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Ichnology of mixed siliciclastic-carbonate sedimentary cycles and their sequence stratigraphic context: Kaladongar Formation (Middle Jurassic) of Kachchh, western India

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Key words: sequence stratigraphy, mixed siliciclastic-carbonates, ichnology, Kachchh Basin, western India.

Abstract. The Middle Jurassic Kaladongar Formation, Patcham Island, Kachchh, western India, comprises of a 353 m-thick mixed siliciclastic-carbonate succession of asymmetrical shallowing and deepening upward sedimentary cycles. It is subdivided into five main facies *i.e.*, micritic sandstone, allochemic sandstone, sandy allochem limestone, micritic mudrock, and sandy micrite along with shales and conglomerates. Eight trace fossil assemblages comprising 34 ichnogenera are defined, including the *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites–Palaeophycus*, *Phycodes*, *Ophiomorpha*, and *Skolithos* assemblages that reflect five depositional facies: offshore, transitional, lower, middle, and upper shoreface. The sedimentary packages and associated trace fossil assemblages are separated by various discontinuities, stratigraphic surfaces and stratigraphic boundaries within the succession of the Kaladongar Formation and reveal three phases of regression (RST-I, RST-II and RST-III) and three phases of transgression (TST-II, III and IV) within the 3rd order systems tracts developed in the slowly transgressing sea during the Bajocian-Bathonian time interval.

INTRODUCTION

Trace fossils are considered as a useful tool to delineate various stratigraphic surfaces and to demarcate stratigraphic boundaries related to sequence stratigraphy (*e.g*., Pemberton, MacEachern, 1995). Various workers have investigated parts of the Jurassic succession of Kachchh with respect to ichnology (Howard, Singh, 1985; Shringarpure, 1986; Ghare, Kulkarni, 1986, Kulkarni, Ghare, 1989, 1991; Fürsich, 1998; Patel *et al*., 2008, 2009, 2014; Joseph *et al*., 2012a), but only a few sequence stratigraphic studies related to trace fossils (Patel *et al*., 2010; Patel, Joseph, 2012; Bhatt *et al*., 2012) and shell concentrations (Fürsich, Pandey, 2003) have been carried out.

Subsidence of the tectonically active rift basin provided sufficient space for the accommodation of the sediments (Biswas, 1982). The predominance siliciclastic Kaladongar Formation was formed in tidally influenced open marine environments, repeatedly interrupted by further siliciclastic input observed lithostratigraphically (*e.g.*, Biswas, 1980; Fürsich *et al*., 1994, 2001). Non-marine beds have been reported at the margins of Khadir island, Bela island (Mouwana dome) and possibly in Patcham island below the *Leptosphinctes* pebbly rudstone bed (Fürsich *et al*., 2001, 2004); however such beds not have been observed at the equivalent stratigraphic level in the present Patcham island sections. The purpose of this paper is to demonstrate the presence of 3rd order transgressive–regressive cycles in the northern part of the Kachchh Basin by integrating sedimentological and ichnological data, leading to a better understanding of the genetic sequences.

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LOCATION AND GEOLOGICAL SETTING

The Kachchh Basin, situated at the western margin of the Indian plate (Biswas, 1987) opened westwards towards the so-called Malagassy Gulf, which was a southern extension of the Tethyan Ocean (Fürsich *et al*., 2004) during the Jurassic. The sea inundated the Kachchh Basin during the Early Jurassic and receded during the Early Cretaceous when the basin became filled with sediments. Probably during the Late Cretaceous, the Mesozoic sediments of the Kachchh Basin were uplifted and exposed as six major uplifts (Kachchh Mainland, Wagad, Patcham, Khadir, Bela and Chorar) (Biswas, 1980).

The present study is focused on the Bajocian-Bathonian succession which is exposed in Patcham island, the westernmost island of the island belt in the Great Rann of Kachchh, which forms the northern part of the Kachchh Basin (Fig. 1) and is bounded sharply by the Kaladongar and Goradongar faults (from the north and the south, respectively) (Biswas, 1980). These marginal hills are faulted and folded forming asymmetrical anticlines and domes.

The Kaladongar Formation of Patcham island is the oldest exposed rock unit of the Kachchh Basin and comprises mixed siliciclastic-carbonate sediments and, at certain levels, is highly fossiliferous and bioturbated (Joseph *et al*., 2012a; Patel *et al*., 2010). As exposed at Kaladongar Hill,

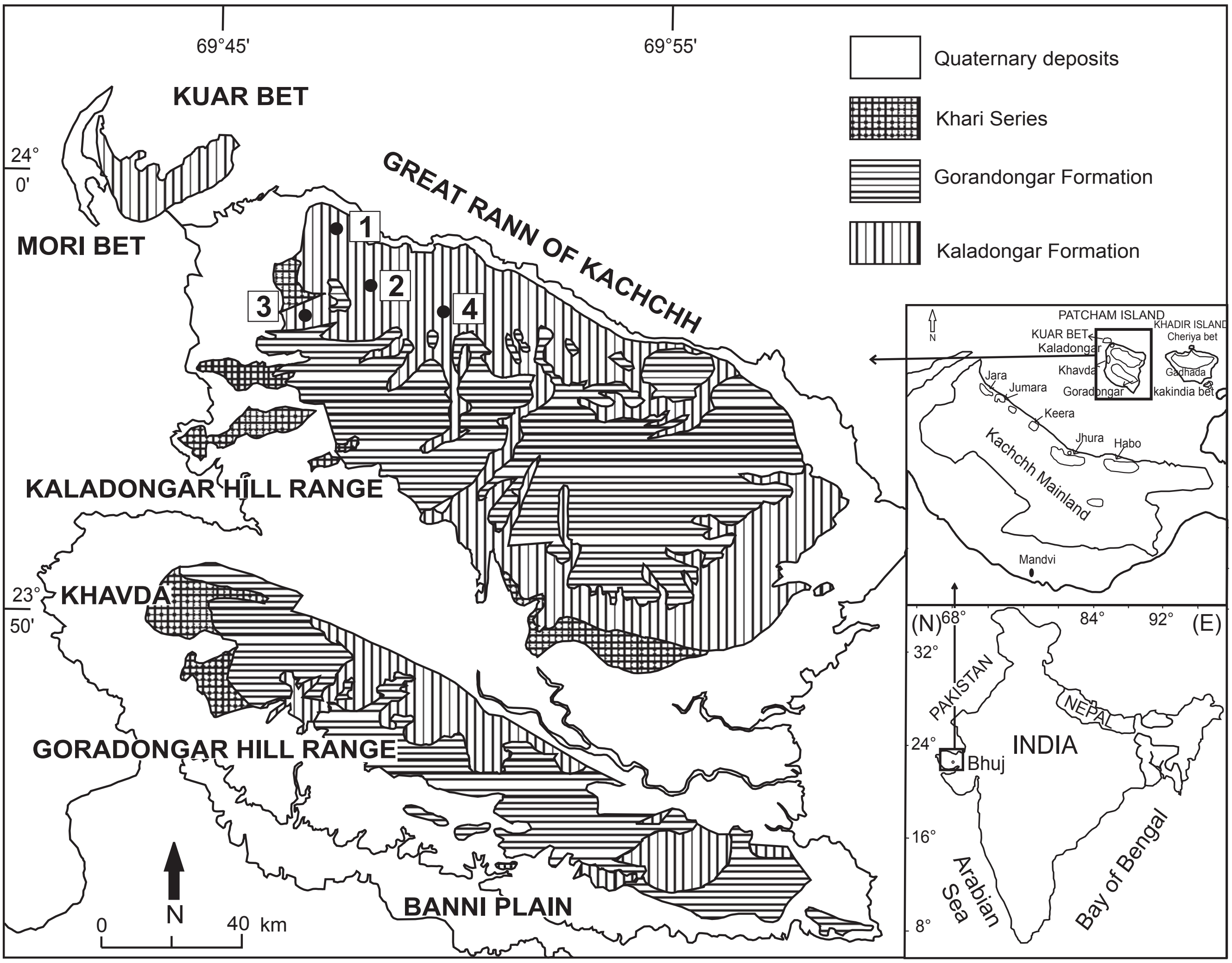


Fig. 1. Geological map of Patcham island; modified after Biswas (1992)

1 – Chhappar Bet, 2 – Dingy Hills, 3 – Kuran village, 4 – Babia Peak

the Kaladongar Formation comprises 353 m of strata and is subdivided into the Dingy Hill /Kuar Bet, Kaladongar Sandstone, and Babia Cliff Sandstone members (Biswas, 1980). The Kuar Bet Member of Kuar Bet, consists of rocks stratigraphically coeval to the Dingy Hill Member of Kaladongar, and contains dinosaur remains (Ghevariya, Srikarni, 1994; Satyanarayana *et al*., 1999; Jana, Das 2002) along with molluscan, corals, and plant fossils (Patel *et al*., 2010; Joseph *et al.*, 2012 a, b). The stratigraphic sequence of Dingy Hill Member shows intercalated sandstone-shale sequences while the Kaladongar Sandstone Member chiefly consists of various types of mixed siliciclastic-carbonate sediments with thin shale layers (Joseph *et al*., 2012 b). The Babia Cliff Sandstone Member resembles the underlying Kaladongar Sandstone Member but can still be differentiated by the presence of a thin bed of olive green bed overlain by thin grey, hard calcareous siltstone band (Biswas, 1980). Kaladongar Hill also exposes the younger Goradongar Formation which conformably overlies the Kaladongar Formation and is bordered by Miocene sediments (Biswas, 1980) to the west (Fig. 1).

The present study maps and illustrates the different parts of the depositional system, to visualize the accommodation space available and to document the sea-level dynamics of the Kaladongar Formation during the Bajocian-Bathonian time.

METHODS

Stratigraphic sections were studied at four localities on the Patcham island, namely Chhappar Bet, Dingy Hills, Kuran village, and Babia cliff. Representative samples were collected, and the lateral as well as vertical continuity noted, with the type of contacts, and the identification and photography of the associated physical and biogenic structures. Based on conventional facies analysis of the outcrops, as well as on quantitative analysis under the microscope, the mixed siliciclastic-carbonate sediments have been subdivided into different facies associations (Joseph *et al*., 2012b) according to the classification scheme of Mount (1985), subsequently used by Zonneveld *et al.* (2001), McNeill *et al.* (2004), Ryan-Mishkin *et al.* (2009) and Flügel (2010). The sedimentary facies in three measured sections (Chhappar Bet, Dingy Hill, and Kaladongar Hill range) were correlated and grouped into depositional environments. Ichnological observations focused on the density, diversity, and distribution of ichnogenera and on ichnoassemblages. The trace fossil assemblages within the sedimentary cycles were further analyzed to reconstruct the sequence stratigraphic framework.

ICHNOLOGY

The open marine mixed siliciclastic-carbonate deposits of the Kaladongar Formation are, at certain levels, highly bioturbated and contain abundant distinct and indistinct trace fossils. Many of the ichnogenera re-occur (or just occur) in more than one sedimentary/depositional facies (Fig. 2). In total, 34 ichnogenera were identified, and their ethological category, feeding mode and probable producers are summarized in Table 1. The detailed taxonomy of these ichnogenera and the ichnoassemblages, and ichnofacies have been documented by Patel *et al*. (2010) and Joseph *et al*. (2012a).

Eight ichnoassemblages were identified and named after the dominant ichnofossils, *i.e*., the *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites–Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages, which recur throughout the Kaladongar Formation and are a powerful tool for recognizing various aspects of the palaeoenvironment and its biota as well as for recognizing stratigraphic surfaces. The stratigraphic distribution, characteristic trace fossils and palaeoecological interpretations of the ichnoassemblages are summarized in Table 2.

DEPOSITIONAL FACIES

The structural and textural assessment of the mixed siliciclastic-carbonate sediments of the Kaladongar Formation along with their associated trace fossils indicates a wide range of depositional facies belts including offshore, offshore-shoreface transitional, upper, middle and lower shoreface (Fig. 3). These depositional facies consist of seven recurring sedimentary facies; five mixed siliciclastic-carbonate sediment facies including micritic sandstone, allochemic sandstone, sandy allochem limestone, micritic mudrock, and sandy micrite and argillaceous/calcareous shale and intraformational conglomerate facies. The depositional facies are described in a seaward to landward order within the shallow, open marine environments (Table 3).

Offshore facies. The calcareous shale, characterized by the *Planolites–Palaeophycus* and *Rhizocorallium* assemblages, indicates slow accumulation of fine siliciclastic sediments and micrite in protected deeper water facies intermittently experiencing moderate energy conditions and relatively fully marine salinity. This fine-grained micritic material deposited in either calm or very low energy conditions has allowed deposit-feeders to feed on the organic matter in the sediments, but intermittent vertical burrows of *Diplocraterion* and *Arenicolites* indicate temporary changes in the mode of life of organisms due to storm action.

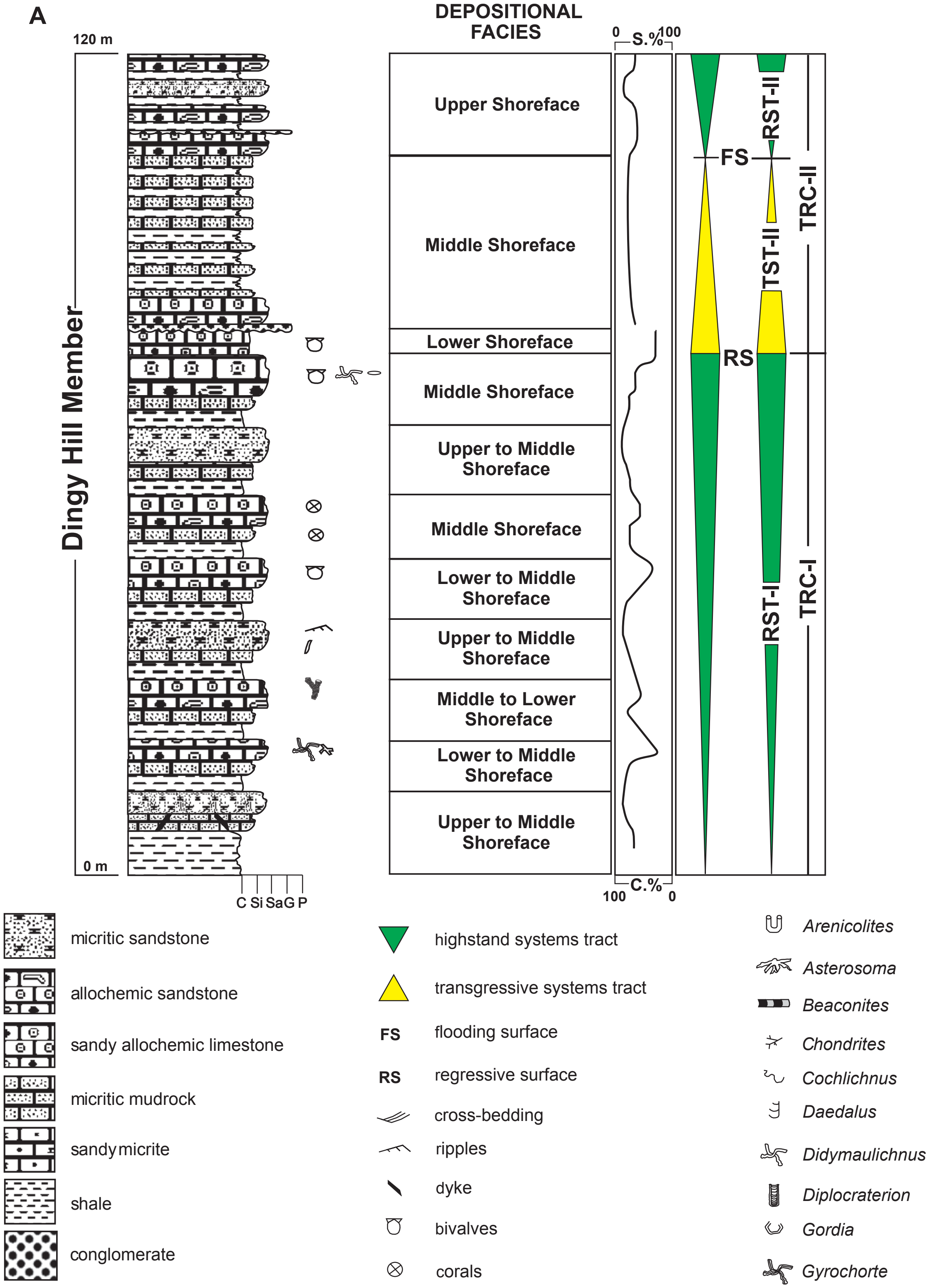
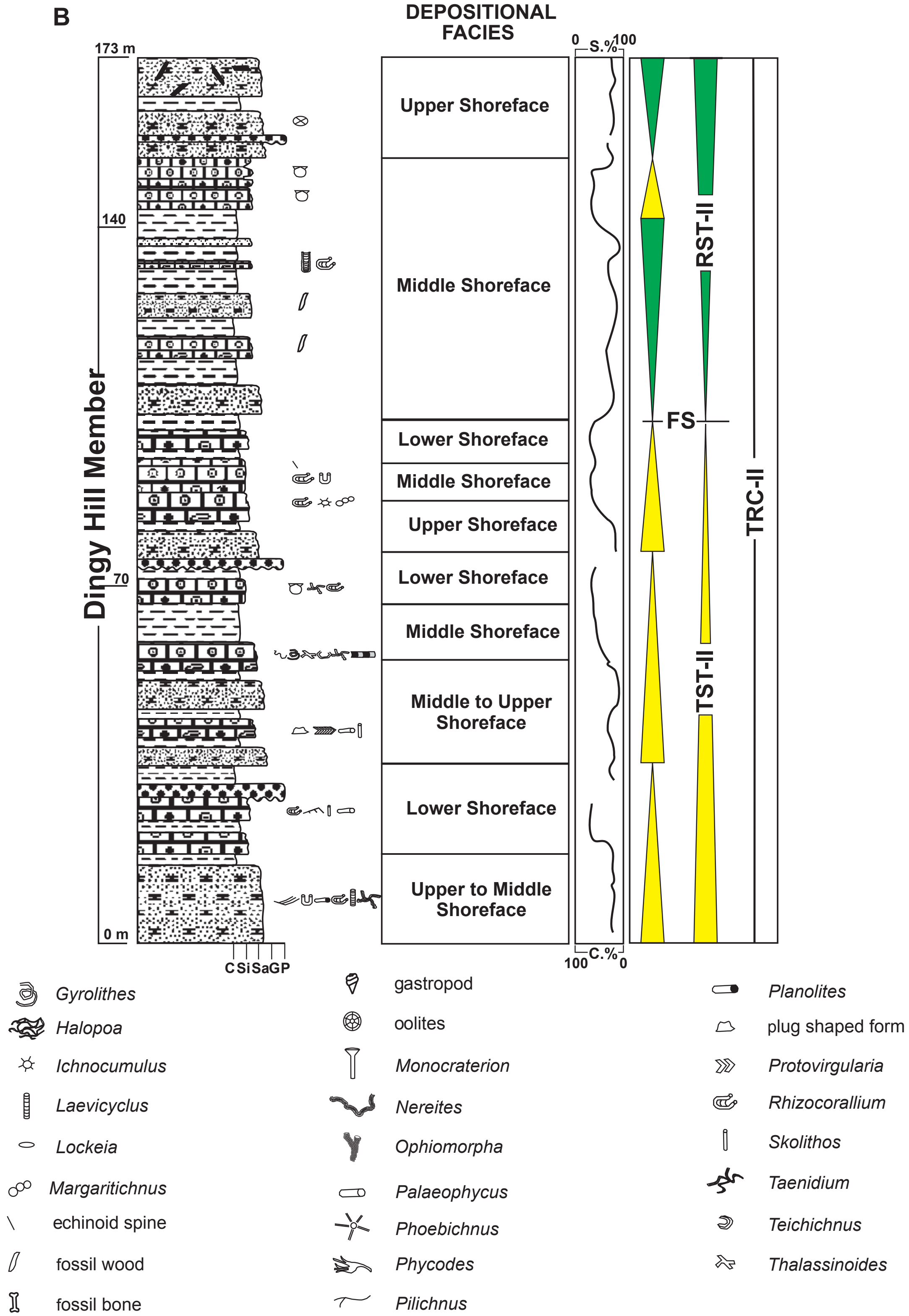


Fig. 2. Lithology and sequence stratigraphy

A – Chhappar Bet, B – Dingy Hills, C – Kaladongar Hill range;



of the Kaladongar Formation in the study area

S% = % of siliciclastics

Fig. 2 cont.

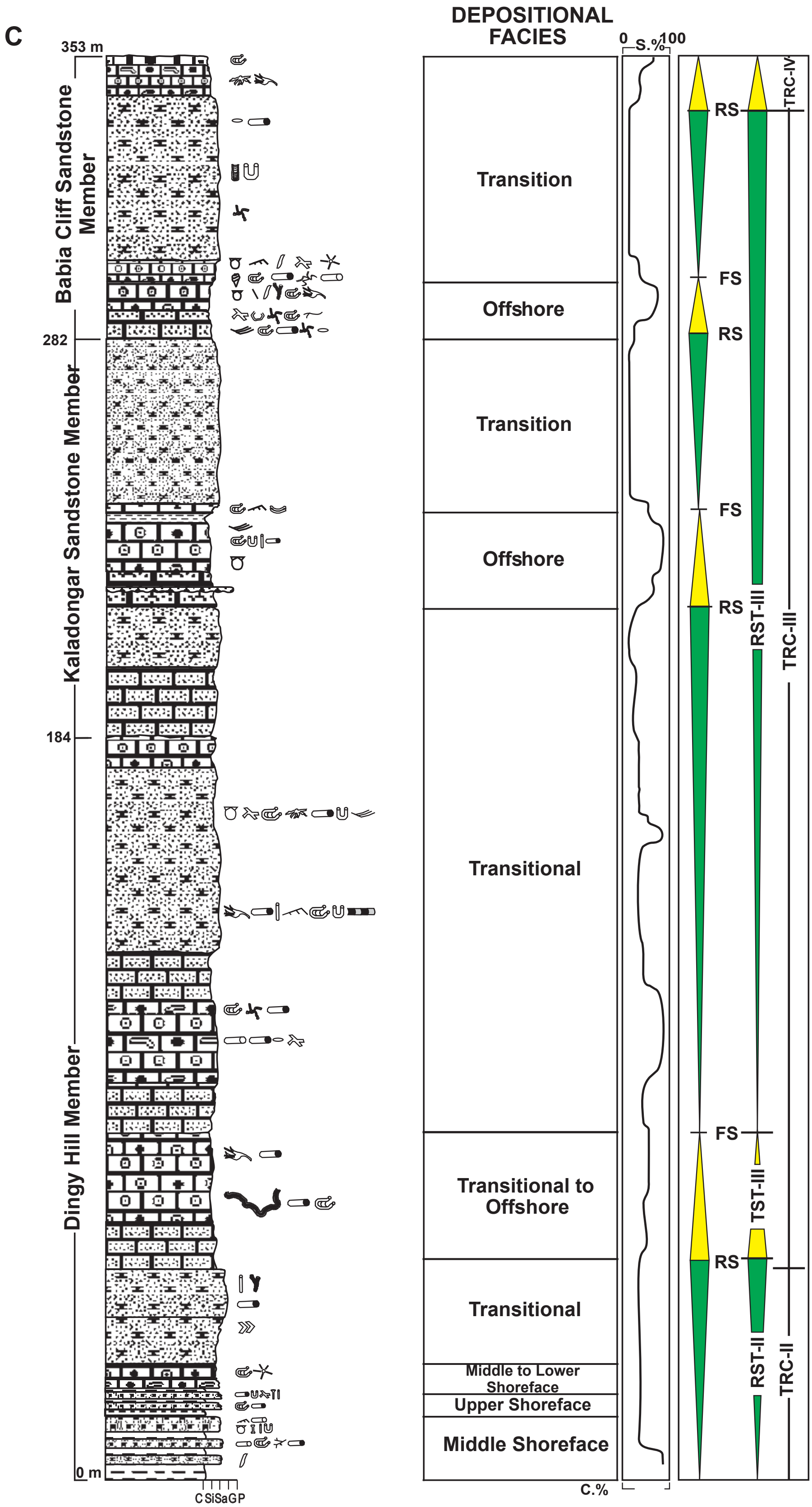

C
353 m
282
184
0 m
Babia Cliff Sandstone Member
Kaladongar Sandstone Member
Dingy Hill Member
C Si Sa G P
DEPOSITIONAL FACIES
Transition
Offshore
Transition
Offshore
Transitional
Transitional to Offshore
Transitional
Middle to Lower Shoreface
Upper Shoreface
Middle Shoreface
0 S.% 100
C.%
RS
FS
RS
FS
RS
FS
RS
TRC-IV
RST-III
TRC-III
TST-III
RST-II
TRC-II

Table 1

Ethology, feeding behavior and possible producers of the trace fossils from Middle Jurassic rocks of the Kaladongar Formation of the Patcham Island

Ichnogenera	Ethology	Feeding behavior	Possible producer
Arenicolites	Domichnia	Suspension-feeder	Polychaetes
Asterosoma	Fodinichnia	Deposit-feeder	Crustaceans
Beaconites	Pascichnia/repichnia	Deposit-feeder	Arthropods
Bergaueria	Cubichnial/domichnia	Suspension feeder	Coelenterates
Chondrites	Fodinichnia	Chemichnia	Sipunculids, polychaetes
Cochlichnus	Pascichnia/repichnia	Deposit-feeder	Annelids, nematodes
Daedalus	Fodinichnia	Deposit-feeder	Arthropods
Didymaulichnus	Repichnia	Deposit-feeder	Mollusca
Diplocraterion	Domichnia	Suspension-feeder	Annelids, crustaceans
Gordia	Fodinichnia	Deposit-feeder	Worm-like animals
Gyrochorte	Pascichnia/repichnia	Deposit-feeder, scavengers, carnivores	Arthropods
Gyrolithes	Domichnia/fodinichnia	Deposit-feeder	Crustaceans
Ichnocumulus	Cubichnia	?	?
Laevicyclus	Domichnia	Suspension-feeder	Annelids
Lockeia	Cubichnia	?	Infaunal bivalves
Margaritichnus	-	Deposit-feeder	Worm-like animals
Monocraterion	Domichnia	Suspension-feeder	Worm-like animals
Nereites	Pascichnia	Deposit-feeder	Worm-like animals, ?phoronids
Ophiomorpha	Domichnia/fodinichnia	Deposit-, suspension-feeder, scavenger, predator	Crustacean-shrimp
Palaeophycus	Domichnia/?fodinichnia	Deposit-, suspension-feeder, predator	Polychaetes
Phoebichnus	Domichnia/?fodinichnia	Deposit-feeder	?
Phycodes	Fodinichnia	Deposit-feeder	Annelids
Pilichnus	Fodinichnia	Deposit-feeder	Polychaetes
Planolites	Fodinichnia/pascichnia	Deposit-feeder	Vermiform animals
Plug shaped form	Cubichnia	?	Infaunal bivalves or small ray
Protovirgularia	Fodinichnia	Deposit-feeder	Bivalves, annelids
Rhizocorallium	Fodinichnia/pascichnia	Deposit-feeder	Vermiform animals
Scolicia	Pascichnia	Deposit-feeder	Echinoides
Skolithos	Domichnia	Suspension-feeder	Polychaetes, annelid or phoronids
Taenidium	Pascichnia	Deposit-feeder	Worm-like animals
Teichichnus	Fodinichnia	Deposit-feeder	Polychaetes
Thalassinoides	Domichnia/fodinichnia	Deposit-, suspension-feeder, scavenger, predator	Crustaceans

Table 2

Characteristic trace fossils of different ichnoassemblage, their stratigraphic distribution, occurrence, and palaeoecological interpretation

Ichno-assemblage	Member-facies association	Characteristic trace fossils	Palaeoecology
Asterosoma assemblage	Dingy Hill Member – MS	*Asterosoma ludwigae*, *Phycodes* cf. *palmatum*, *Rhizocorallium irregulare*, *Thalassinoides suevicus*, *Beaconites coronus*, *Cochlichnus anguineus*, *Phycodes circinnatum*, *Thalassinoides horizontalis*	Deposit feeders mainly crustaceans in low energy and stable substrate condition of the upper offshore to transition zone
	Babia Cliff Sandstone Member – AS	*Asterosoma ludwigae*, *Phycodes* cf. *palmatum*	
Gyrochorte ssemblage	Dingy Hill Member – AS & SAL	*Gyrochorte comosa*, *Thalassinoides suevicus*, *Rhizocorallium irregulare*, *Planolites beverleyensis*, *Lockeia siliquaria*, *Palaeophycus tubularis*	Deposit as well as suspension feeders like crustacean and polychaetes in moderate-low energy conditions of transitional zone between offshore and the wave & storm influenced shoreface environment
	Babia Cliff Sandstone Member – MS & SAL	*Gyrochorte comosa*, *Thalassinoides suevicus*, *Rhizocorallium irregulare*, *Planolites beverleyensis*, *Lockeia siliquaria*, *Gordia arcuata*, *Pilichnus dichotomus*, *Arenicolites carbonarius*, *Diplocraterion parallelum*	
Rhizocorallium assemblage	Dingy Hill Member – MS, AS, & SAL	*Rhizocorallium irregulare*, *R. jenense*, *Planolites beverleyensis*, *Palaeophycus tubularis*, *P. annulatus*, *Gyrochorte comosa*, *Thalassinoides suevicus*, *T. horizontalis*, *Thalassinoides* isp., *Arenicolites carbonarius*, *Diplocraterion parallelum*, *Laevicyclus* isp., *Chondrites targonii*, *C. intricatus*, *Phoebichnus trochoides*, *Beaconites coronus*, *Cochlichnus anguineus*, *Asterosoma ludwigae*, *Skolithos linearis*, *Phycodes circinnatum*, *P.* cf. *palmatum*, *Ichnocumulus* isp., *Margaritichnus* isp., *Lockeia siliquaria.*	Deposit feeders and mobile voracious such as crustaceans in low energy condition of offshore to shoreface environment.
	Kaladongar Sandstone Member – SAL & SM	*Rhizocorallium irregulare*, *R. jenense*, *Planolites beverleyensis*, *Arenicolites carbonarius*, *Skolithos linearis*, *Teichichnus rectus*	
	Babia Cliff Sandstone Member – AS & SAL	*Rhizocorallium irregulare*, *Planolites beverleyensis*, *Gyrochorte comosa*, *Thalassinoides suevicus*, *Phoebichnus trochoides*, *Phycodes* cf. *palmatum*, *Palaeophycus striatus*, *Gordia arcuata*, *Pilichnus dichotomus*, *Ophiomorpha nodosa*, *Taenidium serpentinum*	
Thalassinoides assemblage	Dingy Hill Member – MS, AS, & SAL	*Thalassinoides suevicus*, *T. horizontalis*, *Thalassinoides* isp., *Gyrochorte comosa*, *Rhizocorallium irregulare*, *Planolites beverleyensis*, *Palaeophycus tubularis*, *Gordia arcuata*, *Gyrolithe* isp., *Beaconites coronus*, *Lockeia siliquaria*, *Phycodes* cf. *palmatum*, *Phycodes circinnatum*, *Cochlichnus anguineus*, *Asterosoma ludwigae*	Deposit as well as the suspension feeders like crustaceans and polychaetes in low to moderate energy conditions and unstable, soft, unconsolidated substrate of the shoreface environment
	Babia Cliff Sandstone Member – AS & SAL	*Thalassinoides suevicus*, *Gyrochorte comosa*, *Rhizocorallium irregulare*, *Planolites beverleyensis*, *Gordia arcuata*, *Phycodes* cf. *palmatum*, *Ophiomorpha nodosa*, *Palaeophycus striatus*, *Taenidium serpentinum*, *Pilichnus dichotomus*, *Phoebichnus trochoides*	
Planolites–*Palaeophycus* assemblage	Dingy Hill Member – MS, AS & SAL	*Palaeophycus tubularis*, *P. annulatus*, *Planolites beverleyensis*, *Rhizocorallium irregulare*, *Thalassinoides suevicus*, *Lockeia siliquaria*, *Gyrochorte comosa*, *Laevicyclus* isp., *Chondrites targionii*, *C. intricatus*, *Monocraterion tentaculatum*, *Ophiomorpha nodosa*, *Protovirgularia* isp., *Plug shaped form*, *Arenicolites carbonarius*, *Skolithos linearis*	Deposit as well as the suspension feeder like crustaceans and polychaetes in low energy transitional zone to lower shoreface environment
	Kaladongar Sandstone Member – SAL	*Planolites beverleyensis*, *Rhizocorallium irregulare*, *Arenicolites carbonarius*, *Skolithos linearis*	
	Babia Cliff Sandstone Member – MS, AS & MMu	*Planolites beverleyensis*, *Palaeophycus striatus*, *Rhizocorallium irregulare*, *Thalassinoides suevicus*, *Lockeia siliquaria*, *Diplocraterion parallelum*, *Gyrochorte comosa*, *Arenicolites carbonarius*, *Taenidium serpentinum*, *Phoebichnus trochoides*	

Table 2 cont.

Ichno-assemblage	Member-facies association	Characteristic trace fossils	Palaeoecology
Phycodes assemblage	Dingy Hill Member – MS	*Phycodes* cf. *palmatum*, *Phycodes circinnatum*, *Rhizocorallium irregulare*, *Asterosoma ludwigae*, *Beaconites coronus*, *Cochlichnus anguineus*, *Thalassinoides suevicus*	Dominance of deposit feeders like vermiform annelids and crustaceans in low energy conditions of the offshore to transition-shoreface environment
	Babia Cliff Sandstone Member – AS & SAL	*Phycodes* cf. *palmatum*, *Rhizocorallium irregulare*, *Asterosoma ludwigae*, *Asterosoma radiciforme*, *Ophiomorpha nodosa*, *Gordia arcuata*, *Gyrochorte comosa*, *Pilichnus dichotomus*, *Thalassinoides suevicus*	
Ophiomorpha assemblage	Dingy Hill Member – MS& AS	*Ophiomorpha nodosa*, *Planolites beverleyensis*, *Skolithos linearis*, *Protovirgularia dichotoma*	Opportunistic like decapods crustaceans in high energy conditions of the middle-shoreface to foreshore environment
	Babia Cliff Sandstone Member – SAL	*Ophiomorpha nodosa*, *Gyrochorte comosa*, *Rhizocorallium irregulare*, *Thalassinoides suevicus*, *Gordia arcuata*, *Pilichnus dichotomus*, *Phycodes* cf. *palmatum*	
Skolithos assemblage	Dingy Hill Member – MS & SAL	*Skolithos linearis*, *Rhizocorallium irregulare*, *Arenicolites carbonarius*, *Monocraterion tentaculatum*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Ophiomorpha nodosa*, *Protovirgularia dichotoma*, *Thalassinoides suevicus*	Suspension as well as the deposit feeders like vermiform annelids in high energy conditions of tide influenced shoreface-foreshore environment
	Kaladongar Sandstone Member – SAL	*Skolithos linearis*, *Rhizocorallium irregulare*, *Planolites beverleyensis*, *Arenicolites carbonarius*	

MS – micritic sandstone, AS – allochemic sandstone, SAL – sandy allochem limestone, SM – sandy micrite, MMu – micritic mudrock

The presence of the *Rhizocorallium*, *Gyrochorte*, and *Planolites–Palaeophycus* assemblages (Pl. 1: 1) indicates the presence of deposit feeding organisms in calm and soft substrate conditions (MacEachern, Pemberton, 1992) and comprises the *Cruziana* ichnofacies. The geometry and contacts of beds, their structural variability and the sedimentary characteristics of the facies associations suggest deposits in the offshore region and the waning flow deposits of storm-generated currents in an open marine environment below storm wave base.

Offshore-shoreface transition facies. The presence of highly diverse ichnoassemblages (Pl. 1: 2, Pl. 1: 3; Table 3) and of soft substrate conditions indicates deposition of sediments under low-energy conditions in the offshore-transitional zone between the fair-weather wave-base and the storm wave-base (Cantalamessa, Celma, 2004) with the fine to medium quartz grains intermixed with carbonate sediments. The presence of physical sedimentary structures (such as cross-bedding) in the thick micritic sandstones suggests shallowing. The characteristic feature of the cross bedded sandstone with an erosional base seems to be similar to the channel bed deposits of Fürsich *et al* (2004). However, they are calcareous in nature and show the presence of abundant horizontal traces.

Lower Shoreface Facies. This contain fodinichnia-dominanted ichnoassemblages such as *Gyrochorte* (Gibert, Benner, 2002), *Thalassinoides*, *Rhizocorallium* and *Planolites–Palaeophycus* (Pl. 1: 4) which suggest low energy conditions and organic-rich soft substrates. However, the incursion of the *Skolithos* assemblage may indicate shallow and highly agitated water indicating a temporary increase in energy gradients in the lower shoreface zone (Allington-Jones *et al*., 2010). Intense bioturbation and the appreciable amount of siliciclastic-bioclastic material suggest that deposition took place above the offshore transition facies, but still in the lower shoreface below the fair-weather wave-base, with some temporary waning of oscillatory waves evidenced by ripple surfaces, small-scale cross-stratification and the ichnogenus *Skolithos*.

Middle shoreface facies. The high percentage of quartz grains, and the presence of algae and ooids in a micritic matrix suggests an agitated water environment (Plumley *et al.*, 1962; Flügel, 2010), and the succession of planar laminated, cross-stratified and wave-rippled sediments, indicates a wave-dominated setting. The presence of trace fossils such as *Ophiomorpha*, *Skolithos*, *Arenicolites*, *Phycodes* (Pl. 1: 5) along with physical sedimentary structures in the allochemic sandstone reflect the mixed

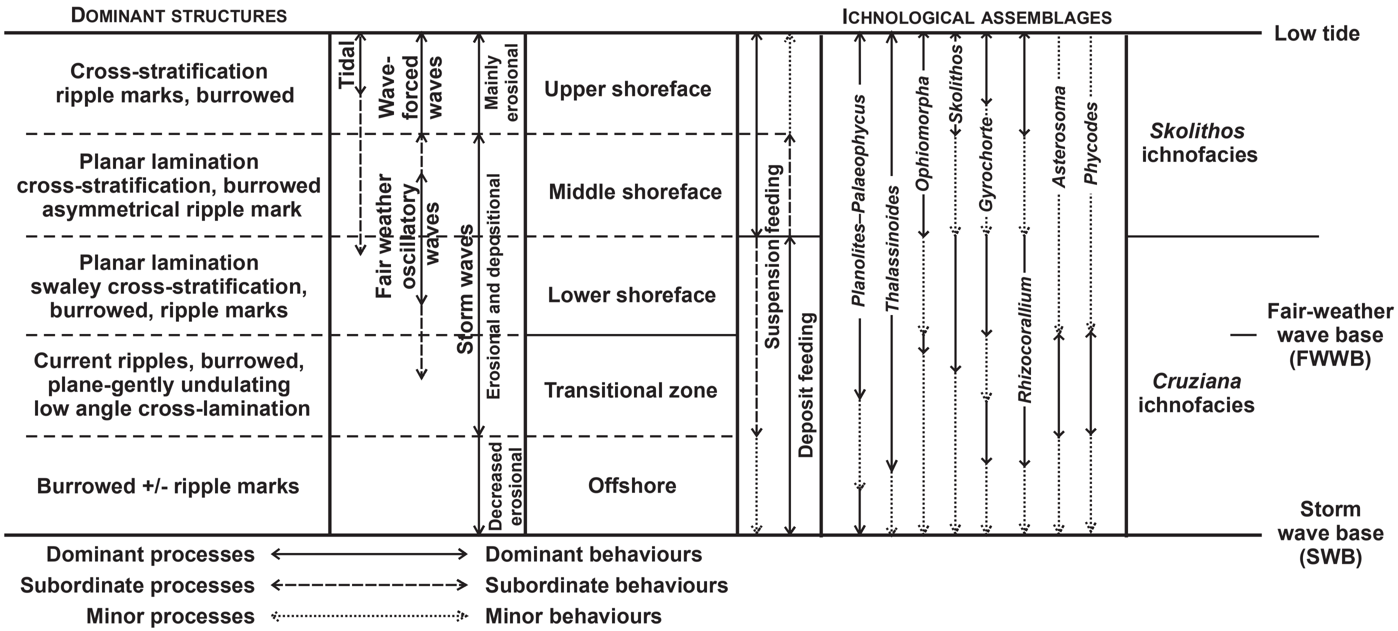


Fig. 3. An ichnological-sedimentological model for the Middle Jurassic (Bajocian–Bathonian) mixed siliciclastic-carbonate shoreface deposits of Kaladongar Formation, Patcham Island (modified after MacEachern *et al.*, 1999)

Table 3

Summary of the facies associations

Facies	Constituents	Structures	Trace fossils	Interpretation
Offshore Facies Association				
Muddy Micrite (MuM)	High percent of micritic material over the silt; very fine grained, hard & massive rock, devoid of sedimentary structures & body fossils	–	–	Lower offshore region; no tidal or current influence
Sandy Micrite (SM)	Proportion of micrite higher than the siliciclastic grains	Planar laminations, ripple marks locally	*Rhizocorallium*, *Teichichnus*	Intermittent to moderate energy offshore region
Micritic Mudrock (MMu)	Proportion of well sorted, silt grains higher than micrite	Planar laminations, small scale cross-beddings	*Lockeia*, *Didymaulichnus*, *Planolites*, *Gyrochorte*, *Diplocraterion*, *Arenicolites*	Low energy condition of the lower offshore region
Sandy Allochemic Limestone (SAL)	Proportion of carbonate higher than siliciclastic grains; oolites (radial-fibrous) and echinoid spines	Planar laminations and small scale cross-bedding, locally fossiliferous	*Nereites*, *Rhizocorallium*, *Arenicolites*, *Skolithos*, *Planolites*, *Thalassinoides*, *Gordia*, *Gyrochortes*, *Pilichnus*, *Ophiomorpha*, *Phycodes*	Moderate to low energy conditions of the deeper part of the transitional or offshore region
Calcareous Shale (CSh)	Dirty light yellow to dark yellow shale, frequently intercalated with mixed siliciclastic-carbonate sediments	Planar lamination	*Planolites*, *Rhizocorallium*	Intermittent moderate energy condition and normal salinity levels; lagoonal setting

Offshore Transitional Facies Association				
Micritic Mudrock (MMu)	Proportion of well sorted, silt grains higher than micrite	–	–	Low energy condition of the lower offshore transitional region
Sandy Allochemic Limestone (SAL)	Higher proportion of carbonate compared to siliciclastic grains; oolites (radial-fibrous) and echinoid spines	–	*Rhizocorallium*	Moderate to low energy conditions of the deeper part of the transition zone
Allochemic Sandstone (AS)	Proportion of well sorted, subangular to subrounded siliciclastics grains higher than carbonate; allochems (pellets & bioclasts) common	Ripple marks and locally fossiliferous (gastropods)	*Planolites*, *Palaeophycus*, *Lockeia*, *Thalassinoides*, *Rhizocorallium*, *Gyrochorte*, *Phoebichnus*, *Taenidium*, *Asterosoma*, *Phycodes*	Moderate energy conditions of offshore transitional environments
Micritic sandstone	Thick beds of moderately sorted and fine-grained sandstone; sand contains 60–65%, lower carbonate content	Low angle cross-bedding, ripple marks	*Planolites*, *Skolithos*, *Protovirgularia*, *Ophiomorpha*, *Phycodes*, *Beaconites*. *Rhizocorallium*, *Cochlichnus*, *Asterosoma*, *Thalassinoides*, *Gyrochorte*, *Diplocraterion*, *Arenicolites*, *Lockeia*	Moderate energy condition and stand still conditions of the shore line for a long duration with a continued supply of the sand
Lower Shoreface Facies Association				
Micritic Mudrock (MMu)	High percent of silt-sized quartz, micritic matrix; few oolites & algae	–	–	Low energy conditions of the lower shoreface region
Sandy Allochemic Limestone (SAL)	Poorly sorted angular to subrounded grains of quartz (25–30%) abundant biogenic structures; high fossil content	Planar lamination & small scale swaly cross-bedding, locally fossiliferous	*Rhizocorallium*, *Phoebichnus*, *Gyrochorte*, *Thalassinoides*, *Daedalus*, *Skolithos*, *Palaeophycus*, *Arenicolites*	Low to moderate energy conditions of the lower shoreface region
Middle Shoreface Facies Association				
Micritic mudrock (MMu)	Higher percentage of silt-sized quartz, micritic matrix; few oolites & algae	–	–	Low energy conditions of the middle shoreface region
Allochemic Sandstone (AS)	High percent of siliciclastic grains (65–70%) over the carbonate proportion; with appreciable bioclasts & pellets	Planar lamination, cross-bedding, linguoid ripple marks	*Ophiomorpha*, *Didymaulichnus*, *Lockeia*, *Margaritichnus*, *Ichnocumulus*, plug shaped form, *Rhizocorallium*, *Walcottia*, *Palaeophycus*, *Diplocraterion*	Moderate wave energy conditions of the middle shoreface zone
Micritic Sandstone (MS)	High proportion of siliciclastic grains (80–85%) very little of micritic material	Asymmetrical ripple, interference ripple mark, herringbone cross-stratification	*Palaeophycus*, *Planolites*, *Rhizocorallium*, *Chondrites*, *Arenicolites*, *Laevicyclus*, *Didymaulichnus*	High wave energy condition and winnowing activity of the foreshore region
Upper Shoreface Facies Association				
Allochemic Sandstone (AS)	Percentage of siliciclastic grains (65–70%) higher than carbonates; appreciable amount of bioclasts & pellets.	–	–	High wave energy conditions in the upper shoreface zone
Micritic Sandstone (MS)	High proportion of siliciclastic grains (80–85%); amount of micrite very low	Asymmetrical, interference ripples, herringbone cross-stratification	*Arenicolites*, *Thalassinoides*, *Monocraterion*, *Skolithos*	High wave energy condition and winnowing activity of the foreshore region
Intraformational Conglomerate (IC)	Different size of quartz grains, mud pebbles, embedded with broken shells & fossil wood	–	–	Storm condition of the shoreface region
Argillaceous-rich Shale (ASh)	Grey to dark grey fine-grained carbonaceous shale with layers of thinly laminated silt & clay; secondary gypsum	Planar lamination	–	Reducing environments of quiet water condition in protected lagoon

Skolithos-Cruziana ichnofacies (MacEachern, Pemberton 1992). It points to fluctuating energy conditions in a middle shoreface environment. The large thickness of allochemic sandstone beds and sub-angular to sub-rounded and moderately sorted grains reflect a continuous supply of siliciclastic sand and winnowing and grain attrition by wave action. Intercalation of argillaceous shale suggests intermittent quiet water conditions of a protected lagoon, behind the barrier, where fine-grained sediments slowly accreted.

Upper Shoreface Facies. The trace fossil associations of the allochemic sandstone of the upper shoreface facies belong to the *Ophiomorpha*, *Planolites–Palaeophycus* and *Thalassinoides* assemblages, which are related to Seilacher's (1967) Skolithos and proximal Cruziana ichnofacies (MacEachern, Pemberton 1992). Micritic sandstone characterized by the *Ophiomorpha*, *Thalassinoides*, *Planolites–Palaeophycus*, *Rhizocorallium*, *Gyrochorte* and *Skolithos* (Pl. 1: 6) assemblages reflect the proximal mixed Skolithos/ Cruziana ichnofacies that is indicative of fluctuating energy conditions of the upper shoreface environment. The thick allochemic sandstone (20 m) and micritic sandstone (45 m) of barrier bar origin also indicate a continued supply of sand. Thus, the physical and biogenic structures and the nature of the sediments indicate moderate to comparatively low energy conditions of the upper shoreface facies and the geometry and bed contacts suggest barrier bar deposits.

SEDIMENTARY CYCLES AND DEPOSITIONAL TRENDS

The arrangement of sedimentary facies and trace fossils represent a strongly asymmetrical, cyclic sedimentation patterns in the sequences of the Kaladongar Formation (Fig. 2). The stratigraphic surfaces and boundaries of the cycles are recognized by observing the textural and ichno-component variations in the sedimentary facies. The present study shows the presence of three asymmetrical deepening- and shallowing-upward transgressive-regressive sedimentary cycles. These consist of two types of systems tracts: regressive systems tracts (RST-I, II and III) and transgressive systems tracts (TST-II, III and IV), bracketed by sequence boundaries. Lowstand systems tract deposits occur as reworked relicts within the transgressive deposits (Fürsich *et al*., 2001). Each of these systems tracts shows different trace fossil associations and reveals an ethologically diverse group of trace fossils (Fig. 4).

TRANSGRESSIVE-REGRESSIVE CYCLE-I

The TST deposits of the T-R cycle-I are not observed in the sequence, which may be either due to the erosion of the thin transgressive bed, or may be undifferentiated from the observed RST-I or present in the subsurface

Regressive System Tract (RST)-I: This is characterized by coarsening and shallowing upward sedimentary cycles, consisting of the mixed siliciclastic-carbonate sequence of the lower 77 m of Dingy Hill Member exposed at Chhappar Bet. These sediments contain trace fossils such as *Gyrochorte*, *Lockeia*, *Ophiomorpha* and *Thalassinoides* which belong to the *Gyrochorte*, *Ophiomorpha* and *Thalassinoides* assemblages representing, fodinichnia/domichnia/repichnia/pascichnia/cubichnia (Fig. 4). The top of the systems tract is capped by a regressive surface.

TRANSGRESSIVE REGRESSIVE CYCLE-II

Transgressive Systems Tract (TST)-II: This is characterized by the lower +98 m thick succession of the Dingy Hill Member at Dingy Hill and middle 28.6 m sequence of Dingy Hill Member exposed at the Chhappar Bet (Fig. 2A). Trace fossils such as *Arenicolites*, *Beaconites*, *Didymaulichnus*, *Gordia*, *Gyrolithes*, *Gyrochorte*, *Ichnocumulus*, *Laevicyclus*, *Margaritichnus*, *Palaeophycus*, *Protovirgularia*, *Skolithos* and *Thalassinoides* are observed in the Dingy Hill. The sediments represent a retrograding deposit within which, intermittently, aggradation is also observed which may represent the end phase of transgression.The top of the transgressive systems tract represents the maximum flooding surface and the end of the transgression. The trace fossils show fodinichnia/ domichnia/ pasicichnia/ repichnia/ cubichnia represented in descending order of their abundance. The *Gyrochorte*, *Planolites–Palaeophycus*, *Rhizocorallium*, *Skolithos* and *Thalassinoides* assemblages occur in this systems tract. The TST-II displays many minor regressions and transgressions within the retrograding deposits and shows variability in facies at different localities but the top of the sequence is marked by a flooding surface

Regressive Systems Tract (RST)-II: RST-II is represented by the mixed siliciclastic-carbonate sediments observed in the Dingy Hill Member at Chhappar Bet (~24.4 m), upper 75 m of the Dingy Hill Member at Dingy Hill and the lower 53 m at the Kaladongar Hill range. Trace fossils such as *Arenicolites*, *Chondrites*, *Diplocraterion*, *Monocraterion*, *Planolites*, *Palaeophycus*, *Phoebichnus*, *Protovirgularia*, *Rhizocorallium*, *Skolithos*, which belong to *Planolites–*

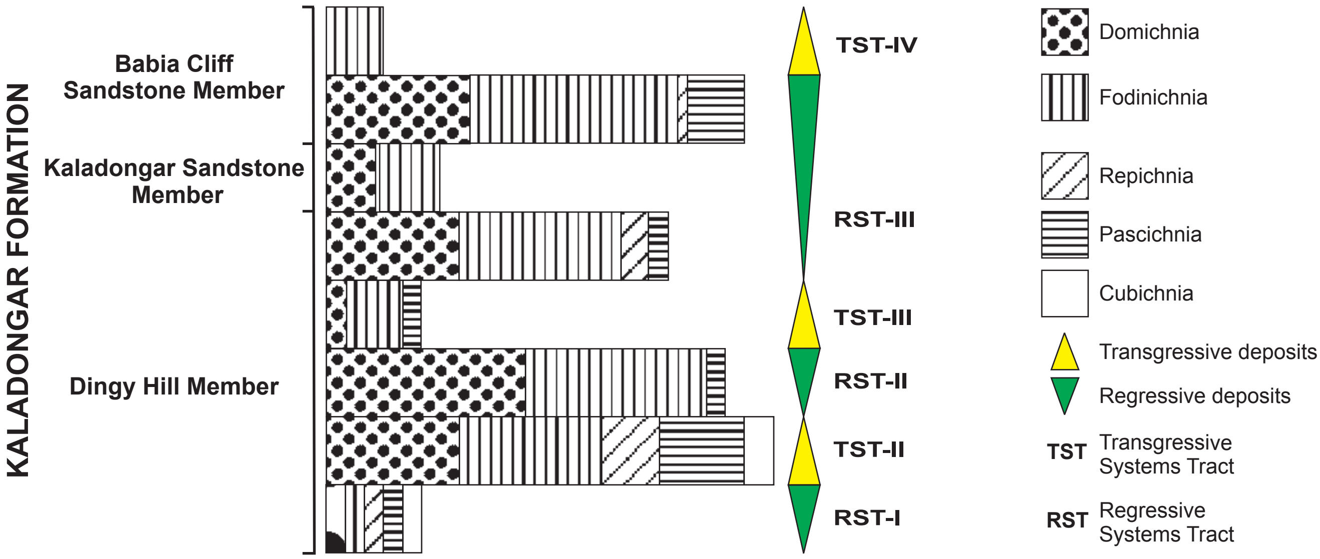


Fig. 4. Trace fossil diversity and ethological abundance in the systems tract deposits

Palaeophycus, *Rhizocorallium*, *Skolithos* assemblages are observed. These show Dominichnia/Fodinichnia/Pasichnia in descending order of their abundance. The presence of monodominant chemichnian burrows of *Chondrites targionii* and *C. intricatus* suggests extremely low oxygen levels in the interstitial and bottom waters (Seilacher, 2007). However, successive increase in ichnofaunal diversity and the abundant presence of *Chondrites*, *Planolites* and *Arenicolites*, *Monocraterion*, *Skolithos*, *Thalassinoides* indicate a change from poor to well oxygenated water (Mieras *et al*., 1993), and a relative increase in the water energy of the shoreface region. The overlying middle-lower shoreface to transitional zone contains horizontal traces which indicate nutrient-rich retrograding-aggrading sediments. The dominant aggradational stacking pattern within prograding sediments observed towards the end of progradation may be suggestive of the late regressive phase of the sediments.

TRANSGRESSIVE REGRESSIVE CYCLE-III

Transgressive systems tract (TST-III): TST- III is characterized by the and 33.7 m-thick deepening and fining upward mixed siliciclastic-carbonate sequence of Dingy Hill Member exposed at the Kaladongar Hill (Fig. 2C). In the Kaladongar Formation, the trace fossil suite is dominated by fodinichnia/domichnia–pascichnia (in decreasing order of abundance) but a diminutive and sporadically distributed mixture of structures, produced by grazing/foraging and deposit-feeding behaviour of the *Rhizocorallium* and *Nereites* produce representing a stressed distal Cruziana ichnofacies indicate fully marine condition with persistent environmental fluctuations. This sequence represents retrograding deposits capped by the sequence containing the distal Cruziana ichnofacies intercalated with the micritic mudrock facies that represent the flooding surface. This upward transition from shallow to deeper water deposits may be reflecting a relative “slow” sea-level rise.

Regressive systems tract (RST-III): This regressive systems tract is characterized by sediments comprising the Dingy Hill Member, Kaladongar Sandstone Member, and Babia Cliff Sandstone Member exposed at the Kaladongar Hill (~308.35 m). These contain abundant trace fossils including *Planolites*, *Palaeophycus*, *Lockeia*, *Thalassinoides*, *Rhizocorallium*, *Gyrochorte*, *Phycodes*, *Beaconites*, *Cochlichnus*, *Asterosoma*, *Arenicolites*, *Skolithos*, *Didymaulichnus*, *Gordia*, *Pilichnus*, *Ophiomorpha*, *Taenidium*, *Phoebichnus* and *Diplocraterion.* Cross-bedding and ripple marks are observed locally in the Dingy Hill Member and Babia Cliff Sandstone Member. Bivalve shells are also observed locally in the Dingy Hill Member and Kaladongar Sandstone Member while bivalves, gastropods and echinoids (locally) are observed in the Babia Cliff Sandstone member.

The beginning of the regressive phase shows continuous aggradation with an improved oxygenation in prograding shoal deposits from the offshore transitional zone showing fodinichnia- domichnia- pascichnia in descending order of their dominance. During late regression, the dominance changes to fodinichnia-domichnia-repichnia. Slipper- shaped oblique forms and U-shaped burrows up to 70 cm long commonly developed as spiral and lobate forms which are the phenotypic differentiation (behavioural modification) of *Rhizocorallium*, that is considered to be caused directly by differences in the substrate tiering and cohesion as well as by resource availability and patchiness (Seilacher, 2007). The sequential trace fossils and their related sediments suggest offshore shoal deposits.

Moreover, the co-occurrence of *Ophiomorpha* with long u-shaped *Rhizocorallium* and *Phycodes* suggests fluctuation in the energy conditions. The presence of trace fossils such as *Arenicolites* and *Diplocraterion* suggest high energy conditions (Fürsich, 1974, 1981), whereas the presence of *Asterosoma*, *Palaeophycus*, *Phoebichnus* and *Taenidium* suggests low energy conditions in the transitional to the upper offshore region.

TRANSGRESSIVE REGRESSIVE CYCLE-IV

Transgressive systems tract (TST-IV): The top of the Babia Cliff Sandstone Member represents retrograding sediments characterized by change in the trace fossil occurrence from the *Asterosoma* and *Phycodes* assemblages to the *Rhizocorallium* assemblage. These trace fossils are dominated by fodinichnia and belong to the transitional environment showing a change in the energy conditions and representing the onset of transgression of the next transgression-regression cycle.

DISCUSSION

The mixed siliciclastic-carbonate sedimentary succession of the Kaladongar Formation includes five depositional facies which display stratal geometry, thickness and associated physical and biogenic sedimentary structures. Each aggradational sequence represents standstill conditions of the relative sea-level while the progradational and retrogradational sequences represent the regressive and transgressive condition of the sea, respectively. Shallowing-upward and symmetrical cycles occur in protected lagoon-shoreface areas (Chhappar Bet – Dingy Hill Member) and in the shallow-marine, high-energy domain (upper part of the Dingy Hill Member, Kaladongar Sandstone Member and Babia Cliff Sandstone Member), while deepening-upward and aggradational cycles are generated in low-energy, open marine areas below fair weather wave-base (Dingy Hill Member and Kaladongar Hill – Dingy Hill Member).

The whole sequence reflects regressive systems tracts (RST-I, II and III) and transgressive systems tracts (TST-II, III and IV). RST-I, TST-II and RST-II are represented by sediments deposited under low- to high-energy shoreface condition, TST-III can be interpreted as having been deposited in the shoreface-transition-lower offshore environment, while the RST-III can be interpreted as belonging to the offshore/transition zone/shoreface and TST-IV to the lower transitional zone. The sedimentation pattern and the succession of the sediments suggest a sea-level rise with high to low sediment influx during deposition of the rocks of the Kaladongar Formation (Fig. 4). This might be the reason for the varying influx of siliciclastics and the production of carbonates. Therefore, this succession represents a number of T-R cycles (Fig. 5) but overall indicates a slowly transgressive sea during deposition of the mixed siliciclastic-carbonate sediments during Bajocian-Bathonian time.

The sea floor shallowed up to the upper shoreface as marked by presence of the *Skolithos* and *Ophiomorpha* assemblages of the Skolithos ichnofacies in the Dingy Hill Member, whereas the offshore zone characterized by the presence of the *Planolites–Palaeophycus*, and *Rhizocorallium* assemblages of the distal Cruziana ichnofacies (*cf.* MacEachearn, Pemberton, 1992) is present in the upper part of the Dingy Hill Member. The gradual deepening within the shoreface shows presence of the *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites–Palaeophycus* and *Phycodes* assemblages. These assemblages belong to the proximal Cruziana ichnofacies (MacEachearn, Pemberton, 1992) and typically mark the middle-lower shoreface.

These sedimentary cycles consist of a short retrogradational portion corresponding to a extensional tectonic pulse leading to subsidence, followed by a longer stage of progradation during tectonic quiescence. This pattern resembles the typical rift sequence suggested by Martins-Neto and Catuneanu (2010). The present sequence shows an absence of the lowstand systems tract (LST) in the sediments of the Kaladongar Formation which also accordingly may be considered due to the strong asymmetrical shape of the base-level curve, with a fast rise followed by prolonged still stand. The transgressive deposits of the Kaladongar Formation do not show any ravinement surface which indicates that the deposits are characteristic of low-energy coastlines and are typically developed in mud-dominated successions (Cattaneo, Steel, 2003). Moreover, the common aggradational or even retrogradational deposition in the regressive systems tract reflects the influence of environmental factors on stratigraphic stacking patterns (Potma *et al.*, 2001).

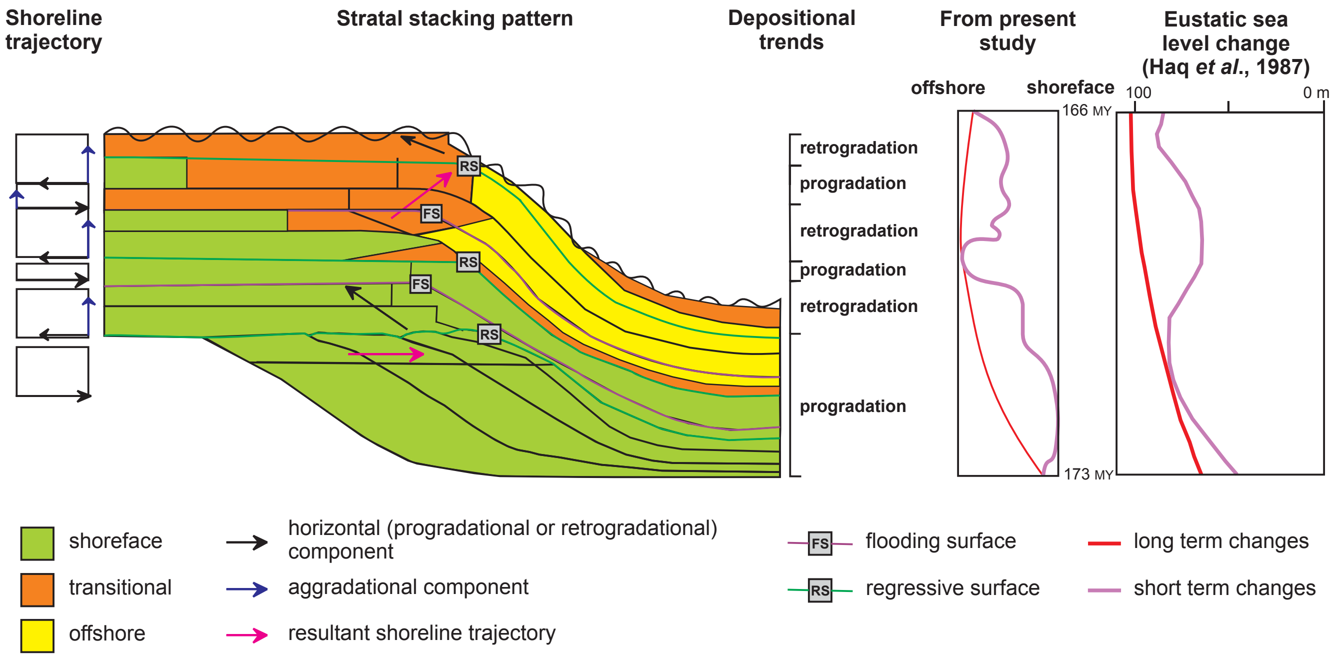


Fig. 5. Sequence stratigraphic model representing the shoreline trajectory and depositional trends in the stratal stacking pattern

REGIONAL AND GLOBAL CORRELATION

The mixed siliciclastic-carbonate sediments of the Kaladongar Formation and their associated trace fossils are evidence of a slowly transgressing sea over low energy coastlines during the initial rifting phase of the Kachchh Basin during Bajocian or Aalenian. The sediments of the Kaladongar Formation can be correlated regionally with those of the Jaisalmer Basin studied by Pandey and Choudhary (2007) which show similar depositional system and comparatively gradual deepening of the basin with an increase in marine sediments during the late Bajocian. Moreover, the overall transgressive trend of the formation (Fig. 5) seems to be correlative to the Bajocian-segment of the world-wide sea-level of the Toarcian-Bathonian time interval (Haq *et al*., 1987; Hallam, 2001). This sea level rise is also documented in the Tethyan/Boreal scheme of Hardenbol *et al.* (1998) and the T-R facies cycles of Jacquin *et al*. (1998).

CONCLUSIONS

The Kaladongar succession formed in tide-influenced high to low-energy offshore-shoreface environments, and exhibited variations in textural parameters as well as in proportions of siliciclastic and carbonate sediments.

The stratigraphic development of the succession, sedimentary bodies, and the sediment nature (siliciclastic versus carbonate) suggests a sea-level rise with varying (high to low) rates of sediment influx.

The accommodation space generated by the flooding controlled the thickness and facies variations. Environmental changes and tectonics also strongly influenced the sequence patterns.

The mixed siliciclastic-carbonate sediments of the Kaladongar Formation and their associated trace fossils are evidence of a slowly transgressing sea over a low-energy coastline during the initial rifting stage of the Kachchh Basin during Aalenian time.

The sedimentary cycles, depositional trends and stratigraphic surfaces of the Kaladongar Formation reflect fluctuations in water energy condition, sediment influx, environmental changes, depositional bias and sea-level conditions which are correlatable to the world-wide Bajocian-Bathonian sea-level rise.

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PLATE 1

Fig. 1. *Palaeophycus tubularis* Hall, 1852 (i) associated with *Planolites beverleyensis* Billings, 1862 (ii) in Babia Cliff Sandstone member

Fig. 2. *Asterosoma* isp. (i) associated with *Phycodes* cf. *palmatum* Hall, 1852 (ii) of *Asterosoma* assemblage in allochemic sandstone facies of Babia Cliff Sandstone Member

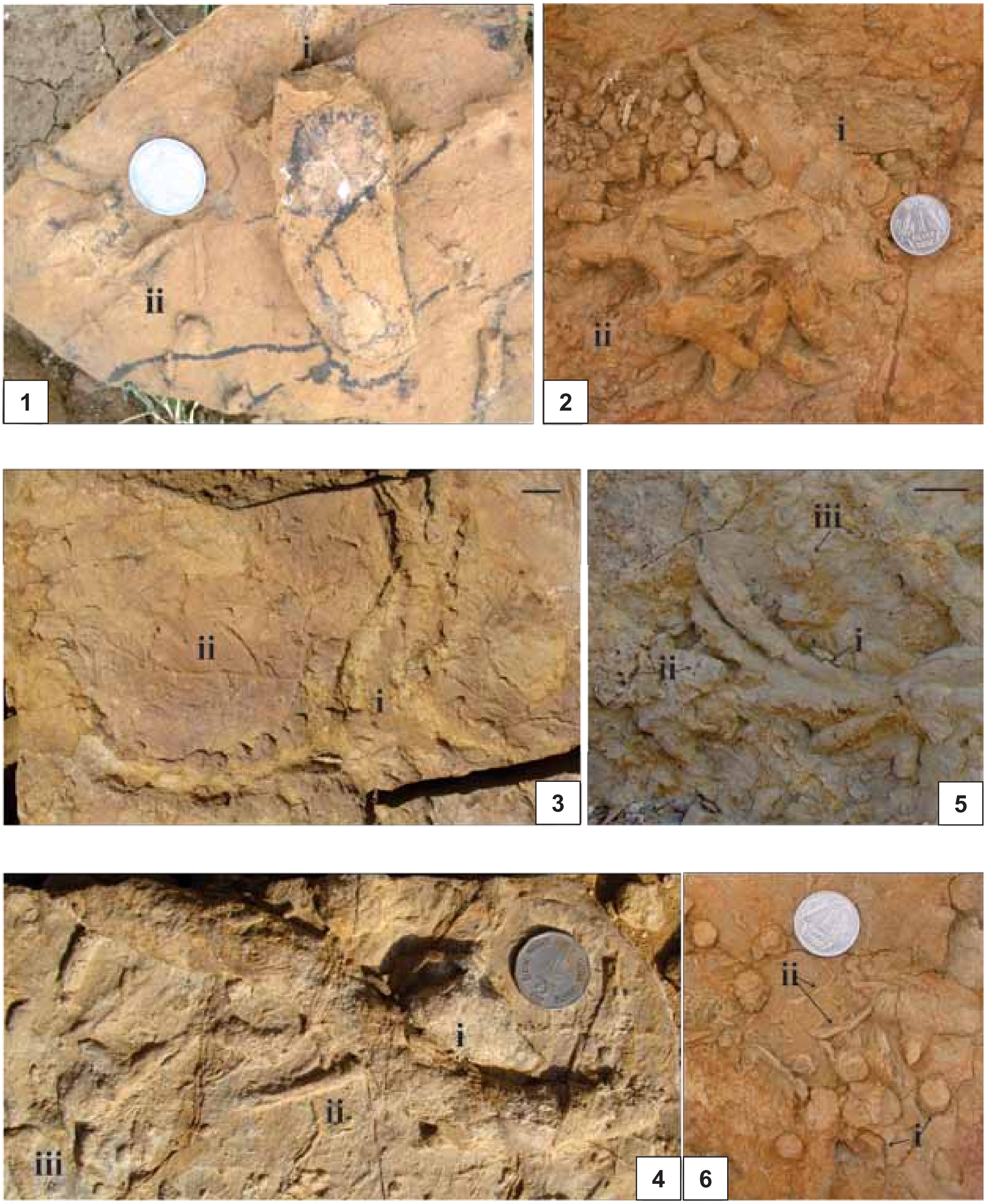
Fig. 3. *Nereites* (i) and *Planolites* (ii) in Dingy Hill Member

Fig. 4. *Palaeophycus tubularis* Hall, 1852 (i) associated with *Planolites beverleyensis* Billings, 1862 (ii) and *Lockeia* (iii) in Dingy Hill Member

Fig. 5. *Phycodes* assemblage in micritic sandstone showing *Phycodes* isp. (i), associated with *Arenicolites* (ii), and *Skolithos* (iii) in Dingy Hill Member

Fig. 6. *Skolithos linearis* Haldman, 1840 (i) associated with *Planolites beverleyensis* Billings, 1862 (ii) in Dingy Hill Member

Bar length = 2.0 cm, coin diameter = 2.4 cm



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