Depositional environments of Bathonian sediments from the Jaisalmer Basin, Rajasthan, western India*

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Abstract The pericratonic sedimentary Jaisalmer Basin, west of the Aravalli Ranges, on the westerly dipping eastern flank of the Indus Shelf, is a principal structural element of Rajasthan. Jurassic sediments in the SE comprise non-marine sandstones and conglomerates to nearshore, brackish to marine sands, silts, clays and carbonates, grouped lithostratigraphically into the Lathi, Jaisalmer, Baisakhi, and Bhadasar formations. The Late Bajocian to Oxfordian Jaisalmer Formation is divided, in ascending order, into the Hamira, Joyan, Fort, Badabag, Kuldhar, and Jajiya members. Fossil records providing a Bajocian to Bathonian age for the lower and middle parts of the formation include: a Late Bajocian coral *Isastraea bernardiana* (d'Orbigny) in the uppermost Joyan Member; Bathonian ammonite *Clydoniceras* in the basal part of the Badabag Member; Bathonian foraminiferal/bivalve assemblages in the Fort Member. The topmost bed of the Joyan Member represents the peak of first marine transgression of the Jaisalmer Basin, probably contemporaneous with the Late Bajocian one in the neighbouring Kachchh Basin. Based on faunal studies Bajocian to Bathonian sediments of the Jaisalmer Basin can be broadly correlated with those of the Kachchh Basin. The Fort and Badabag members represent the following depositional environments, in chronological order: (a) brackish to shallow fully marine; (b) fully marine with rapidly fluctuating water energy and sedimentation rates; (c) near-shore to lower shoreface with fluctuating energy conditions, salinity and sedimentation rates; (d) near-shore to shoreface channels and storm-dominated marine above fair-weather wave-base; (e) lagoon with fluctuating low to moderate energy, salinity and sedimentation rates; (f) storm-dominated shelf to lower shoreface.

Keywords: Jaisalmer Basin, Jaisalmer Formation, Bathonian, microfacies, depositional environments.

The Jaisalmer sedimentary basin is a shelf basin neighbouring the Kachchh Basin in the south. It is one of four structural elements of Rajasthan (Fig. 1; viz. Bikaner-Nagaur Basin, Pokharan-Nachna High, Jaisalmer Basin and Barmer-Sanchor Basin)[1], on the northwestern margin of the Indian craton to the west of the Aravalli axis. During the Jurassic, the Jaisalmer Basin occupied a latitude of about 30° S[2] (Fig. 2(a)). The area was the westerly dipping eastern flank of the Indus Shelf of the Indus-Baluchistan geosyncline or Indo-Arabian Geological Province (Fig. 2(b))[3–6].

Tectonically, the basin has been subdivided into three: the Kishangarh and Shahgarh sub-basins and the Mari-Jaisalmer Arch (Fig. 3)[7,8]. The raised, NW-SE trending Mari-Jaisalmer Arch extends through the central part of the basin and separates the Kishangarh sub-basin in the north from the Shahgarh sub-basin in the south. The sediments in the Jaisalmer Basin range from non-marine sandstones and conglomerates to nearshore, littoral, brackish to marine sands, silts, clays and carbonates. The sediments record shallowing-deepening cycles. Just like the neighboring sedimentary basin of Kachchh (Fig. 1), the Jaisalmer Basin is particularly well suited to study the relationship between organisms and their environment both in a spatial and a temporal context.

Oldham[9] was the first to study the sediments of the Jaisalmer Basin. Ghosh[10], Sahni & Bhatnagar[11], Swaminathan et al.[12], Subbotina et al.[13], Lubimova et al.[14], Narayanan[15], Singh & Krishna[16], Raghavendra Rao[7], Lukose[17], Das Gupta[8], Bhatia & Mannikeri[18], Pareek et al.[19], Krishna[20–23], Pareek[24], Singh & Mishra[25], Kachhara & Jodhawat[26], Garg & Singh[27], Kalia & Chowdhury[28], Kalia & Roy (in Kalia)[29], Mahender & Banerji[30,31], Fürsich et al.[32], Pandey & Fürsich[33], Dave & Chatterjee[34], Pandey & Dave[1] and Pandey et al.[35] all contributed to elucidating the tectonic framework, geological setting, taxonomy of fossils, and depositional environments of the basin.

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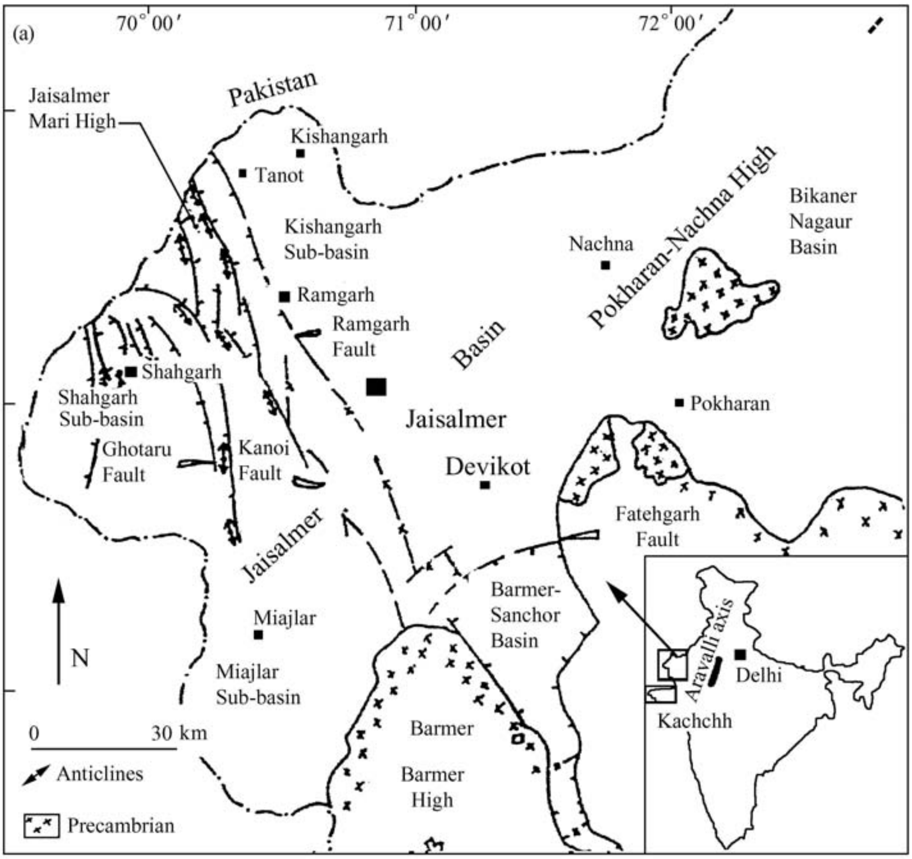

Fig. 1. Location map. Structural elements in western Rajahstan (modified from Pandey and Dave 1998[1]).

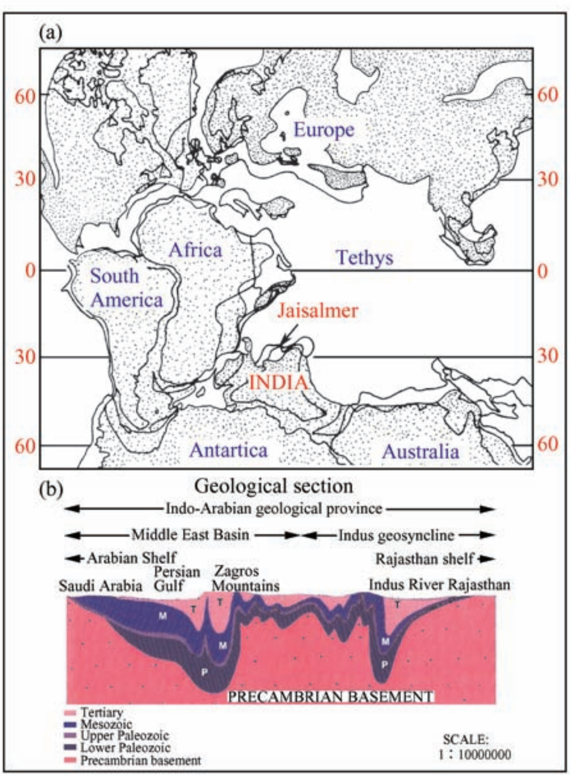

Fig. 2. Palaeogeographic position of the Indian Craton during Jurassic (modified from Barron et al.[6] (a) and geological section across the Indo-Arabian geological province (modified from Ganss-

1 Lithostratigraphy

The sediments in the Jaisalmar Basin range from Palaeozoic to Quaternary (Table 1). The Jurassic sediments are exposed in the southeastern part of the basin, on the raised Mari-Jaisalmer Arch. Lithostratigraphically, these sediments of the Jaisalmer Basin have been grouped into the Lathi, Jaisalmer, Baisakhi, and Bhadasar formations (Fig. 3).

1.1 First marine transgression

Das Gupta[8] concluded that Jurassic sedimentation in the Jaisalmer area started with the continental/deltaic to littoral Lathi sediments. Mahender & Banerji[30,31] proposed beach and shallow marine depositional environments for the Middle Jurassic Jaisalmer carbonates and sandstones. However, details of the depositional history of the continental shelf are not available. Due to the lack of index fossils and proper time correlation, paleoenvironmental reconstruction of the individual rock-units is not very useful.

The Jaisalmer Formation, overlying the predominantly continental Lathi Formation, represents a time interval when the first marine transgression cov-

Table 1. Stratigraphic succession of Jurassic-Quaternary sediments exposed in the southeastern part of the Jaisalmer Basin on the raised platform of the Jaisalmer-Mari Arch (modified after Das Gupta[8]; Pandey and Fürsich[33]).

Event	Lithology	Formation	Age
	Unconsolidated sediments	Shumar Formation	? Subrecent
Third marine transgression	Clay and limestone	Bandah Formation	Lutetian
	Nummulitic limestone	Khuiala Formation	Upper Paleocene to Ypresian
			Lower to Middle Paleocene
Regression	Glauconitic and silty sandstone		
Second marine transgression	Sandy limestone, sandy marl	Sanu Formation	Aptian
Continental sandstones		Habur Formation	Neocomian
Regression	Sandstone	Pariwar Formation	Tithonian
		Bhadasar Formation	
First marine transgression	Shales	Baisakhi Formation	Kimmeridgian
	Carbonate rocks	Jaisalmer Formation	Bajocian-Oxfordian
Sedimentation starts with continental deposits		Lathi Formation	Triassic/Lower Jurassic
Older Formations			

ered the west Rajasthan shelf. The fossil record[33] suggests that the sea inundated the basin contemporaneously with the Late Bajocian transgression in the neighbouring Kachchh Basin[36,37].

1.2 Jaisalmer Formation

The formation consists of both carbonate and siliciclastic sediments deposited during the first marine transgression. Ammonoids, rhynchonellid and terebratulid brachiopods, pelecypods, gastropods, echinoids, bryozoans, and corals are common fossils, in addition to diverse trace fossils. The sediments range from Late Bajocian to Oxfordian[33]. The original name of "Jaisalmer Limestone" was given by Oldham[9] and this was redefined by Swaminathan et al.[12] as the Jaisalmer Formation. Lithostratigraphically, the formation has been divided, in ascending order, into the Hamira, Joyan, Fort, Badabag, Kuldhar, and Jajiya members[8,26,37].

Index fossils, in particular ammonites, are rare in the formation. They occur from the Kuldhar Member (Early Callovian-Oxfordian) onwards, and determine the upper age limit of the formation. From the lower members (Hamira, Joyan, Fort and Badabag), ranging from Bajocian to Bathonian, no ammonites were recorded, until a recent collection of the Bathonian ammonite genus *Clydoniceras* Blake, 1905, from the basal beds of the Badabag Member1). Therefore, prior to the record of *Clydoniceras* there was no direct evidence of sediments older than Callovian. However, the record of the coral *Isastraea bernardiana* (d'Orbigny)[33] from the topmost bed of the Joyan Member, a characteristic of the Late Bajocian, and occurrences of Bathonian foraminiferal/bivalve assemblages from the Fort Member[14,26] point to a Bajocian to Bathonian age of the lower and middle parts of the formation (Fort and Badabag members), below the Lower Callovian ammonite-bearing beds (Kuldhar Member)[16,28,32].

1) Dr. Surendra Prasad of Geological Survey of India collected a specimen of Bathonian ammonite genus *Clydoniceras* from the basal beds of the Badabag Member of the Jaisalmer Formation (personal communication)

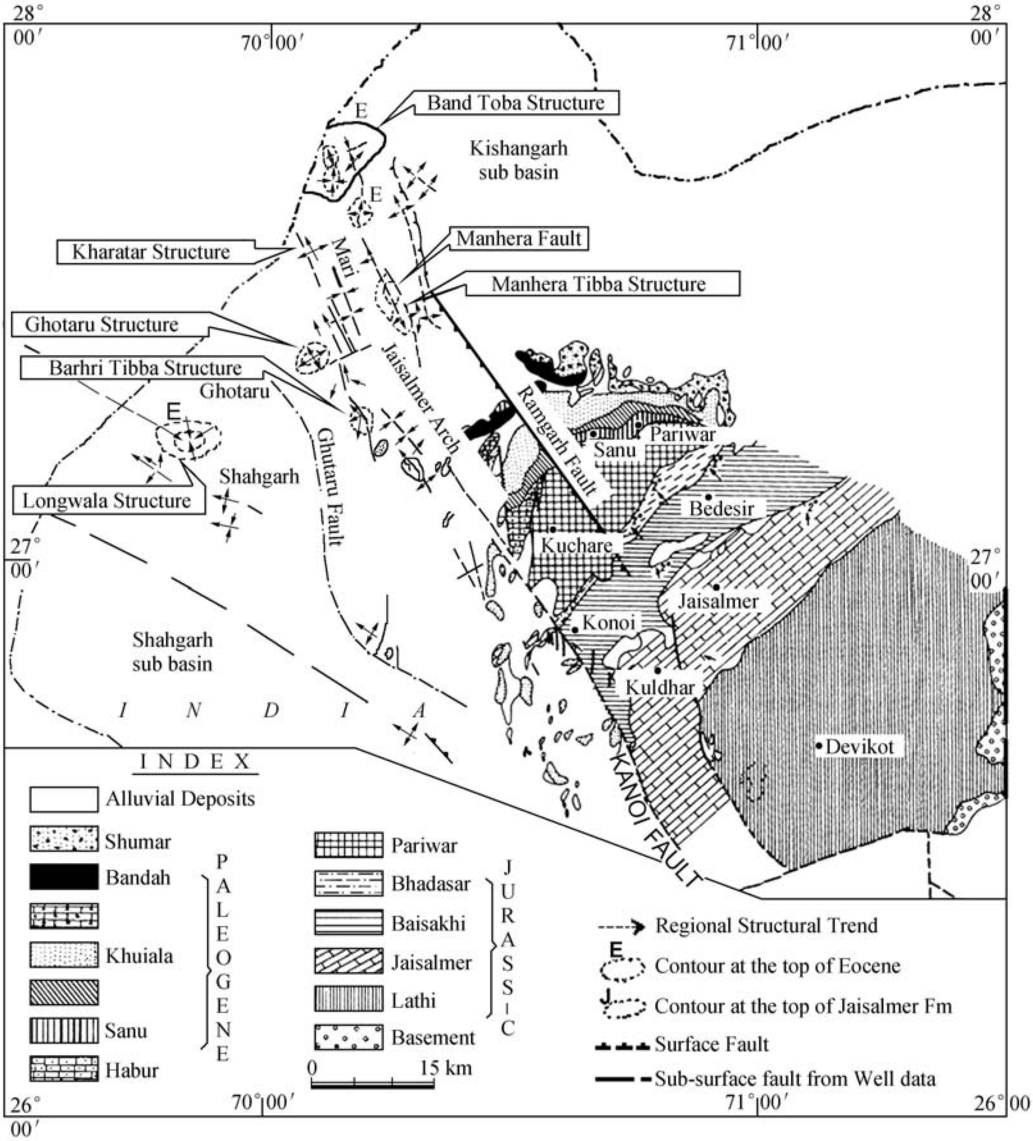

Fig. 3. Geological map of western Rajahstan (after Das Gupta[8]).

The temporal changes in lithology, fossil content, and microfacies suggest that the basal beds of the Jaisalmer Formation represent the beginning of first marine transgression of the Jaisalmer Basin. Faunal studies reveal that Bajocian to Bathonian sediments of the Jaisalmer Basin can be broadly correlated with those of the neighbouring Kachchh Basin[38]. The present paper deals with depositional environments of the Bathonian sediments (Fort and Badabag members) of the Jaisalmer Basin.

2 Depositional environments of Bathonian sediments of the Jaisalmer Basin

The sediments range from siliciclastics to mixed carbonate-siliciclastics and occasional beds of carbonates. Broadly speaking, the middle part is more calcareous (i.e. the upper part of the Fort Member), whereas the lower and upper parts are more arenaceous (i.e. lower part of the Fort Member and Badabag Member, respectively). In the present study, the depositional environments of the various Bathonian sediments (Fort and Badabag members) have been interpreted in chronological order, based on detailed facies analysis including primary sedimentary structures, biotic elements and microfacies. Several sections through the Fort and Badabag members were measured in order to obtain a comprehensive idea of each facies. An account of the temporal facies variation and the depositional environments of the two members is given below.

2.1 Fort Member at Fort section (Early to Middle Bathonian)

Three sections measured along the Cliff about 1 km north of Jaisalmer Fort, at lateral intervals of about 200 m, reveal that the member consists of about 27 units with a total thickness of more than 30 m. Lithologically, the Fort section can be broadly grouped into three facies (Fig. 4).

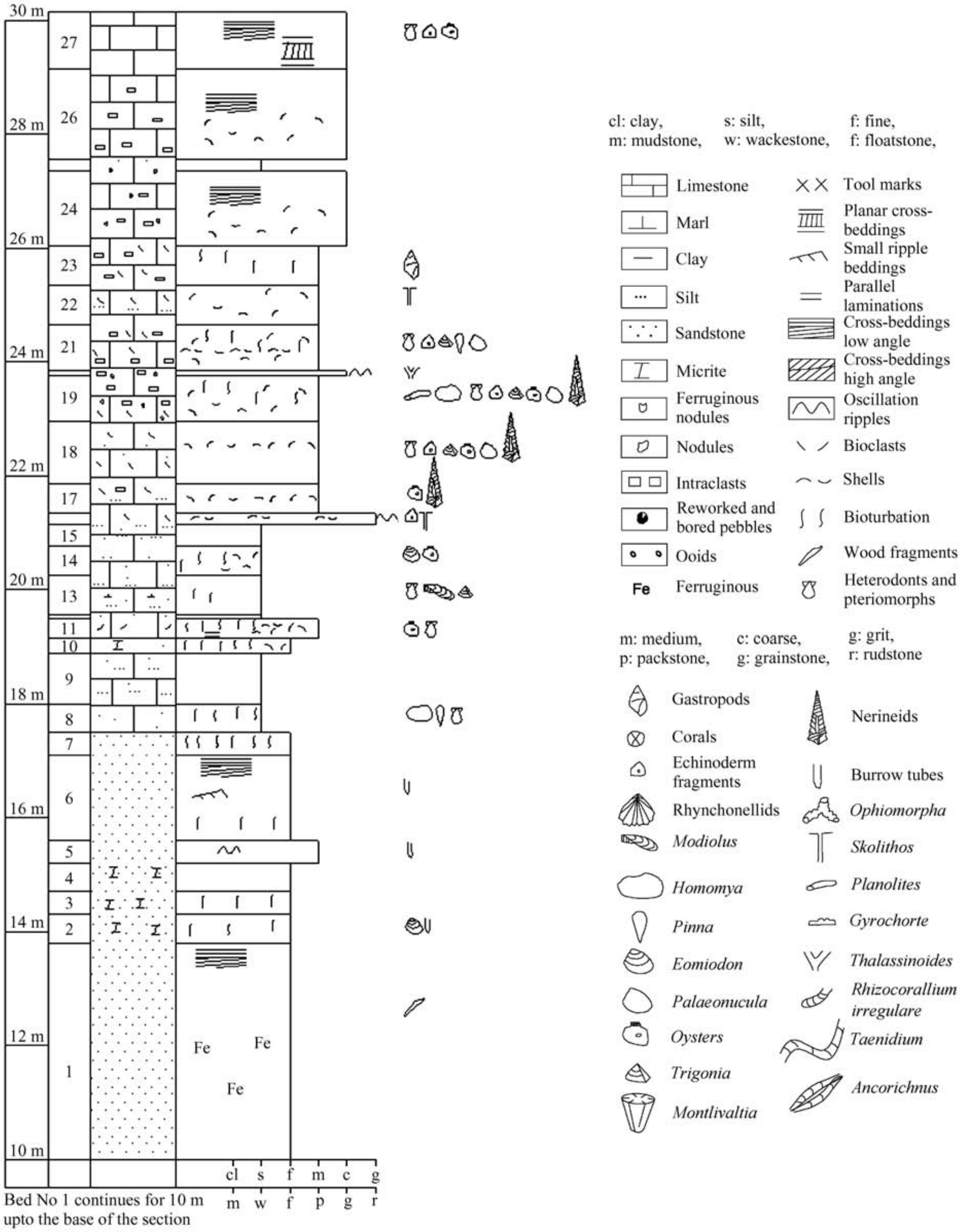

Fig. 4. Section of the Fort Member exposed along the Fort Cliff-section, ENE of Jaisalmar.

2.1.1 Well-sorted, fine-grained sandstone (Bed No. 1) This is the oldest unit exposed at the base of the Fort Cliff (Fig. 5 (c)). The unit is a poorly cemented, well-sorted fine-grained sandstone, with several purple-colored, thin, indurated ferruginous crusts in the middle part and medium-scale cross-stratification in the upper part. From the adjacent areas, wood fragments have been collected from this facies and they are the only fossils.

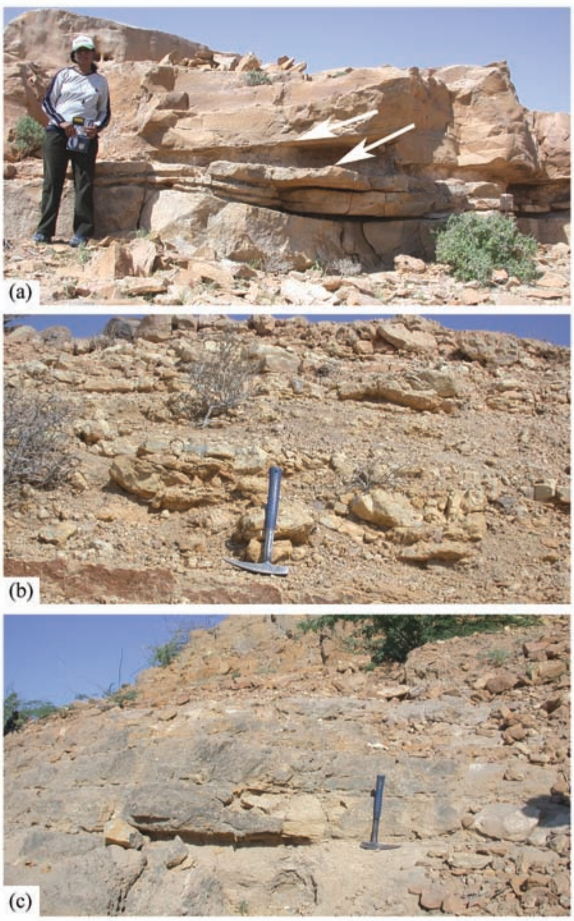

Fig. 5. (a) Thick (~180 cm thick), well cemented, low angle large scale trough cross-bedded bio-packstone (uppermost Fort Member, Jaisalmer Formation) exposed along the top of the Fort Cliff-section, 1.5 km NNE of the Jaisalmer Fort. Note the bedded structure on the lower part with sharp upper and lower contacts (arrowed). (b) Thinly bedded alternating poorly and well-cemented, richly fossiliferous, bioturbated wacke-to bio-packstone, occasionally with superficial ooids. Basal part exhibits tempestites. Uppermost Fort Member of the Jaisalmer Formation, top Fort Cliff-section at about 1 km N of the Jaisalmer Dak Bungalow. Note the sharp and uneven base of the individual beds. (c) Thick (>2 m) low angle cross-bedded, poorly cemented, well-sorted fine-grained sandstone unit. Lowermost Fort Member, Jaisalmer Formation; basal Fort Cliff-section ~1.5 km NNE of the Jaisalmer Fort.

The characters of the unit suggest near-shore, high-energy conditions and a distinct terrestrial influence.

2.1.2 Mixed siliciclastic-carbonates (Bed Nos. 2—15) The mixed siliciclastics-carbonates of the middle part are principally fine-grained, mostly bioturbated and richly fossiliferous. The following three subfacies can be identified:

(1) Bioturbated fine-grained calcareous sandstone/fine-sandy wackstone/packstone with scattered quartz (Bed Nos. 2, 3, 6; partially, 7—15);

(2) poorly sorted fine-grained calcareous sandstone, occasionally with oscillation ripples (Bed Nos. 4, 5);

(3) low-angle cross-bedded, fine-grained sandstone with small-scale ripples (Bed No. 6; only partially).

Bioturbation, in general, suggests low energy conditions below fair-weather wave-base with low influx of sediments. The articulated bivalve *Eomiodon* (a shallow infaunal suspension-feeder) and the low diversity of the fauna (in Bed No. 2) suggest environmental stress most likely due to reduced salinity. The high proportion of autochthonous fossils (in Bed Nos. 8, 10, 11, 13, 14), all of them suspension-feeders, includes the semi-infaunal *Pinna* and the deep burrowing *Homomya*, both in life position. Parautochthonous or allochthonous bivalves such as endobyssate articulated *Modiolus*; articulated and single-valved shallow infaunal trigoniids, *Corbulomima*, *Protocardia*, other heterodonts, and epifaunal cemented oysters all suggest fully marine conditions. The microfacies, which is a predominantly silty to fine-sandy wackestone (except for Bed No. 11, which is a packstone with scattered quartz grains) also suggests a low energy condition. The co-occurrence of brackish water faunal elements (*Eomiodon*) and fully marine taxa (*Actinostreon gregareum*) in Bed No. 14 and their poor preservation suggests a mixed assemblage. All evidence points to low energy conditions and a soft substrate with variable salinity and low rate of sedimentation.

Poorly sorted fine-grained calcareous sandstone (Bed Nos. 4, 5) associated with oscillation ripples point to occasional higher energy events. The presence of micrite, in contrast, supports a low to moderate water energy.

The low-angle cross-bedded, fine-grained sandstone with small-scale ripples (part of Bed No. 6) indicates a shallow but protected environment, occasionally touched by storms.

2.1.3 Predominantly carbonates (Bed Nos. 16—27) The upper one-third part of the section (about 9 m) consists mainly of carbonates (Bed Nos. 16—27). The individual beds show sharp base (Fig. 5(a), (b)), with occasional tempestites. Sometimes this unit exhibits elongated chert nodules or about 1 m-long bands. In between the individual-cross beddings are bioturbated, moderately cemented silty biomicrite (maximum thickness about 20 cm). The fossil assemblage of this unit is similar to the Middle Bathonian sequence of Kachchh, particularly to that of Kala Dongar, Gora Dongar, Jhura Dome, etc.[38]. The uppermost bed (about 100 cm thick) is a small-scale low angle cross-bedded well cemented fine-grained ferruginous sandstone.

Quartz grain size ranges from silt to fine-grained, their shape from angular to rounded. Bioclasts comprise up to 30%, most are silt- to sand-sized, rare grains reaching up to 8 mm in size. Additional components are intraclasts, ooids (2.5%), and peloids (10%). The packing is predominantly clast-supported. The cement is micrite, rarely sparite. In terms of microfacies the succession can be grouped into five subfacies:

(1) Bio-rudstone to grainstone, forming shell-beds and topped with ripple surfaces (Bed Nos. 16, 20);

(2) fossiliferous, bio-intra-packstone to bio-packstone (Bed Nos. 17—18);

(3) fossiliferous, bioturbated bio-packstone (Bed Nos. 19, 21—23);

(4) sandy wackestone (Bed No. 25);

(5) large-scale, low-angle cross-bedded, fine-grained sandy grainstone (Bed Nos. 26—27).

The occurrence of a rich marine fauna (Fig. 4; Bed Nos. 16—27) indicates fully marine conditions. Most of the benthic elements were shallow burrowers, and except for deposit-feeding nuculids, all of them were suspension-feeders, indicative of a soft substrate.

Different degrees of bioturbation, the admixture of allochems, sedimentary structures and trace fossils suggest fluctuating water energy. The bio-rudstone (Bed. No. 16) indicates high-energy conditions. Grainstones (Bed Nos. 20, 26—27) and shell beds (Bed Nos. 16, 19, 21) point to constant winnowing. Wave-ripple surfaces (Bed Nos. 16, 20) and low-angle cross-beds (Bed Nos. 24, 26—27) point to depths above the fair-weather wave-base. In addition, tempestites and intraclasts indicate phases of erosion and distal storm action. Partly laminated sediments, strong bioturbation and occurrence of the deep burrower *Homomya* in life position points to low energy conditions. Lack of orientation of shell fragments and parautochthonous echinoid spine concentrations also suggest relatively low water energy. Similarly, the strong bioturbation indicates a low rate of sedimentation. The occurrence of oysters in beds 17—18 points to the presence of secondary hard substrates. In summary, the upper third of the Fort Cliff-section represents fully marine environments with fluctuating water energy (occasionally storm dominated) and rates of sedimentation, a depth oscillating between below and above the fair-weather wave-base, and soft substrates.

2.2 Badabag Member at Bara bagh (Upper Bathonian)

Of the six sections of the Badabag Member measured at 50 to 1000 m intervals near Bara bagh the one opposite to the Cenotaphs is most complete (Fig. 6). However, for the purpose of description all six have been used. Based on microfacies, primary sedimentary structures and biotic components, the Badabag Member can be broadly divided into five units.

2.2.1 Poorly cemented, alternate bioturbated silty clay and medium-grained calcareous sandstone

Opposite the Cenotaphs this unit is only partially exposed (Bed No. 1), most of it being covered with scree. The unit (7.3 m thick) is best exposed about 2 km north of Jaisalmer Dak Bungalow, where it has yielded bakevellids, *Eomiodon*, corbulids, *Modiolus*, *Anisocardia* and wood fragments.

Alternations of silty clay and calcareous sandstone reflect fluctuating water energy. All the fossils are suspension-feeders and most of them lived semi-infaunally or as shallow burrowers. Bioturbation suggests low rates of sedimentation below fair-weather wave-base. Low diversity and mixed faunal assemblages point to fluctuating salinity, ranging between

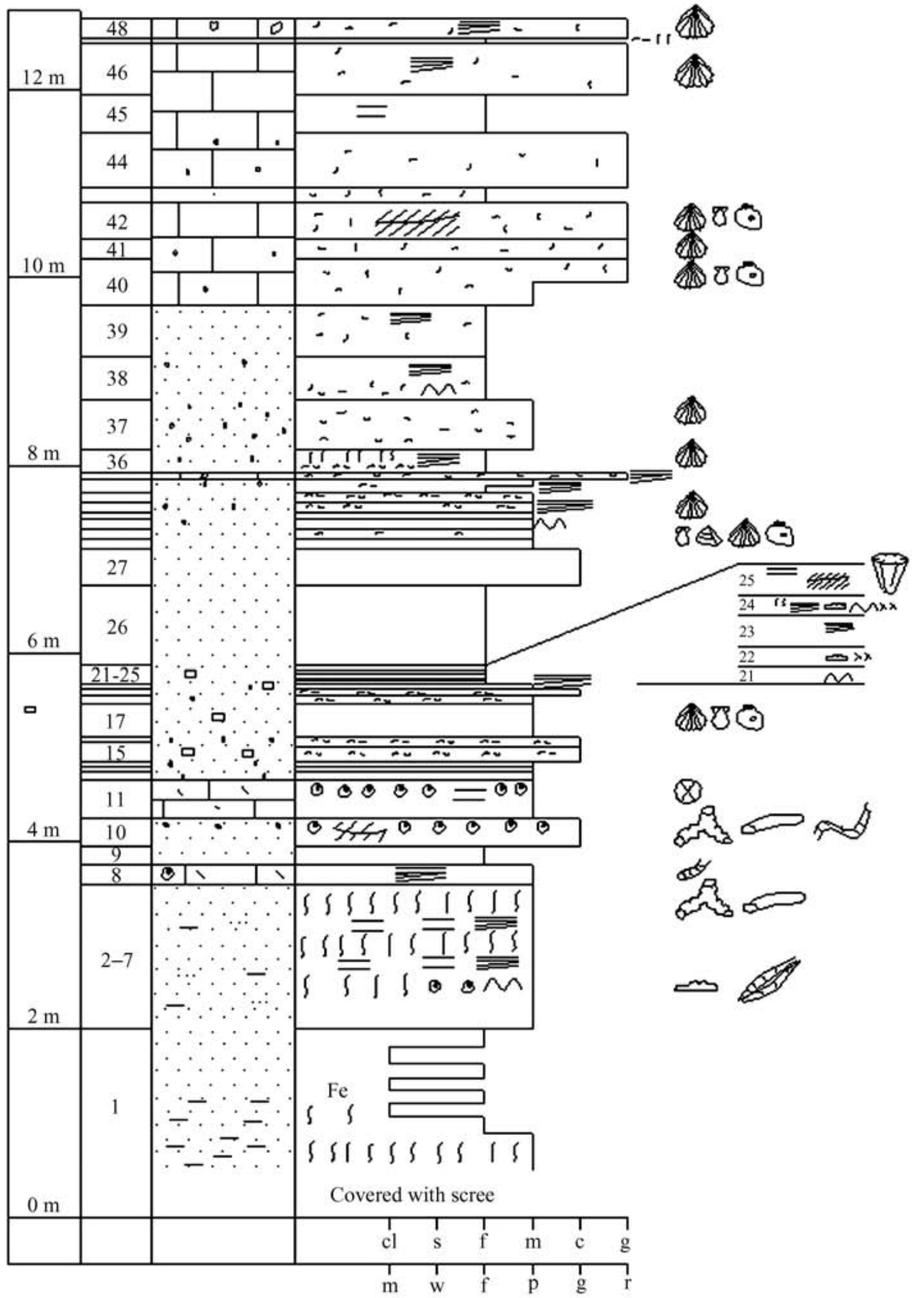

Fig. 6. Section of the Badabag Member exposed opposite to the Bara bagh Centotaphs; for key of symbols see Fig. 3.

brackish (*Eomiodon*) and normal marine. In all probability, the sediments were deposited in a protected near-shore environment, where energy level and salinity varied periodically.

2.2.2 Alternations of bioturbated and low angle cross-laminated fine-to medium-grained calcareous sandstone

This facies (Bed Nos. 2—7; about 1.55 m thick) is best measured along the base of the section opposite to Bara bagh Cenotaphs. Except for bioclasts no megafossils could be collected. The trace fossils are *Ancorichnus*, *Gyrochorte* (Fig. 7(c)), *Ophiomorpha* and *Planolites*. Here bioturbated and low angle cross-laminated fine-to medium-grained calcareous sandstone alternate.

Interbedded bioturbated and thinly cross-laminated sandstones suggest fluctuating water energy and a depth below and around the fair-weather wave-base. Occasional bored pebbles in Bed No. 3 are suggestive of erosion and transport. The trace fossils are commonly found on the rippled upper surface of fine-

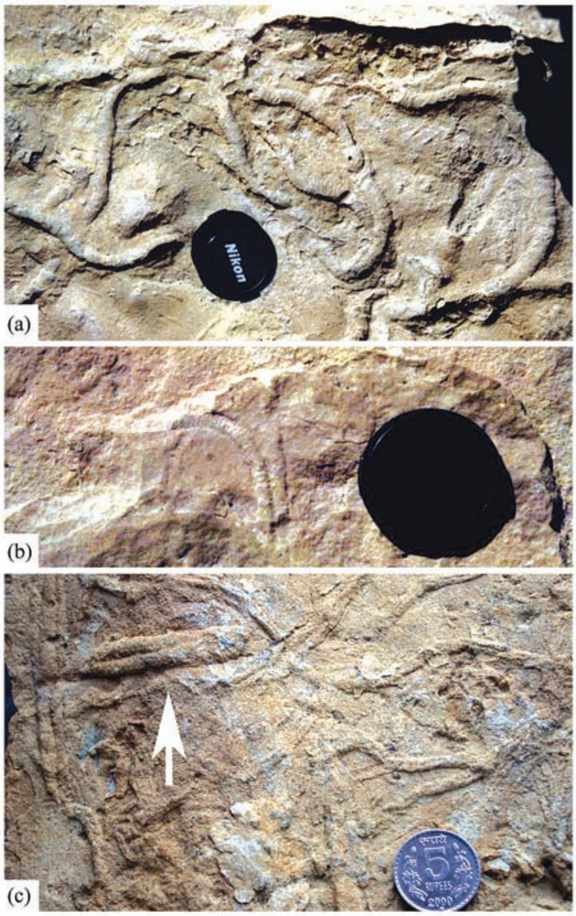

Fig. 7. (a)—(b) Close-up views of a sinuous trace fossil, *Taenidium* isp. on the upper surface of a cross-bedded, calcareous sandstone below the conglomeratic calcareous sandstone to bio-packstone bed (Fig. 6, Bed No. 10) exposed near the top of the basal escarpment opposite to the Bara bagh Cenotaphs, 6 km N of Jaisalmer; lower Badabag Member, Jaisalmer Formation. (c) Close-up view of *Ancorichnus* isp. (arrowed) and several *Gyrochorte* on the oscillation-ripple upper surface of a fine-to medium-grained argillaceous, calcareous sandstone occasionally with small bored pebbles (Fig. 6, Bed No. 3): basal part facies no. 5, lower Badabag Member, Jaisalmer Formation; near the base of the basal escarpment section opposite to the Bara bagh Cenotaphs, 6 km N of Jaisalmer.

to medium-grained sandstone. *Ancorichnus* is characterized by meniscate backfill and the presence of a distinct mantle. It represents the burrow of a deposit feeder. The ichnogenus *Gyrochorte* is a bilobed positive epirelief produced by worms or crustaceans. The lobes are biserially arranged with a median furrow[39,40]. *Gyrochorte* indicates a shallow marine environment and has been reported from Jurassic sediments very commonly. *Ophiomorpha*, a three-dimensional, cylindrical, branching vertical and horizontal crustacean burrow systems, lined with pellets, is regarded as an indicator of high energy, shallow marine environments. The pellets have been suggested as being made to stabilize a soft substrate against collapse. *Planolites* is the product of deposit-feeders, inhabiting low energy environments. The above features suggest a near-shore, inner shelf environment with fluctuating water energy.

2.2.3 Cross-bedded conglomeratic calcareous sandstone to sandy bio-packstone

Due to their indurated nature beds 8—11 (about 1.3 m thick) are scarp forming, they are best exposed along the top of the basal escarpment opposite to the Bara bagh Cenotaphs. The facies consists of well-cemented, cross-bedded, bored pebble-bearing, poorly sorted, calcareous sandstone to sandy packstone. The pebbles were bored before becoming incorporated in the conglomeratic sediment. Occasionally, the pebbles exhibit cracks. The base and top of the individual lithic units are sharp and uneven (Fig. 8(b)). Abraded, reworked heads of the cerioid coral *Isastrea* sp. are the only body fossils recorded. Trace fossils observed in this facies are *Ophiomorpha*, *Rhizocorallium* (Fig. 8(c)), *Planolites* and *Taenidium* (Fig. 7(a),(b)). *Taenidium* has an unbranched winding course with a crowded meniscate backfill. This trace fossil also has been found in the Kachchh Basin in beds that have been interpreted as a storm deposit[41].

High-angle cross-beds (Fig. 8(b)) and reworked pebbles within the calcareous sandstone/sandy packstone suggest a high-energy depositional environment above the fair-weather wave-base. Pebbles bored all over suggest a long residence time on the sea floor with no or only negligible sedimentation. Their sharp and erosional bases of the beds are probably the result of storm action. The components of the conglomerate such as the pebbles and coral-heads have no equivalents in the underlying succession, which indicates total erosional obliteration of some part of the succession. *Rhizocorallium irregulare* and *Planolites* are the products of deposit-feeders, inhabiting low energy environments, whereas *Ophiomorpha* is characteristic of high-energy conditions. In all probability, the sediments were deposited near-shore during phases of strongly fluctuating energy conditions and rates of sedimentation.

2.2.4 Low-angle cross-bedded, poorly sorted calcareous sandstone with poorly preserved calcareous components

This unit (Bed Nos. 12—34, more than 3 m

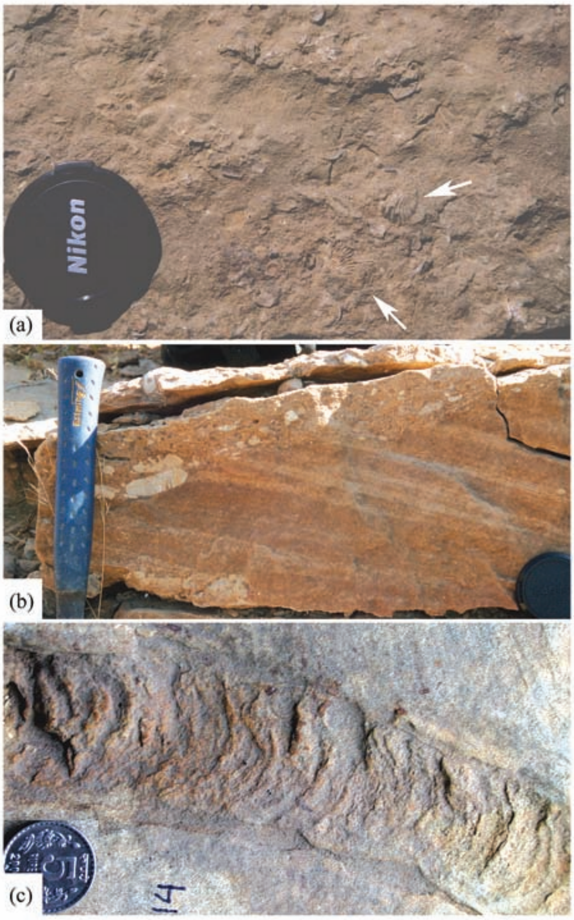

Fig. 8. (a) Close-up view of a monospecific pavement of small rhynchonellid brachiopods and other shell fragments (arrowed) within the facies (7), middle Badabag Member, Jaisalmer Formation; exposed opposite Bara bagh Cenotaphs, 6 km N of Jaisalmer. (b) Cross-bedded fine-to coarse-grained calcareous sandstone (Fig. 6, Bed No. 10) overlain by a conglomeratic calcareous sandstone to sandy bio-packstone (Fig. 6, Bed No. 11), lower part Badabag Member, Jaisalmer Formation; exposed along the top of the basal escarpment opposite to the Bara bagh Cenotaphs, 6 km N of Jaisalmer. Note the sharp base of the conglomerate unit (facies no. 5) that can be traced for several km. (c) Close-up view of *Rhizocorallium irregulare* on the upper surface of a low angle cross-bedded, well cemented bioclastic packstone (Fig. 6, Bed No. 8): lower Badabag Member, Jaisalmer Formation; exposed near the top of the basal escarpment opposite to the Bara bagh Cenotaphs, 6 km N of Jaisalmer.

thick) is best exposed opposite the Cenotaphs (Fig. 9(b)) resting on a bed of conglomerate (Bed No. 11). This facies is a monotonous, poorly to moderately cemented, thinly laminated/bedded, poorly sorted, argillaceous to calcareous sandstone. Only in some cases cross-stratification is evident. Biodiversity in the facies is low. Biotic components are small rhynchonellids, *Trigonia*, oysters, *Plicatula*, *Montlivaltia*, and fragments of other bivalves. Occasionally, shell fragments form pavements (Fig. 8(a)), and tool marks are observed on lower surfaces. *Gyrochorte* is associated with ripple surfaces (Fig. 9(c)).

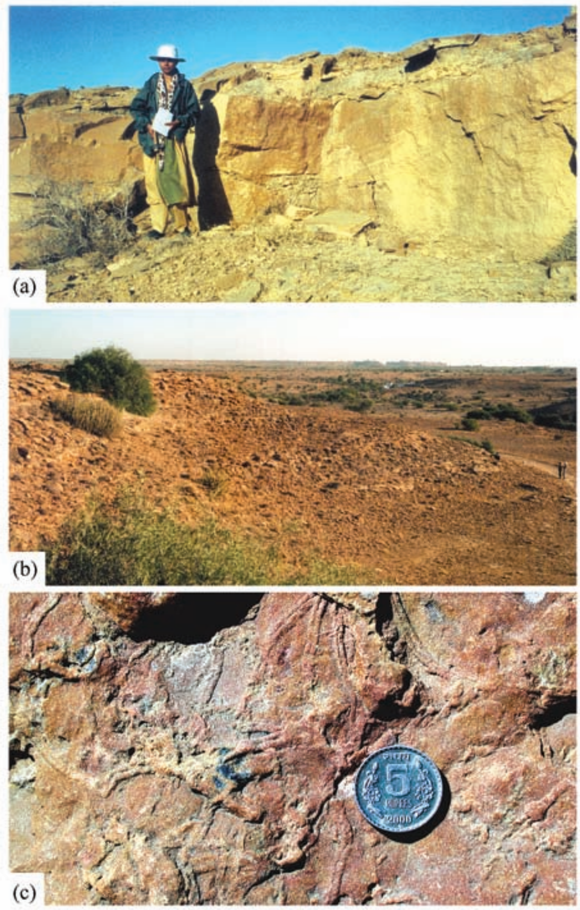

Fig. 9. (a) Thick (>40 cm) cross-bedded, well cemented biorudstone beds with sharp base alternating with thin (minimum 6 cm) fine-grained argillaceous calcareous sandstone with small shell fragments, occasionally bioturbated: topmost facies (Bed No. 8), Badabag Member, Jaisalmer Formation; exposed along the upper escarpment of the Bara bagh Cliff opposite the Bara bagh Cenotaphs, 6 km N of Jaisalmer. (b) Panoramic view of low-angle cross-bedded, poorly to moderately cemented, poorly sorted calcareous sandstones (facies no. 7) best exposed opposite to the Bara bagh Cenotaphs, 6 km N of Jaisalmer; middle Badabag Member, Jaisalmer Formation. (c) Close-up view of *Gyrochorte*, positive epirelief calcareous fine-grained sandstone of facies (7).

The poor sorting and the occasional cross-stratification suggest fluctuating energy conditions. The calcareous components (ooids, intraclasts and peloids) record episodic sediment input from a calcareous source. Sharp erosional bases of the beds and tool marks indicate currents, quite likely caused by storms. The shell pavements can also be interpreted as current concentrations[42]. The scarcity of fossils points to environmental stress. The solitary coral *Montlivaltia* is not very sensitive to environmental change. It is eurytopic, occurring in both siliciclastic and carbonate sediments, and has a high physiological tolerance of environmental stress[43]. The exclusive occurrence of the trace fossil *Gyrochorte*, product of a deposit-feeder on the rippled surfaces of the fine-grained sandstones suggest moderate energy conditions. From these features it appears that the facies represents a near-shore environment, where periodic changes of current intensity, salinity, and influx of sediment were main stress factors responsible for the low diversity.

2.2.5 Alternations of cross-bedded coarse-and fine-grained sediments with shell concentrations

This facies (Bed Nos. 35—48, about 5 m thick) is exposed along the upper escarpment of the Bara bagh Cliff opposite the Cenotaphs (Fig. 9(a)). Due to the indurated nature of the top rudstone it forms an escarpment and the sheet-like top bed all around the area. The facies consists of alternations of cross-bedded coarse-and fine-grained sediments with shell concentrations and sharp bases. The fine-grained sediments are low-angle cross-laminated calcareous sandstones with small shell fragments, occasionally followed by a thin bioturbated unit. The coarse layers consist of cross-bedded rudstones with large shell fragments, and clay pebbles (size up to 0.5 cm) and exhibit a sharp base. Shell fragments are either arranged along the foresets, as shell concentrations, or disseminated throughout the bed. Rhynchonellids are the most common fossils in this facies, but oysters and *Pseudolimea* also occur. In another section about a kilometer west of the cenotaphs, a bed equivalent in stratigraphic position to bed no. 46 has yielded a rich fossil assemblage, e.g. terebratulids, mytilids, pectinids, *Trigonia*, *Mytiloperna*, *Anisocardia*, crinoid ossicles, echinoderm spines, and poorly preserved thamnasterioid corals.

The rich fossil assemblage indicates fully marine conditions. Cross-bedded units of rudstone with large shell fragments and the pebbles suggest very high-energy conditions. Most of the organisms were suspension-feeders, corroborating a high-energy environment. The sharp erosional base of the rudstones and the shell concentrations can be explained by storm action. Alternations of fine-grained sediments and shell hash suggest fluctuations of the energy level. Bioturbated layers between low-angle cross-bedded fine-grained calcareous sandstone can be interpreted as low-energy, post-storm intervals.

The above-mentioned features suggest drastic changes of water energy in a fully marine environment. Compared to the underlying beds, the present facies was shallower, having been deposited in a near-shore storm-dominated environment.

3 Discussion

The picture emerging from the present study is that, although the sea had inundated the Jaisalmer Basin during Late Bajocian, the area was not an open shelf sea for a longer period of time during the Bathonian (Fort and Badabag members). The lower part of the Fort Member reveals a near-shore, very shallow high-energy depositional setting with a strong terrestrial influence. In the middle part, the basin was still very shallow but protected and experienced low to moderate water energy condition. Salinity changed from brackish to marine water at the beginning of the middle part. During the upper part of the deposition of the Fort Member, the conditions were fully marine. The calcareous facies with infaunal deep burrowing bivalves (e.g. *Homomya*) is similar to that of the upper Middle Bathonian Goradongar Flagstone Member of the Kachchh Basin[38].

The overlying Badabag Member represents lagoonal, delta front, shoreface to offshore environments, with fluctuating salinity and water energy. The topmost part of the Badabag Member suggests a major marine transgression (during the uppermost Bathonian). Nektic elements were distinctly less common during this time interval in the basin, compared to the overlying Callovian sediments of the Kuldhar Member[16,28,32] and to Bathonian sediments of the neighbouring Kachchh basin[38], where the coeval facies are more or less the same. Constantly and rapidly fluctuating environmental parameters such as water energy, rate of sediment influx, salinity and possibly turbidity prevented the establishment of a rich and diverse biota.

4 Conclusions

The pericratonic sedimentary basin of Jaisalmer, situated on the westerly dipping eastern flank of the Indus Shelf contains Jurassic sediments, which are exposed in the southeastern part of the basin. Deposits range from non-marine sandstones and conglomerates to nearshore, brackish to marine sands, silts, clays and carbonates. They have been grouped lithostratigraphically into four formations.

The Jaisalmer Formation with the Hamira, Joyan, Fort, Badabag, Kuldhar, and Jajiya members ranges from Late Bajocian to Oxfordian. Fossil records provide Late Bajocian and Bathonian ages for the uppermost bed of the Joyan Member and the basal beds of Badabag Member, respectively. Foraminiferal/bivalve assemblages from the Fort Member point to a Bajocian to Bathonian age for the lower and middle parts of the formation.

The topmost bed of the Joyan Member represents the first marine transgression within the Jaisalmer Basin. This transgression appears to have been contemporaneous with the Late Bajocian event in the neighbouring Kachchh Basin. Faunal studies reveal that Bajocian to Bathonian sediments of the Jaisalmer Basin can be broadly correlated with those of the Kachchh Basin.

The Fort and Badabag members of the Jaisalmer Basin represent the following depositional environments in chronological order: (1) brackish water to shallow, fully marine environments; (2) fully marine environments with rapidly fluctuating water energy and rates of sedimentation; (3) near-shore to lower shoreface with fluctuating energy conditions, salinity and rates of sedimentation; (4) near-shore, shoreface channels and storm-dominated marine environments above fair-weather wave-base; (5) lagoon with fluctuating low to moderate energy, salinity and rates of sedimentation; (6) storm-dominated shelf to lower shoreface.

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