margin of the Tethyan Ocean (e.g. Keupp et al. 1990), no microbial crusts are associated with the sponges from the Kachchh Basin, probably as a result of oligotrophic conditions.

The hot, arid to semi-arid climate apparently existed for much of the early Middle Jurassic, which is indicated by the widespread occurrence of red beds, partly with caliche nodules, in Bajocian-Bathonian rocks of the islands.

In the Callovian, in contrast, the predominantly silty sediment of offshore areas and the presence of large deltaic sand bodies near the eastern margin of the basin indicate increased sediment input from a terrestrial source, probably caused by a wetter climate. The abundant deposit-feeding nuculid bivalves *Palaeonucula, Nuculoma, Mesosaccella, Praesaccella*, and *Dacryomya* point to an abundant food source within the sediment in connection with a high nutrient supply. Eutrophic conditions are therefore envisaged to have prevailed during the Callovian. As a result, species diversity of benthic associations was lower than in the Late Bathonian. Corals occur either as scattered individuals or as monospecific patch reefs (*Amphiastraea piriformis* association) indicating that conditions for reef corals were no longer ideal. Overall, a warm, humid climate is envisaged for the Callovian-Oxfordian. This is also supported by the presence of ferruginous ooids at several levels in the sedimentary succession.

These general statements about the palaeoclimate disregard the fact that the climate was not uniform within either the Bathonian or Callovian, but that short-term temperature and humidity fluctuations occurred repeatedly. For example, ferruginous ooids occur intermittently also in the Upper Bathonian of the islands and may indicate brief spells of more humid conditions. Similarly, the presence of stacked fluvial channels and brackish water faunas in the Bajocian/Bathonian of the islands points to periods of greater humidity.

Onshore-offshore distribution pattern of facies and benthic fauna during the Middle Jurassic

Integrating sedimentological and palaeoecological data, the distribution of some characteristic facies and associations on the ramp morphology is depicted in Figs. 4 and 5 for the Bathonian and Callovian-Oxfordian, respectively.

Bathonian

In the Bathonian (Fig. 4), the arid climate resulted in a carbonate sedimentary regime, which was characterised by fair-weather wave-influenced crossbedded grainstones and packstones in the coastal zone (e.g. the Raimalro Limestone Member at the top of the Patcham Formation in the Pachchham Island). In an offshore direction, this facies gave way to grainstones and packstones subject to storm waves (e.g. the Patcham Formation of the Habo Dome). Still further offshore, graded, laminated calcarenites produced by storm-induced flows alternate with a bioturbated bioclastic marl, which represents the background sedimentation. Autochthonous community relicts dominated either by bivalves (e.g. *Eligmus*), sponges or corals characterise the outer ramp. The well bedded low energy mud- to wackestones are only occasionally interrupted by thin, graded bioclastic calcarenites, interpreted as distal tempestites.

During more humid interludes, higher amounts of freshwater entered the sea. In brackish water lagoons low diversity associations thrived, dominated by the bivalve *Jurassicorbula*. Above the fair-weather wave base, coastal sands gave way offshore to submarine dune fields and to hummocky crossbedded sand layers indicative of storm-wave influence. Mixed carbonate-siliciclastics prevailed in a mid-ramp setting (e.g. the Goradongar Yellow Flagstone Member, Goradongar Formation, of Pachchham Island). Thin intercalations of graded, laminated sandy calcarenites are evidence of storm-generated currents. This generally low energy environment was colonised by the high diversity variant of the *Indocorbula lyrata* association. During transgression, several m thick skeletal sand sheets developed, which consist of crinoid ossicles with minor amounts of quartz grains.

Callovian-Oxfordian

The ramp situation persisted during the ensuing Callovian-Oxfordian time interval, but the profound changes in climate, discussed above, led to a different facies pattern and set of benthic communities (Fig. 5). Increased run-off, possibly in combination with increased tectonic uplift in the hinterland supplied much terrigenous material to the basin. In the eastern part of the basin (e.g. Wagad Dome), large deltaic sand bodies developed. Waves and currents distributed the sand either during destructive delta phases or transgressive events as sand sheets across the basin. In nearshore areas, dune and megaripple fields formed. Further offshore, storm influence became dominant. Only rarely, relicts of the benthic communities are preserved. Shells were either dissolved during diagenesis or destroyed by biostratinomic processes in these high energy, shallow water environments. However, when these faunas were reworked during transgressive events they occasionally became preserved as shell concentrations (transgressive lags). Typical faunal elements of such lags are large, thick-shelled infaunal bivalves (*Indotrigonia, Seebachia*).

Towards the outer ramp argillaceous silt was the dominant facies containing, in contrast to the usually unfossiliferous sandstones, a rich benthic fauna, characterised either by epibenthic brachiopods (e.g. the *Kutchithyris breviplicata* association) or by infaunal bivalves, among which deposit-feeding nuculids and small suspension-feeding corbulids and astartids were particularly abundant (e.g. the *Praesaccella juriana – Nicaniella pisiformis* association).

As a result of the high rise of relative sea level during the Oxfordian, offshore areas of the basin suffered sediment starvation. Highly condensed shell concentrations accumulated in these areas, together with sedimentary features indicative of omission, such as hardgrounds and ferruginous crusts.

Conclusions

During the Jurassic, environments and biota of the Kachchh Basin were largely controlled by the interplay of general subsidence, local synsedimentary tectonics, eustatic sea level changes, and changes in the regional climate. Depending on the influence of the individual factors, either a carbonate or a siliciclastic sedimentary regime became established. The spatial distribution of the benthic macrofauna was mainly governed by substrate, energy level, rate of sedimentation, and nutrient supply, in nearshore areas also by changes in salinity. These environmental parameters, in turn, were controlled by the four main exogenic factors mentioned above. They not only controlled the spatial distribution pattern, but also the temporal changes of the macrofauna. As a result, the cyclic sedimentation pattern within the basin is mirrored by corresponding changes in the benthic communities (e.g. Fürsich et al. 1991).

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