CHAPTER - 6
PALAEOECOLOGY

6.1 INTRODUCTION

Trace fossils can serve as an important tool for paleoenvironmental analysis as they are rarely transported and provide in situ information during and post deposition of sediments (Bromley, 1996). The importance of trace fossils had been long known; however, the application was limited due to lack of knowledge. With more information building, better understanding of animal behaviour and their relationship with the substrate, ichnological analysis serve as an important tool for paleoenvironmental interpretation. Trace fossils may seem to provide an immediate key to paleoenvironmental interpretation such as *Ophiomorpha nodosa* may serves as an indicator of the littoral and shallow neritic environments (Bromley, 1996; Weimer and Hoyt, 1964, Patel and Desai, 2009). However, the variables involved in the ichnological analysis for paleoenvironmental interpretation tends to be far more complicated as a single ichnogenus may represent more than one environmental setting such as in the case of *Rhizocorallium* where *R. jenense* indicate firm ground while *R. commune* indicate soft ground (Knaust, 2013).

The variables may also include salinity and temperatures, dissolved oxygen and bottom stability (Rhoads, 1975). These variables are also described as limiting factors by Bromley (1996) that impose ecological stress for benthic communities and are recorded by (1) the diversity of species; (2) the size of individuals; and (3) the amount of endobenthic activity. The behavioural response of burrowing organism to *salinity* and *temperature* are similar (Rhodes 1975). The extreme temperature such as lagoon, estuaries and intertidal zone have high salinity and are characterized by deep burrowing euryhaline organism opposite to stenohaline organism which can tolerate minor fluctuation in salinity. Such organism includes brachiopods, echinoderms, polychaetes, sipunculids, echiurans, pogonophores, and prosobranch and opisthobranch gastropods. A fluctuating environmental condition in marine setting may be represented by *Skolithos, Arenicolites, Planolites, Teichichnus, Chondrites, Thalassinoides* and *Gyrolithes* (Beynon et al., 1988; Beynon and Pemberton 1992; Pattison 1992). Bipedal and quadrupedal vertebrate trackways are commonly associated with fluviatile and marginal lacustrine assemblages (Lockley, 1991).

Khadir Island		
Member	Facies	Trace fossils
Bambhanka Member	Sandy allochemic limestone	*Didymaulichnus alternatus, Gyrochorte comosa, Protovirgularia oblitrata*.
	Micritic Sandstone	*Arenicolites* isp., *Curvolithus simplex, Didymaulichnus lyelli, Gyrochorte comosa, Laevicyclus parvus, Monocraterion tentaculatum, Ophiomorpha annulate, O.* isp., *Palaeophycus tubularis, Phycodes curvipalmatum, Planolites beverleyensis, P. montanas, Protovirgularia dichtoma, Rhizocorallium commune var, irregularie, R. commune var auriforme, Skolithos* isp.,
Ratanpur Sandstone Member	Pelloidal packstone/ grainstone	*Laevicyclus parvus, Ophiomorpha annulate, Palaeophucus haberti, Palaeophycus tubularis, Planolites baverleyensis, Protovirgularia, Rhizocorallium commune var. auriform, Taenidium serpentinum*
	Sandy allochemic limestone	*Chondrites targionii, Curvolithus simplex, C. multiplex, Lockeia amygdaloides, Palaeophycus tubularis, Planolites beverleyensis, P. montanus, Ophiomorpha nodosa, Arenicolites statheri, Arenicolites* isp., *Thalassinoide paradoxicus, T. horizontalis*
	Micritic sandstone	*Chondrites targionii, C. intricatus, Hillichnus lobosensis, Arenicolites statheri, A.* isp., *Diplocretereon* isp., *Hillichnus lobosensis, Laevicyclus parvus, Lockeia siliquaria, Monocraterion tentaculatum Ophiomorpha nodosa, O.* isp., *Planolites baverleyensis, Taenidium serpentinum, T.* isp., *Thalassinoides horizontalis*
Hadibhadang Shale member	Micritic sandstone	*Arenicolites* isp., *Thalassinoides* isp., *Diplocraterion* isp., *Skolithos* isp., *Rhizocorallium* isp.

Table 6.1 Distribution of the trace fossils in the various lithofacies of the different stratigraphic unit in the Khadir Island.

Bela Island		
Member	Facies	*Trace fossils*
Ratanpur Sandstone Member	Micritic sandstone	*Monocraterion tentaculatum, Ophiomorpha nodosa, Diplocraterion* isp. *Rhizocorallium commune var irregularie, Helicolithus sampelayoi, Planolites beverleyensis*
	Sandy allochemic limestone	*Arenicolites* isp., *Chondrites targioni, Didymaulichnus lyelli, Diplocraterion* isp., *Hillichnus lobosensis, Lockiea siliquaria, Palaeophycus tubularis, P. anulatus, Phycodes palmatus, Planolites baverleyensis, Protovirgularia rugosa, Protovirgularia* isp., *Rhizocorallium cf commume var auriform, R. commune var irregularie, Skolithos verticalis, Taenidium serpentinum, T.* isp., *Thallasinoides* isp.
Hadibhadang Sandstone Member	Micritic sandstone	*Monocraterion tentaculatum*
Hadibhadang Shale Member	Micritic sandstone	*Thalassinoides horizontalis*

Table 6.2 Distribution of the trace fossils in the various lithofacies of the different stratigraphic unit in the Bela Island.

The decrease in *dissolved oxygen* increases with depth leading to the sparsity of body fossils. The fully aerobic biofacies is characterized by a fair degree of water turbulence and deep bioturbation while the reverse reflects in the absence or reduction in biological traces. With the reduction of dissolved oxygen exceeds about l.0ml/l, shell bearing invertebrate confined to the well mixed shelf waters (Rhodes and Morse, 1971; Tyson and Pearson 1991); below1.0 ml/l in the dysoxic zone, the sea floor is dominated by small infaunal deposit feeders, *Chondrites* and other probers penetrate below the mixed layer, and chemosymbiosis begins and below which bioturbation cease and biomats seal the seafloor which provide a sharp separation between anoxic pore water containing H_2S, and the dysoxic bottom water (Bromley, 1996). Several workers have presented different dissolved oxygen model such as Sageman et al., (1991) where he opined that large shelly colonist as opportunists during short oxic pulses, rather than chemosymbiotic K-strategists. Savrda and Bottjer (1986) and Savrda (1992) developed a model for reconstruction of oxygen-related ichnocoenoses based on ichnofabrics, while Ekdale and Mason (1988) proposed a model based on trace fossil association (ethological association). Their model includes four trace fossil associations to represent a gradient of increasing benthic oxygenation which include (1) 'no ichnia'; (2) an association of fodinichnia, or traces of non-vagile deposit feeders; (3) an association of pascichnia, or traces of vagile deposit feeders; and (4) domichnia dominated by *Skolithos*.

Chorar Island		
Member	Facies	Trace fossils
Ratanpur Sandstone Member	Ferruginous sandstone	*Arenicolites* isp., *Skolithos* isp., *Planolites beverleyensis Diplocraterion* isp. *Palaeophycus tubularis*
	Cross-bedded white sandstone	*Planolites* isp., *Skolithos linearis, S. verticalis, Thalassinoides* isp.
Hadibhadang Sandstone Member	Sandy allochemic Limestone	*Didymaulichnus lyelli, Gyrochorte comosa, Hillichnus lobosensis, Lockeia siliquaria, Megagrapton irregulare, Palaeophycus haberti, Protovirgularia* isp., *Rhizocorallium commune var irregularie, Skolithos* isp., *Thalassinoides horizontalis.*
	Micritic sandstone	*Palaeophycus tubularis, Thalassinoides, Halopoa imbricata, Rhizocorallium var irregularie.*

Table 6.3 Distribution of the trace fossils in the various lithofacies of the different stratigraphic unit in the Chorar Island.

The *bottom stability* is an important variable in the distribution of bottom dwelling organisms. The grain size distribution, organic content of sediment, bottom compaction and rate of sedimentation collective accounts for the bottom stability (Rhodes, 1975). Trace fossils may be used to identify accretion or erosional surfaces. The occurrences of shallow and deep burrows indicate accretion while the occurrences of only deep, truncated burrows indicate erosion (Goldring, 1964). *Diplocraterion* serve as a good example to understand the upward movement of the organism can be recognised by the presence of abandoned horizontal base of the U-spreite during accretion while erosion can be identified by the occurrence of abandoned tubes segments above section of new tube construction (Rhodes, 1975).

In both terrigenous and carbonate setting, the striking changes in trace fossils suites occur perpendicular to the depositional i.e., with depth. (Seilacher, 1964; Rhoads, 1975; Farrow 1966; Bromley, 1996). This bathymetrical zonation is attributed to partitioning of feeding types as related to food resources is described by Seilacher, (1967) in terms of ichnofacies which is given in Table 6.5.

The Mesozoic succession of Khadir, Bela and Chorar Islands are bioturbated at varying intensity at different stratigraphic levels. The trace fossils include 44 ichnospecies belonging to 23 ichnospecies The observed trace fossils and their associated lithofacies of each island is provided in Table 6.1, 6.2 and 6.3 for Khadir, Bela and Chorar Island respectively in stratigraphical order. In the present study an attempt has been made to deduce the palaeoecological parameters considering the ethology, ichnoassemblages and ichnofacies analysis which serve as an important tool to study the sequence stratigraphy of the Island Belt Zone of the western Kachchh Basin.

6.2 ETHOLOGY

Trace fossils provide a tangible animal behavioural activity and are the most natural way to classify them according to their behavioural pattern (Bromley, 1996). Ethological classification is one of the most commonly used methods of classification in ichnological studies. The ethological classification was originally proposed by Seilacher (1953) consisting of five behavioural categories representing the basic building blocks of behavioural interpretations (Buatois and Mángano, 2011). These categories include ‘cubichnia’ for resting traces, ‘repichnia’ for locomotion traces, ‘pascichnia’ for grazing traces, ‘fodinichnia’ for feeding traces and ‘domichnia’ for dwelling traces. However, this classification often overlaps and with additional information, constant modification and addition of new categories have been proposed by several workers to include additional behaviours. The additional major behavioural categories include fugichnia, (Frey, 1973) for escape traces, agrichnia (Ekdale et al., 1984a) for farming traces and traps, praedichnia (Ekdale, 1985) for predation traces, equilibrichnia (Bromley, 1990) for equilibrium traces, chemichnia (Bromley, 1996), calichnia

(Genise and Bown, 1994a), aedifichnia (Bown and Ratcliffe, 1988) for nesting traces. Behavioural categories such as pupichnia (Genise et al., 2007) for pupation chambers, fixichnia (De Gibert et al., 2004) for fixation/anchoring traces, xylichnia, mortichnia (Seilacher 2007a) for death traces, etc are considered subcategories.

ETHOLOGY	**BEHAVIOUR**	**TRACE FOSSILS**	**PRODUCERS**
Cubichnia	Resting traces	NA	NA
Domichnia	Dwelling	*Arenicolites*	Worms
		Diplocraterion	Worms
		Hillichnus	Tellinacean bivalve
		Lockeia	Bivalve
		Monocraterion	Worm like animal
		Ophiomorpha	Crustacean
		Palaeophycus	Polychaetes
		Skolithos	Annelids and polychaetes
Repichnia	Locomotion	*Curvolithos*	Scavenging gastropods
		Didymaulichnus	Molluscans
		Gyrochorte	Annelids
		Halopoa	Priapulid worms
Pascichnia	Grazing	*Megagrapton*	Graphoglyptids
		Planolites	Polyphyletic vermiform
Fodinichnia	Feeding traces	*Asterosoma*	Decapod crustacean
		Chondrites	Chemosymbiotic animal
		Helicolithus	Graphoglyptid
		Hillichnus	Tellinacean bivalve
		Laevicyclus	Annelid
		Phycodes	Vermiform annelids
		Protovirgularia	Bivalve
		Rhizocorallium	Crustacean or scavengers
		Taenidium	Polychaetes/Crustaceans
		Thalassinoides	Crustaceans

Table 6.4: Generalised Seilacherian ethological classification of trace fossils with their possible trace maker from Khadir, Bela and Chorar Islands.

However, in the present studies, for simplification and better understanding, the original five behavioural categories proposed by Seilacher (1953) will be considered as these are the basic building blocks of behavioural interpretation in ichnology. The ethological classification proposed by Seilacher (1953) is simple but have its own loop holes. Certain species such as *Lockeia siliquaria* and *L. amygdaloides* belonging to the same ichnogenera falls under domichnia and cubichnia respectively. However, Schlirf et al., (2001) consider *L. amygdaloides* as a junior synonym of *L. siliquaria*, all the ichnogenus of *Lockeia* is placed under domichnia. Traces such as *Halopoa* is considered dwelling and feeding traces (Jensen, 1997, Uchman, 1998; Knaust 2004), however striations are produced actively by locomotory organs and/or passively by body appendages of the trackmaker hence it is included in repichnia (Uchman (1998). Complex trace fossils such as *Hillichnus* reflect several behaviours, making it impossible to place these complex ichnotaxa into only one category (Miller, 2003; Pickerill, 1994; Rindsberg, 2012) and hence, it is placed under both domichnia and fodinichnia.

In Khadir Island, the Jurassic succession is bioturbated at varying intensities in different facies and at stratigraphic levels. The traces recur in time and dominated by domichnia (dwelling traces) and fodinichnia (feeding traces). The dwelling traces include *Arenicolites, Diplocraterion, Hillichnus, Lockeia, Monocraterion, Ophiomorpha, Palaeophycus* and *Skolithos.* The feeding traces include *Chondrites, Laevicyclus*, *Hillichnus*, *Phycodes, Protovirgularia*, *Rhizocorallium*, *Taenidium* and *Thalassinoides.* Other traces include locomotory traces ‘repichnia’ (*Curvolithus*, *Didymaulichnus*, *Gyrochorte*) and grazing traces ‘pascichnia’ (*Planolites*). The succession shows dominance of dwelling and feeding structures preferentially in micritic sandstone followed by sandy allochemic limestone and pelloidal packstone/grainstone. The thin bands of micritic sandstone intercalated with shales in Hadibhadang Sandstone Member shows small *Arenicolites*, *Diplocraterion* and *Skolithos* indicating strain environment where opportunistic organism strive during temporal change in energy condition.

Micritic sandstone facies of Ratanpur Sandstone Member is bioturbated at varying intensity and shows by wide range of behavioural patterns. The occurrences of *Chondrites intricatus* in thinly bedded micritic sandstone suggest a short interval of low concentrations of oxygen in bottom and interstitial waters (Rhoads and Morse, 1971, Savrda and Bottjer, 1989, Wignall, 1991) while the presence of trace fossils such as *Planolites, Taenidium, Rhizocorallium, Palaeophycus, Protovirgularia, Thalassinoides* etc suggested oxygenated bottom water condition (Frey and Howard, 1990, Bromley, 1990). The occurrences of *Chondrites targioni,* and *Rhizocorallium* suggest nutrient rich substrate. The abundance occurrence of feeding and dwelling trace in peloidal packstone/grainstone facies which include *Palaeophycus, Planolites, Protovirgularia, Laevicyclus* and *Ophiomorpha* also suggest nutrient rich well oxygenated substrate. In Bambhanka Member of Gadhada Formation, micritic sandstone is preferentially bioturbated by a wide range of behavioural traces which include dwelling traces (*Arenicolites, Monocraterion, Ophiomorpha Palaeophycus, Protovirgularia, Rhizocorallium* and *Skolithos*) locomotory traces (*Curvolithus, Didymaulichnus,* and *Gyrochorte*) feeding traces (*Laevicyclus* and *Phycodes*); grazing traces (*Planolites*). Other behavioural traces of *Gyrochorte, Didymaulichnus* and *Protovirgularia* (locomotory) are also observed in sandy allochemic limestone facies.

Micritic sandstone and sandy allochemic limestone are preferentially bioturbated by 23 ichnospecies belonging to 17 ichnogenera in the Jurassic succession of Bela Island. *Thalassinoides* burrows are observed the thin-thickly bedded micritic sandstone intercalated with shales in Hadibhadang Shale Member. *Thalassinoides* were produced by decapods in unconsolidated sediments for permanent dwelling (Yanin and Baraboshkin, 2013). *Skolithos* observed at the base of Hadibhadang Sandstone Member suggest dwelling burrows of annelids or phoronids in a shallow marine paleoenvironment (Alpert, 1974). Maximum bioturbation is observed in Ratanpur Sandstone Member both in micritic sandstone and sandy allochemic lime facies. Trace fossils in sandy allochemic limestone and micritic sandstone facies include domichnia (*Arenicolites, Diplocraterion, Lockiea, Monocraterion, Ophiomorpha, Palaeophycus,* and *Skolithos*), fodinichnia (*Chondrites, Hillichnus, Phycodes, Protovirgularia, Rhizocorallium, Taenidium,* and *Thalassinoides*) pascichnia (*Planolites*) and repichnia (*Didymaulichnus*). The dominance of dwelling burrows ‘domichnia’ and feeding burrows ‘fodinichnia’ with diverse population suggest an environment favourable for a population to flourish.

The Chorar Island also display similar behavioural activities and are dominated by a dwelling structures ‘domichnia’ (*Diplocraterion, Lockeia, Palaeophycus,* and *Hillichnus*), feeding structures (*Asterosoma, Rhizocorallium, Halopoa, Hillichnus,* and *Thalassinoides*), locomotion traces (*Curvolithus, Didymaulichnus, Gyrochorte* and *Protovirgularia*), along with grazing trails (*Megagrapton* and *Planolites*) in sandy allochemic limestone and micritic sandstone facies (Darngawn et al., 2018).

6.3 ICHNOASSEMBLAGE

Ichnoassemblage is the basic collective term, embracing all the trace fossils occurring within a single unit of rock which is non-committal as to the origin of the collection of trace fossils (Bromley, 1996). It represents a community of ecologically related organisms dwelling in a particular time. As trace fossils are rarely transported, it can shed a light on the paleoenvironmental condition in which the sediments are deposited. The Jurassic succession of Khadir, Bela and Chorar Islands exhibits recurring pattern in their occurrence. These ichnoassemblage are assigned based on the dominant ichnogenus which shed a light on the palaeoecology. The ichnoassemblage of each island are described as under.

6.3.1 Ichnoassemblage of Khadir Island

The Jurassic succession of Khadir Island and its neighbouring islets are intensely bioturbated at varying intensity by ecologically related group of trace fossils in each sedimentary unit/bed. The trace fossils observed in Khadir Island comprises of 36 ichnospecies belonging to 19 ichnogenera. The Khadir Island comprises of seven ecologically related and recurring association which include *Diplocraterion*, *Hillichnus*, *Lockeia*, *Planolites-Palaeophycus*, *Rhizocorallium*, *Skolithos* and *Protovirgularia.* These association are described as under.

6.3.1.1 *Diplocraterion* Assemblage

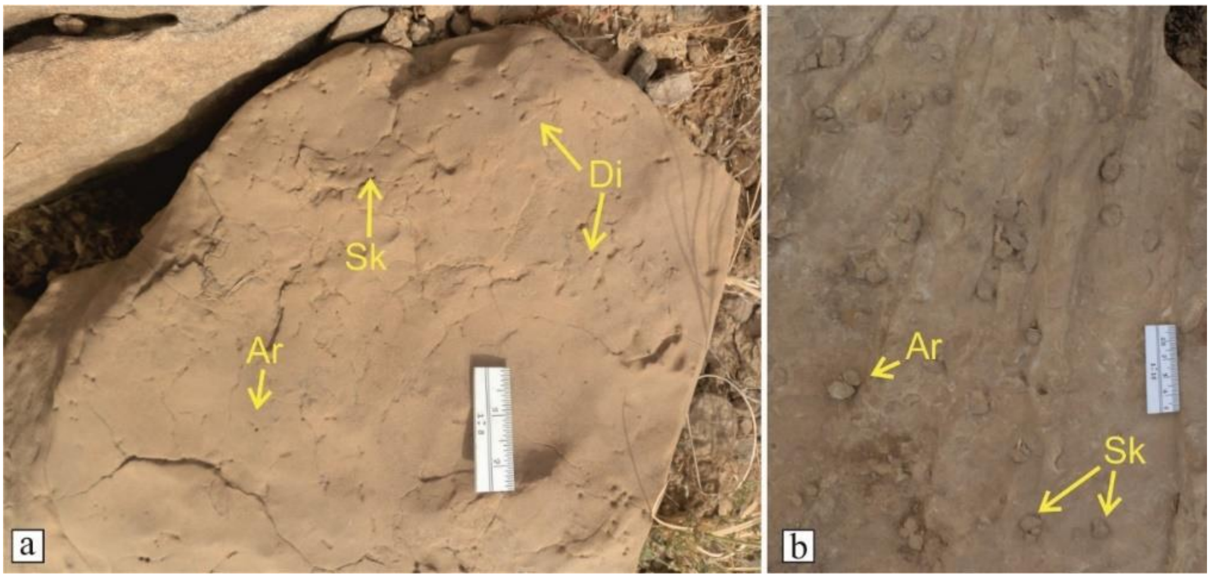

Plate 6.1 Trace fossils of *Diplocraterion* assemblage: (a) Association of *Diplocraterion* (Di), *Arenicolites* (Ar) and *Skolithos* (Sk), (b) *Arenicolites* (Ar) and *Skolithos* (Sk) in a thinly bedded micritic sandstone of Hadibhadang Shale Member.

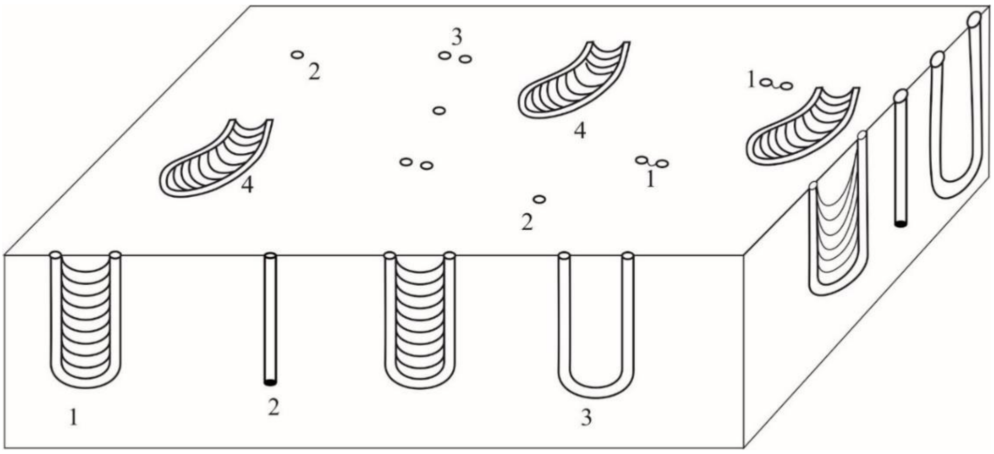

Fig. 6.1 Diagrammatic representation of *Diplocraterion* assemblage. 1. *Diplocraterion,* 2. *Skolithos* 3. *Arenicolites* 4. *Rhizocorallium*.

The observed traces especially *Diplocraterion, Arenicolites, Skolithos* are small usually .0.5mm burrow diameter. The thinly bedded host rock and tininess of the burrows indicate a very narrow colonization window in harsh environmental conditions. The dominance of vertical burrows of suspension feeding structures shows opportunistic behaviour. *Rhizocorallium* can be regarded as either a suspension-feeding or deposit-feeding burrow (Dam, 1990; Rodríguez-Tovar & Pérez-Valera, 2008; Knaust, 2013) while the occurrences of *Thalassinoides,* a burrow of deposit feeder (Uchman, 1995) suggest nutrient-rich substrate for a short interval.

6.3.1.2 *Skolithos* Assemblage

Plate 6.2 Trace fossils of *Skolithos* assemblage. (a) An association of *Skolithos* (Sk) and *Arenicolites* (Ar) in a thickly bedded micritic sandstone facies of Hadibhadang Shale Member exposed at the base of the north facing scarp of Khadir Island. (b) Monodominant *Skolithos* in micritic sandstone facies of Hadibhadang Shale Member.

Skolithos assemblage occurs as a predominant ichnogenus and is observed in association with *Arenicolites* in micritic sandstone facies of Hadibhadang Shale Member at the foot hill of Khadir Island (Fig. 6.2). The highly bioturbated micritic sandstone is often cross-bedded, parallel lamination and intercalated with thick succession of shales. The most probable trace maker of *Skolithos* is vermiform annelids and polychaetes while *Arenicolites* by worms. The occurrences of *Skolithos* (Plate 6.2a) with *Arenicolites* (Plate 6.2b) suggest sudden deposition of sediments during storm condition below the fair-weather wave base where the opportunistic organism dwell for a short period of time.

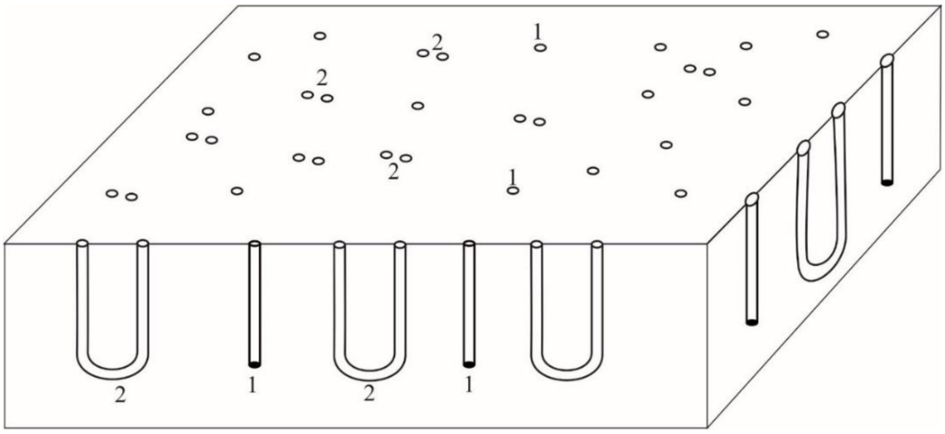

Fig. 6.2 Diagrammatic representation of *Skolithos* assemblage. 1. *Skolithos*, 2. *Arenicolites.*

6.3.1.3 *Lockeia* Assemblage

Plate 6.3 Trace fossils of *Lockeia* assemblage. (a) Monodominant *Lockeia* in micritic sandstone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (b) *Planolites* in highly ferruginised micritic sandstone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (c) *Rhizocorallium* in ferruginised micritic sandstone where the spreiten structures have been destroyed due to erosion (Scale: coin diameter = 2.3 cm).

Lockeia assemblage comprises of *Lockeia* (Plate 6.3a), *Planolites* (Plate 6.3b) and *Rhizocorallium* (Plate 6.3c) observed in ferruginised micritic sandstone facies of Ratanpur Sandstone Member (Fig. 6.3). It is exposed in the eastern part of Khadir Island near Amrapur village where the succession is intercalated with shales and sandy allochemic limestone. The ichnospecies of *Lockeia* had been merged into *Lockeia siliquaria* (Schlirf et al., 2001) and is considered as dwelling trace of bivalves.

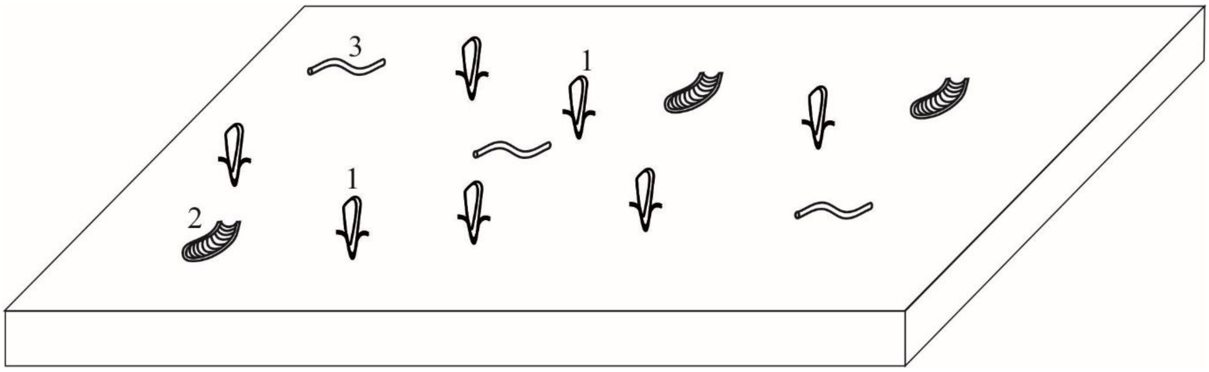

Fig. 6.3 Diagrammatic representation of *Lockeia* assemblage. 1. *Lockeia*, 2. *Planolites,* and 3. *Rhizocorallium.*

6.3.1.4 *Planolites-Palaeophycus* Assemblage

Planolites-Palaeophycus assemblage is observed in the sandy allochemic limestone facies intercalated with shales of Ratanpur Sandstone Member in Khadir Island (Fig. 6.4). It is exposed north of Amrapur village in Eastern part of Khadir Island. The ichnoassemblage comprises of *Palaeophycus* (Plate 6.4a), *Planolites* (Plate 6.4b), *Arenicolites,* Ophiomorpha (Plate 6.4c), *Skolithos,* (Plate 6.4.d) *Thalassinoides* (Plate 6.4e), *Lockeia* and *Curvolithus* with *Thalassinoides* (Plate 6.4f).

The ichnoassemblage is dominated by deposit-feeding producers including polychaetes, annelids, worms suggesting oxygenated conditions during deposition. The occurrences of *Curvolithus* (Plate 6.4f) which is produced by scavenging gastropods (Heinberg, 1973) also suggest favourable conditions for different communities to thrive. The occurrences of *Thalassinoides* also suggest well oxygenated nutrient rich substrate condition while the occurrences of *Arenicolites* and *Skolithos* suggest agitating medium, moderate energy condition.

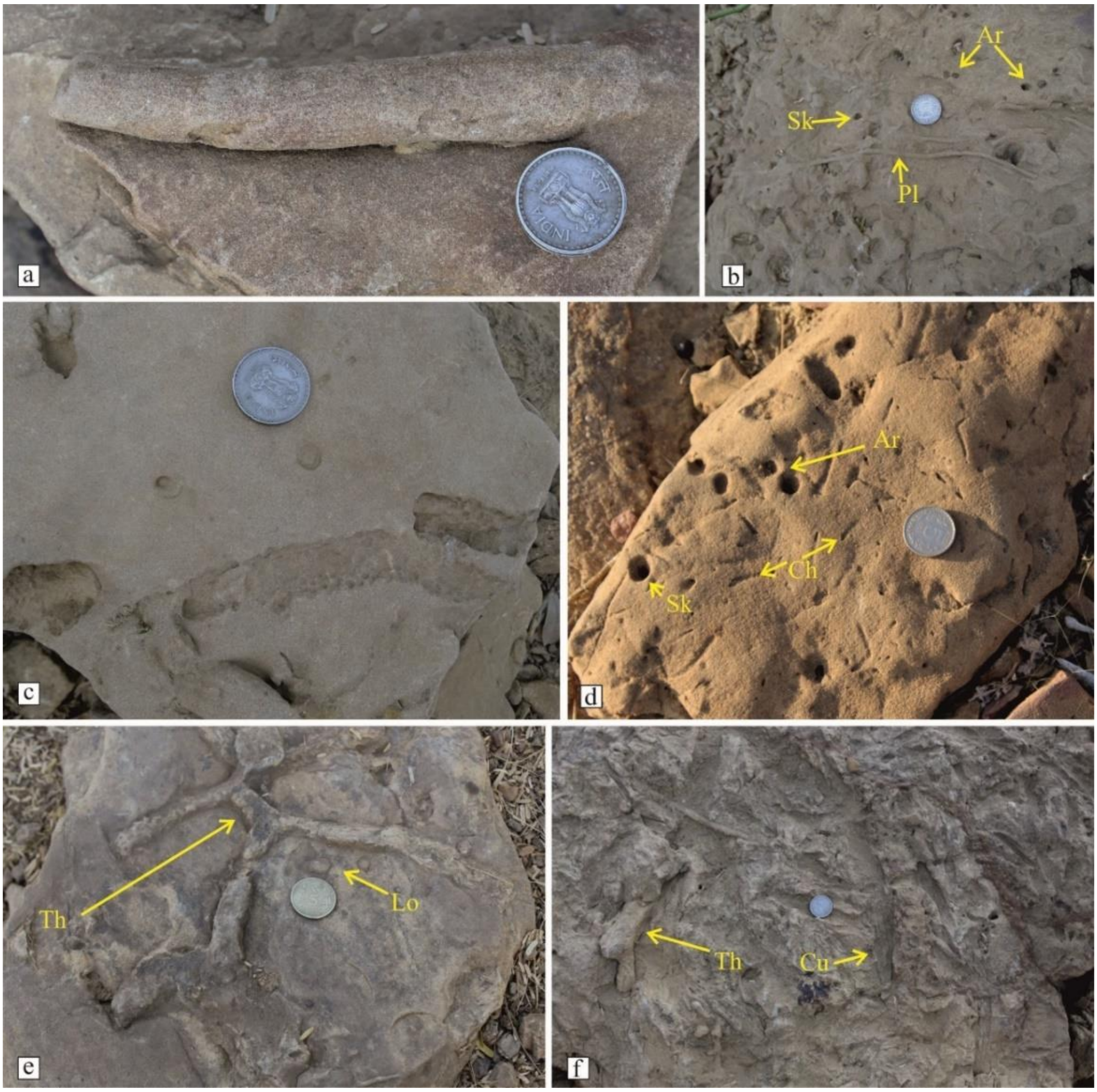

Plate 6.4 Trace fossils of *Planolites-Palaeophycus* assemblage. (a) *Palaeophycus* observed in sandy allochemic limestone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (b) *Planolites* in association with *Arenicolites* and *Skolithos* (Scale: coin diameter = 2.3 cm). (c) *Ophiomorpha* observed in sandy allochemic limestone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (d) *Chondrites* (Ch) in association with *Arenicolites* (Ar) and *Skolithos* (Sk). (Scale: coin diameter = 2.3 cm). (e) *Thalassinoides* in association with *Lockeia* in thinly bedded sandy allochemic limestone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (f) Faintly preserved trilobate *Curvolithus* in association with *Thalassinoides* thinly bedded sandy allochemic limestone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm).

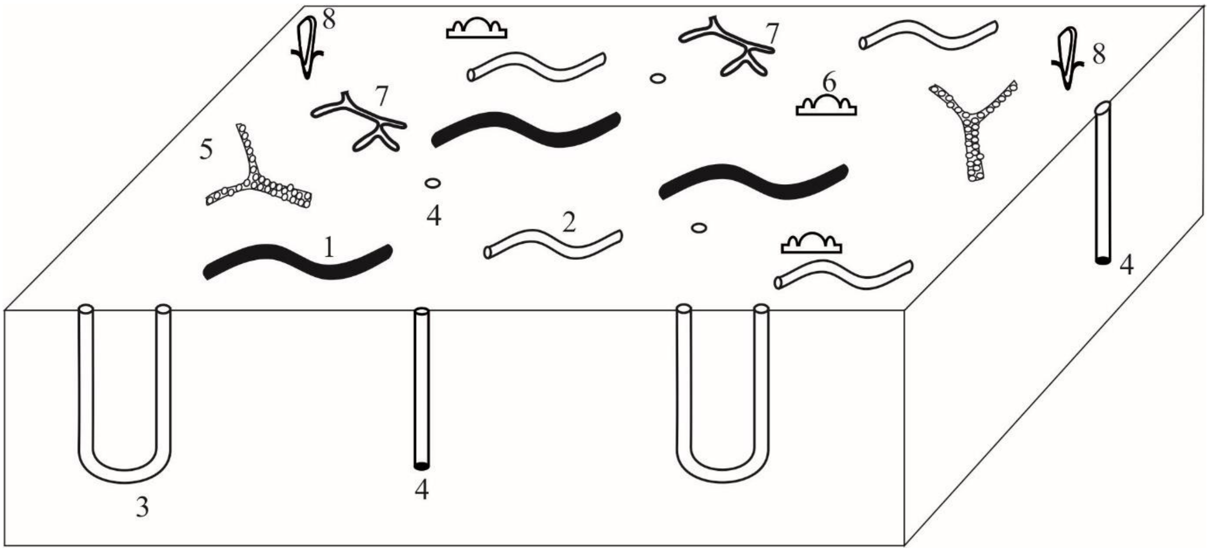

Fig. 6.4 Diagrammatic representation of *Planolites-Palaeophycus* assemblage.1. *Palaeophycus* 2. *Planolites* 3. *Arenicolites,* 4. *Skolithos,* 5. *Ophiomorpha* 6. *Curvolithus* 7. *Thalassinoides* and 8. *Lockeia.*

6.3.1.5 *Rhizocorallium* Assemblage

Rhizocorallium assemblage is a recur and observed in peloidal packstone-grainstone facies of Ratanpur Sandstone Member and micritic sandstone facies of Bambhanka Member of Gadhada Formation, exposed in the southern part of Khadir Island and Kakinda Bet respectively (Fig. 6.5). It occurs in thinly bedded peloidal packstone-grainstone facies intercalated with thick shales. *Rhizocorallium* assemblage includes *Rhizocorallium* (Plate. 5.7a; 6.5a), *Arenicolites,* (Plate. 6.5b), *Diplocraterion* (Plate. 6c), *Monocraterion* (Plate. 6.5c), *Taenidium* (Plate. 6.5b), *Skolithos* (6.5h), *Thalassinoides* (Plate. 6.5g), *and Planolites* (Plate. 6.5b). The *Rhizocorallium* assemblage in a thickly bedded ferruginised micritic sandstone facies of Bambhanka Member in Kakinda Bet, south of Khadir Island. The *Rhizocorallium* assemblage is dominated by *Rhizocorallium* (Plate 5.7b) in association with *Phycodes* (Plate 6.5d), *Ophiomorpha* (Plate 6.5e), *Laevicyclus* (Plate 6.5f), *Thalassinoides* ((Plate 6.5g) and. *Skolithos* (Plate 6.5h). The assemblage shows the dominant producer of crustacean or scavengers in association with few annelids and polychaetes. This assemblage witnesses both suspension-feeding and deposit-feeding trace makers which are mostly worms and crustaceans. The suspension feeding trace which include *Arenicolites*, *Diplocraterion* and *Monocraterion* relatively small and less developed suggesting high energy condition with less oxygen level in substrate.

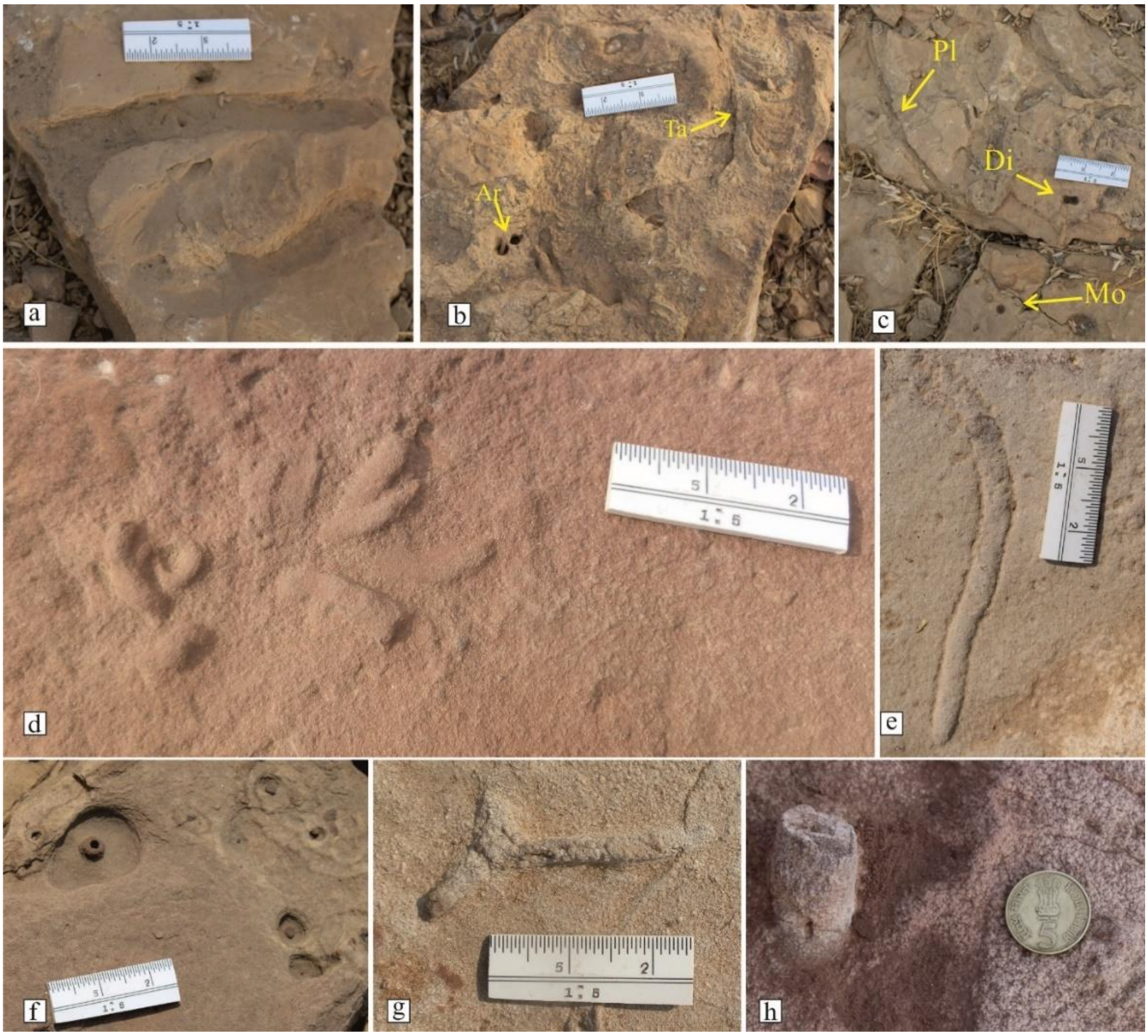

Plate 6.5 Trace fossils of *Rhizocorallium* assemblage. (a) *Rhizocorallium* observed in micritic sandstone facies of Bambhanka Member. (b) *Taenidium* (Ta) in association with *Arenicolites* (Ar) in peloidal packstone-grainstone facies of Ratanpur Sandstone Member exposed towards the southern tip of Khadir Island. (c) *Planolites* (Pl) in association with *Diplocraterion* (Di) and *Monocraterion* (Mo). (d) *Phycodes,* (e) *Ophiomorpha,* (f) *Laevicyclus,* (g) *Thalassinoides* and (h) *Skolithos* observed in micritic sandstone facies of Bambhanka Member in Kakinda Bet (Scale: coin diameter = 2.3 cm).

The *Rhizocorallium* assemblage shows dominance of deposit feeders such as *Rhizocorallium, Phycodes* and *Thalassinoides* indicating oxygenated, nutrient rich substrate traces of shallow marine deposits (Fürsich, 1974a; Knaust, 2013). The occurrences of *Ophiomorpha* in association with *Rhizocorallium*, suggest shoreface sandstones deposited as a barrier bar (Nagy et al., 2016) or shifting, unconsolidated sandy substrates in the marine settings (Ekdale, 1988). The association with *Laevicyclus* and *Skolithos* also indicate shallow marine environment

(Alpert, 1974) in agitating or high energy condition. The trace makers of this *Rhizocorallium* assemblage are crustacean or scavengers, annelids and polychaetes, polyphyletic vermiform.

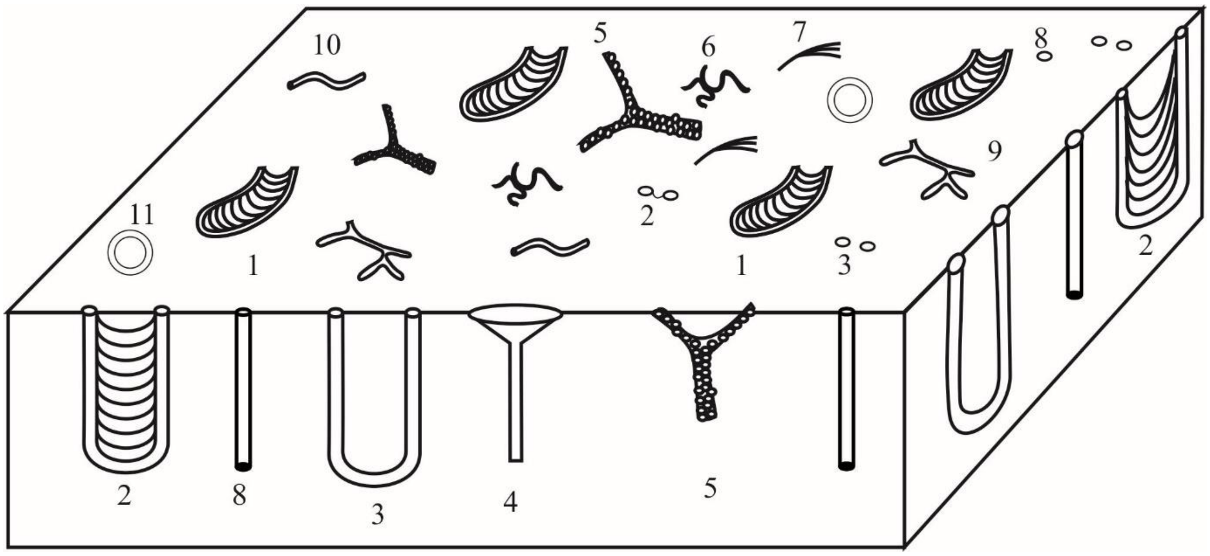

Fig. 6.5 Diagrammatic representation of *Rhizocorallium* assemblage. 1. *Rhizocorallium,* 2. *Diplocraterion,* 3. *Arenicolites,* 4. *Monocraterion,* 5. *Ophiomorpha,* 6. *Taenidium,* 7. *Phycodes,* 8. *Skolithos* 9. *Thalassinoides.* 10. *Planolites*, and 11. *Laevicyclus.*

6.3.1.6 *Protovirgularia* Assemblage

The *Protovirgularia* assemblage is a recur and observed in thinly bedded micritic sandstone facies (Plate 6.6d) and sandy allochemic limestone facies of Bambhanka Member in Kakinda Bet. It is also observed in sandy allochemic limestone facies of Bambhanka Member of Gadhada Formation in Kakinda Bet. The assemblage is observed in association with *Gyrochorte* (Plate 6.6a) and *Didymaulichnus* (Plate 6.6b) in sandy allochemic limestone facies while *Protovirgularia* (Plate 6.6c) is observed in association with *Curvolithus, Diplocraterion* (Plate 6.6d), *Gyrochorte* (Plate 6.6e), *Planolites* (Plate 6.6d), *Palaeophycus, Taenidium* (Plate 6.6g), and *Curvolithus* in micritic sandstone facies (Fig. 6.6).

The trace maker of this assemblage comprises of bivalve and scavenging gastropods. The dominance of locomotory traces than feeding traces indicates poor nutrient substrate. The occurrence of suspension feeding traces indicates agitating environment where opportunistic organisms adapt for a short period of time. However, the occurrences of *Protovirgularia, Taenidium*, *Didymaulichnus, Planolites. Palaeophycus, Diplocraterion, Gyrochorte* and

Didymaulichnus indicates soft substrates, with during a temporal change in energy condition where there is sudden supply of nutrient rich sediments.

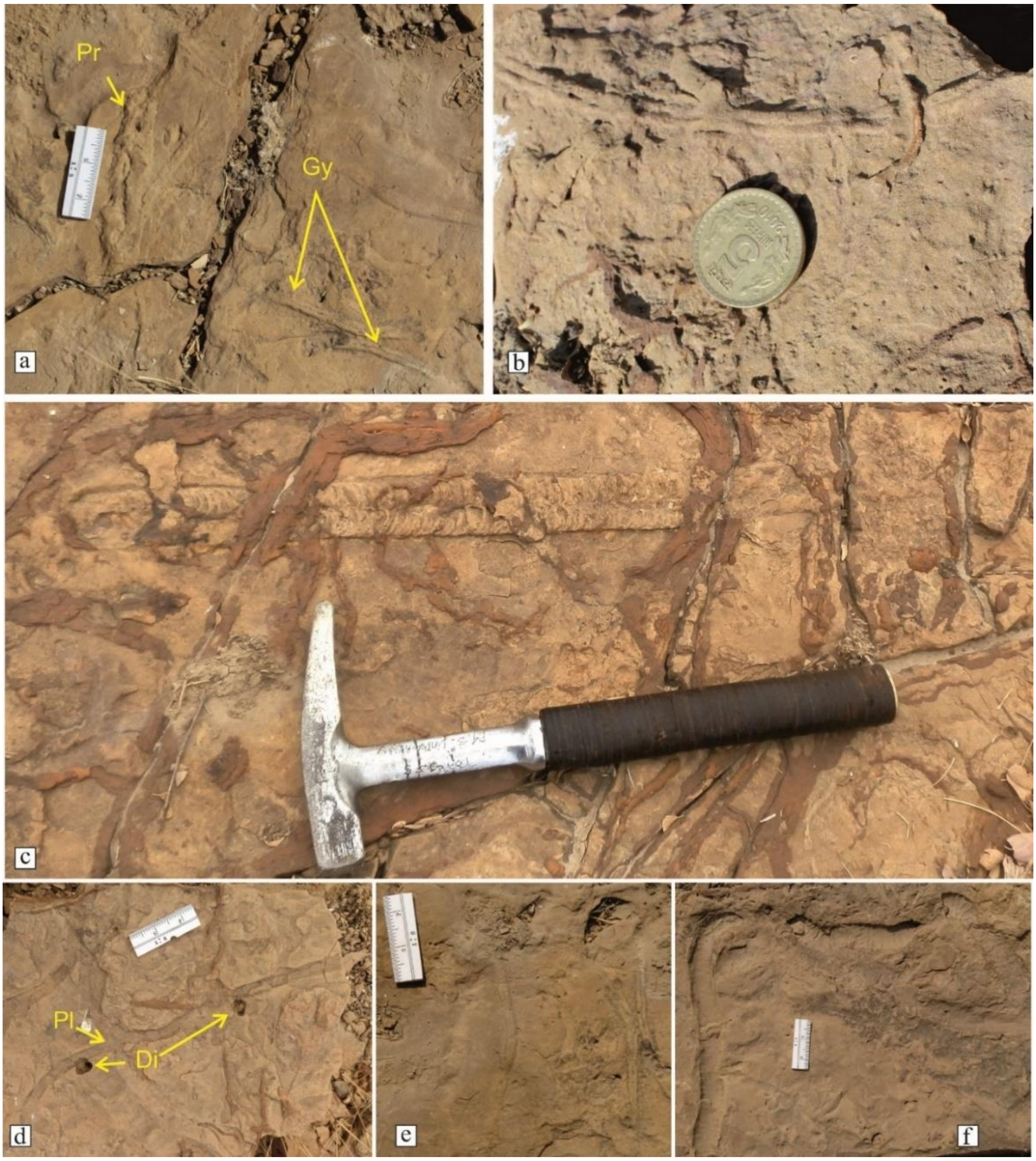

Plate 6.6 Trace fossils of *Protovirgularia* assemblage. (a) *Protovirgularia* (Pr) in association with *Gyrochorte* (Gy) in sandy allochemic limestone facies of Bambhanka Member. (b) *Didymaulichnus* observed in sandy allochemic limestone facies of Bambhanka Member (Scale: coin diameter = 2.3 cm). (c) *Protovirgularia* (Scale: hammer = 35 cm). (d) *Planolites* (Pl) in association with *Diplocraterion* (Di), (e) *Gyrochorte* and (f) *Taenidium* are observed in micritic sandstone facies of Bambhanka Member.

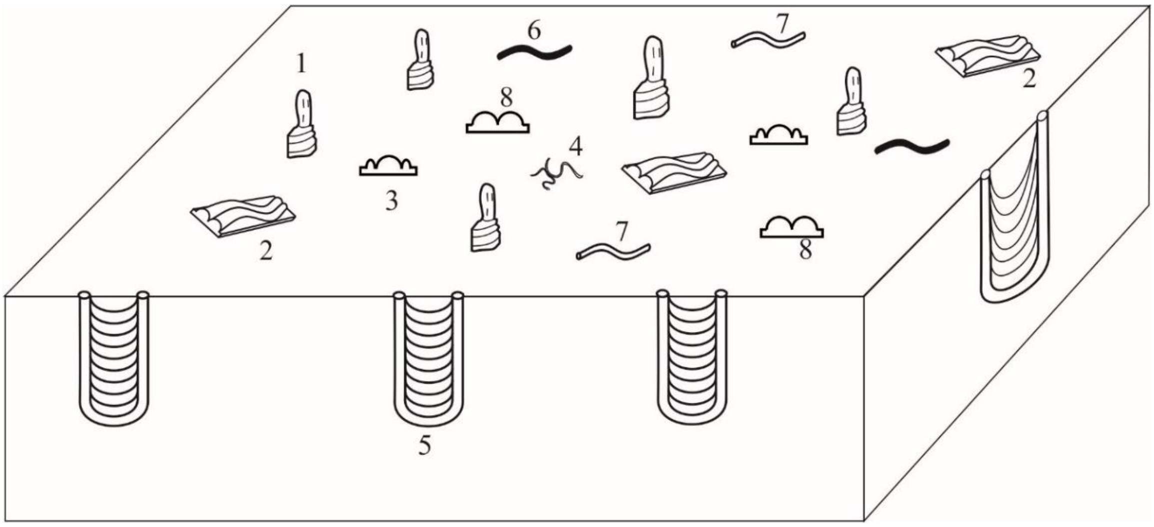

Fig. 6.6 Diagrammatic representation of *Protovirgularia* assemblage. 1. *Protovirgularia*, 2. *Didymaulichnus*, 3. *Curvolithus*, 4. *Taenidium*, 5. *Diplocraterion*, 6. *Palaeophycus*, 7. *Planolites*, 8. *Gyrochorte*.

6.3.1.7 *Hillichnus* Assemblage

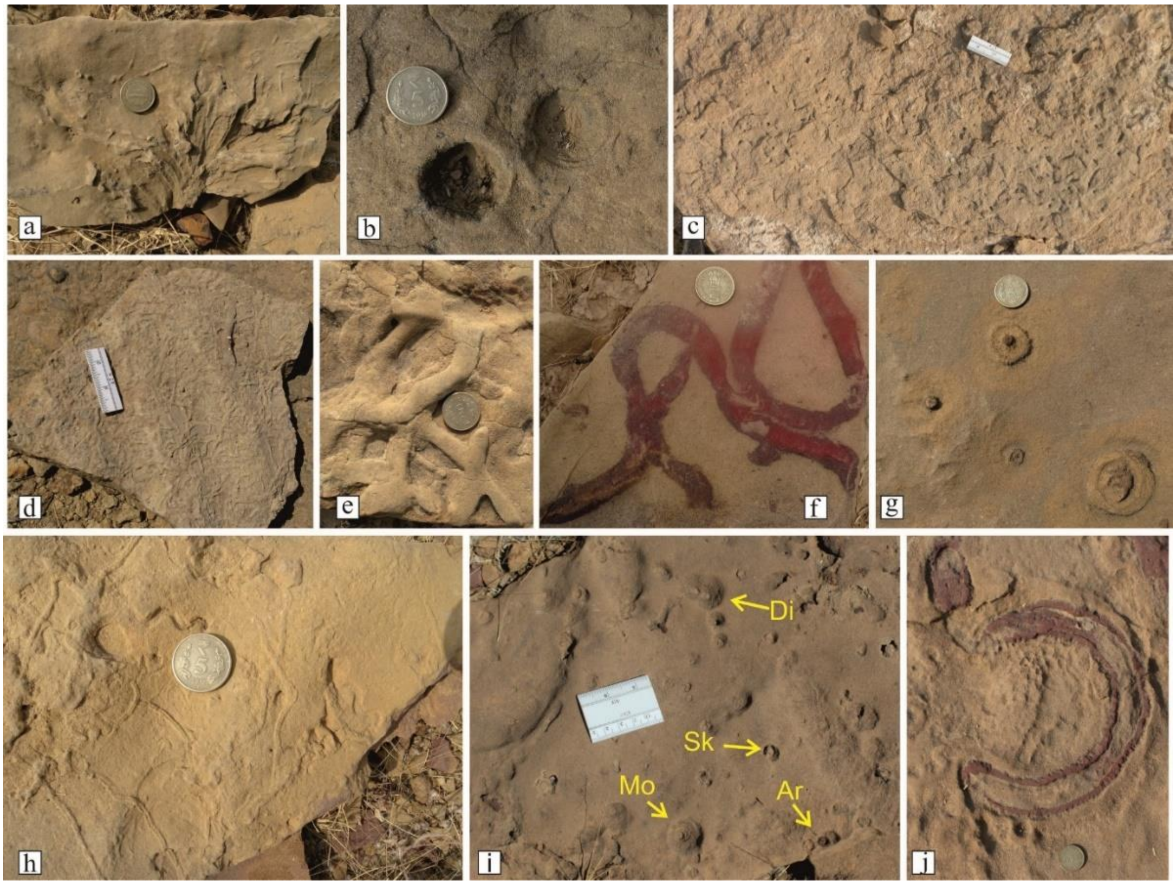

Plate 6.7 Trace fossils of *Hillichnus* assemblage. (a) Level C of *Hillichnus* in micritic sandstone facies of Ratanpur Sandstone Member in Khadir Island (Scale: coin diameter = 2.3 cm). (b) *Arenicolites* observed in micritic sandstone facies of Ratanpur Sandstone Member in Khadir Island (Scale: coin diameter = 2.3 cm). (c) *Chondrites* observed in micritic sandstone facies of Ratanpur Sandstone Member. (d) *Planolites* in thinly bedded micritic sandstone facies in Ratanpur Sandstone Member. (e) *Thalassinoides* observed in micritic sandstone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (f) *Taenidium* in micritic sandstone facies exposed in the western part of Khadir Island (Scale: coin diameter = 2.3 cm). (g) *Laevicyclus* observed in micritic sandstone facies exposed in the back slop of Khadir Island (Scale: coin diameter = 2.3 cm). (h) *Gyrochorte* observed in thinly bedded micritic sandstone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (i) *Diplocraterion* (Di) in association with *Monocraterion* (Mo), *Arenicolites* (Ar) and *Skolithos* (Sk).

Hillichnus assemblage is observed in micritic sandstone facies of Ratanpur Sandstone Member and are exposed at the back slope of Khadir Island (Fig. 6.6). The ichnoassemblage is dominated by *Hillichnus.* The *Hillichnus* specimens, however, are small as compared to other specimens observed in other localities. The assemblage includes *Hillichnus* (Plate 6.7a), *Arenicolites* (Plate 6.7b), *Chondrites* (Plate 6.7c), *Planolites* (Plate 6.7d), *Thalassinoides* (Plate 6.7e), *Taenidium* (Plate 6.7f), *Laevicyclus* (Plate 6.7g), *Gyrochorte* (Plate 6.7h), *Diplocraterion* (Plate 6.7i) *Skolithos* (Plate 6.7i) and *Ophiomorpha* (Plate 6.7i).

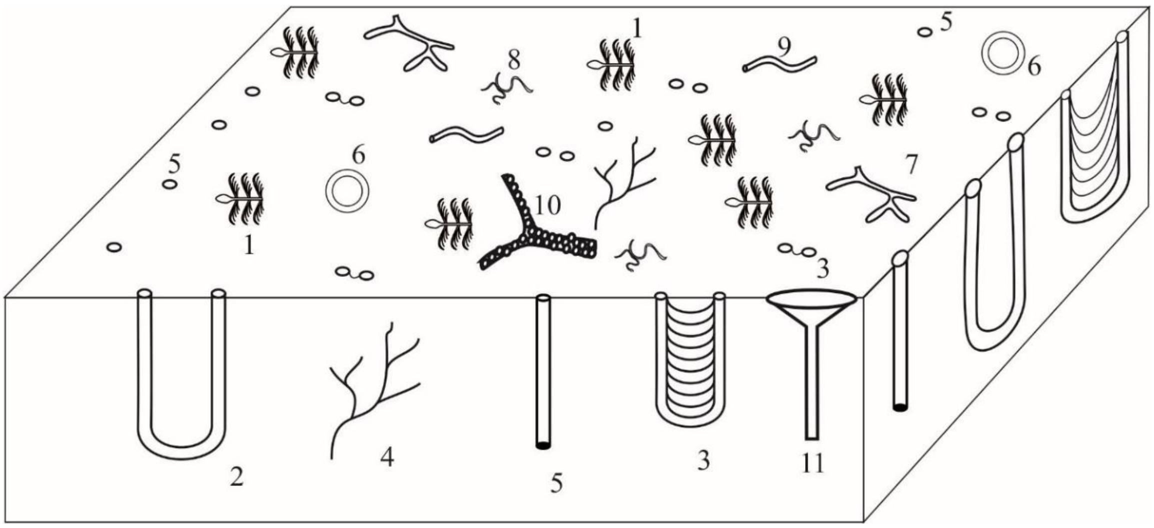

Fig. 6.7 Diagrammatic representation of *Hillichnus* assemblage. 1. *Hillichnus,* 2. *Arenicolites,* 3. *Diplocraterion,* 4. *Chondrites,* 5. *Skolithos,* 6. *Laevicyclus,* 7. *Thalassinoides* 8. *Taenidium,* 9. *Planolites. 10. Ophiomorpha, 11. Monocraterion.*

The occurrences of relatively small feeding *Hillichnus, Chondrites intricatus* indicate the presence of low oxygenated condition level on the substrate in direct contact with the oxygen deficient bottom waters (Neto de Carvalho and Rodrigues, 2007). The occurrences of small size suspension-feeding *Arenicolites, Diplocraterion, Planolites* and *Skolithos* also suggest an adaptive response to the high salinity-related, physiochemical stresses (Beynon et al., 1988) in high energy condition or harsh paleoenvironment. However, in the western side of the island, the micritic sandstone facies increased in the carbonate content to form cross bedded sandy allochemic limestone where it is intensely bioturbated by *Chondrites targioni* suggesting well oxygenated, nutrient rich substrate in moderate energy condition. The occurrences a small size *Chondrites* trace fossils is only in a local scale.

6.3.2 Ichnoassemblage of Bela Island

The Jurassic succession of Bela is bioturbated preferentially in micritic sandstone and sandy allochemic limestone facies of Hadibhadang Sandstone and Ratanpur Sandstone members. The traces fossils comprised 23 ichnospecies belonging to 17 ichnogenera forming three ichnoassemblages including *Monocraterion, Thalassinoides,* and *Hillichnus.*

6.3.2.1 *Monocraterion* Assemblage

It is recurring ichnoassemblage and *Monocraterion* occurs as a predominant ichnogenus in a thickly bedded micritic sandstone facies of the Hadibhadang Sandstone Member in Khadir Formation and in thinly bedded micritic sandstone in Ratanpur Sandstone Member of Gadhada Formation in Bela Island (Fig. 6.7). In Hadibhadang Sandstone Member, the aperture of the trace fossil *Monocraterion* are highly ferruginised due to secondary fluid intrusion. The trace maker of *Monocraterion* is similar to that of *Skolithos* which is vermiform annelids. The main difference between the two is the lack of funnel-shaped aperture in *Skolithos* (Alpert, 1974). The occurrences of *Monocraterion* as predominant ichnogenera suggest high rate of sedimentation in high energy condition in delta front environment or shoreface bar environment.

In Ratanpur Sandstone Member, the *Monocraterion* (Plate 6.7a) occurs in association with *Diplocraterion* (Plate 6.7a), *Rhizocorallium* (Plate 6.7b), *Arenicolites* (Plate 6.7d), *Helicolithus* (Plate 6.7c), *Lockeia* (Plate 6.7e), *Planolites* (Plate 6.7f), *Protovirgularia*, *Palaeophycus* (Plate 6.7g), *Thalassinoides* (Plate 6.7h) and *Skolithos* (Plate 6.7i). The assemblage is dominated by

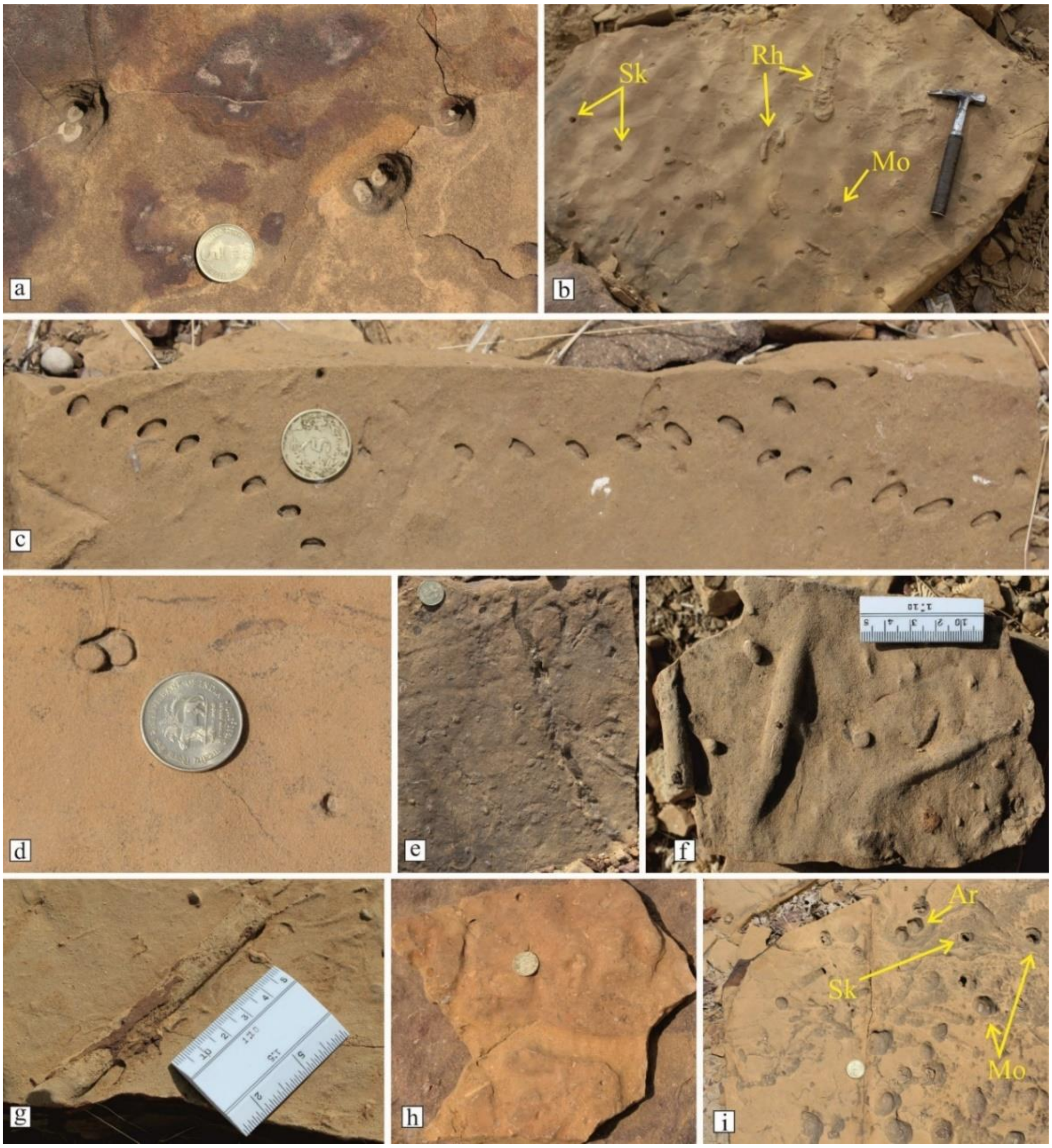

Plate 6.8 Trace fossils of *Monocraterion* assemblage in Bela Island. (a) *Diplocraterion* observed in association with *Monocraterion* in micritic sandstone facies in Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (b) *Rhizocorallium* (Rh) observed in association with *Monocraterion* (Mo) and *Skolithos* (Sk) in a rippled micritic sandstone facies in Ratanpur Sandstone Member. (c) *Helicolithus* (Scale: coin diameter = 2.3 cm). (d) *Arenicolites* (Scale: coin diameter = 2.3 cm). (e) *Lockeia* (Scale: coin diameter = 2.3 cm). (f) *Planolites* in association with *Skolithos* (g) *Palaeophycus*, (h) *Thalassinoides* (Scale: coin diameter = 2.3 cm). (i) *Monocraterion* (Mo) observed in association with *Arenicolites* (Ar) and *Skolithos* (Sk) in micritic sandstone facies in Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm).

vertical structures such as *Arenicolites, Diplocraterion* (Plate 6.7a), *Monocraterion* and *Skolithos* suggesting agitating and shifting substrate. The occurrences of *Helicolithus* suggest nutrient-rich condition (Patel et al., 2014). The occurrences of horizontal dwelling and deposit feeding traces in association with the vertical dwelling traces suggest well oxygenated bottom surface and organic rich (Ekdale, 1988).

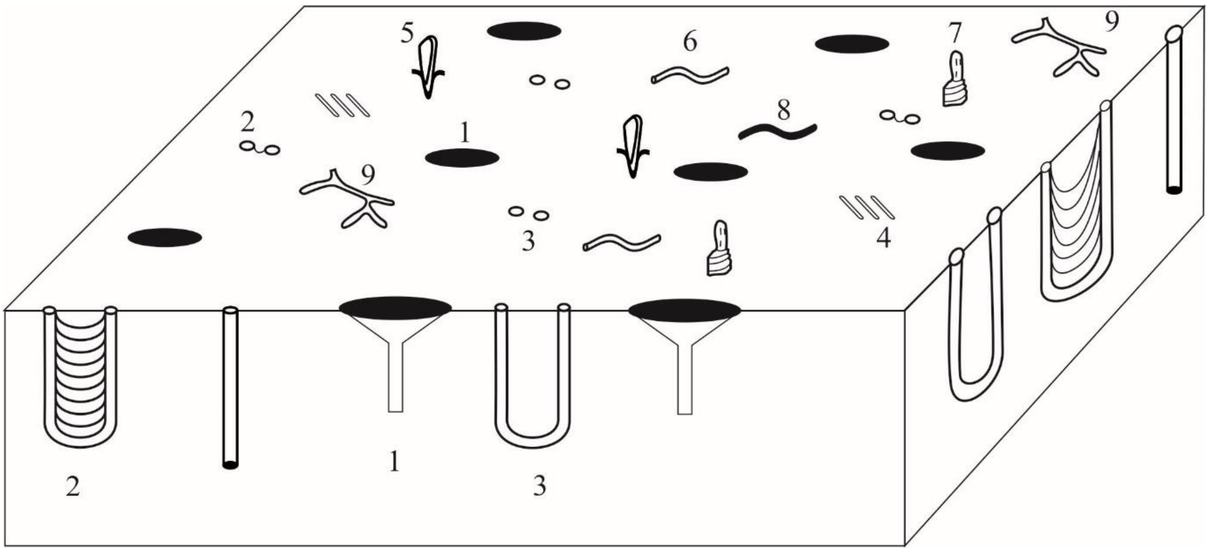

Fig. 6.8 Diagrammatic representation of *Monocraterion* ichnoassemblage. 1. *Monocraterion,* 2. *Diplocraterion,* 3. *Arenicolites,* 4. *Helicolithus,* 5. *Lockeia,* 6. *Planolites,* 7. *Protovirgularia,* 8. *Palaeophycus,* 9. *Thalassinoides.*

6.3.2.2 *Hillichnus* Assemblage

Level C of *Hillichnus* dominated the assemblage which is a horizontal substrate feeding structure. Other feeding traces include *Planolites, Phycodes, Rhizocorallium, Taenidium.* The dominance of horizontal feeding and grazing structures over the vertical suspension feeding structures (*Arenicolites* and *Diplocraterion*) suggest nutrient rich and well oxygenated substrate in low to moderate energy condition in lower shoreface environment.

Hillichnus (Plate 6.9a) assemblage is observed in thinly bedded sandy allochemic limestone faces of Ratanpur Sandstone Member, Gadhada Formation in Bela Island. It occurs in association with *Arenicolites* (Plate 6.9b), *Diplocraterion* (Plate 6.9b), *Rhizocorallium, Planolites* (Plate 6.9c), *Skolithos, Palaeophycus* (Plate 6.9d), *Protovirgularia, Didymaulichnus, Taenidium* (Plate 6.9e), and *Phycodes* (Plate 6.9f).

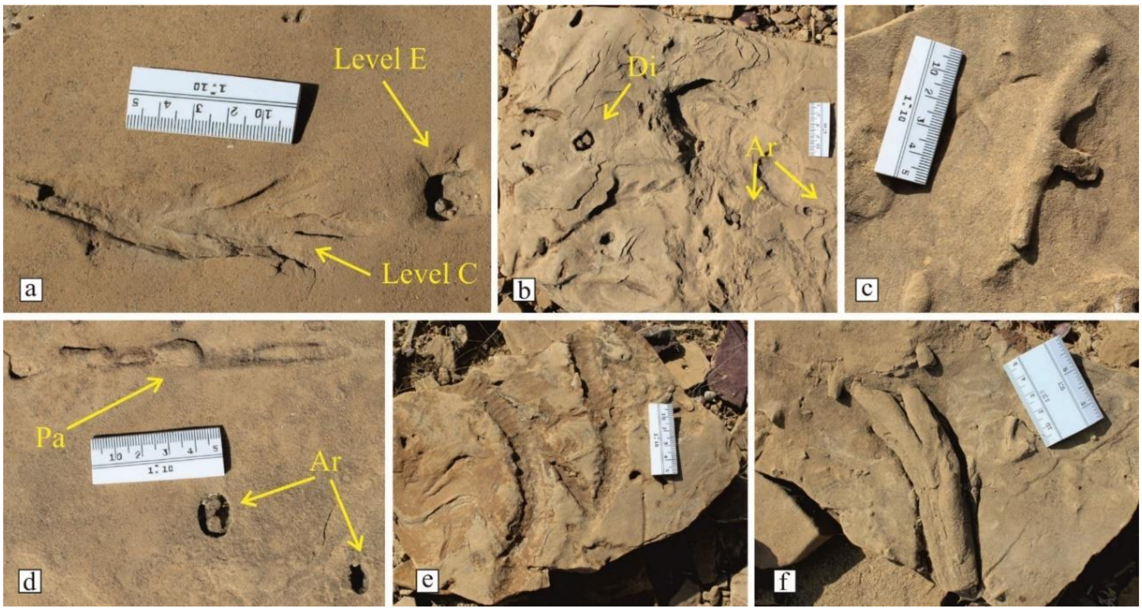

Plate 6.9 *Hillichnus* assemblage observed in Bela Island. (a) Level C of *Hillichnus* in association with Level E. (b) Pared tubes *Arenicolites* in association with *Diplocraterion.* (c) *Planolites* (d) *Palaeophycus* with ferruginised lining in association with *Diplocraterion.* (e) *Taenidium.* (f) *Phycodes.*

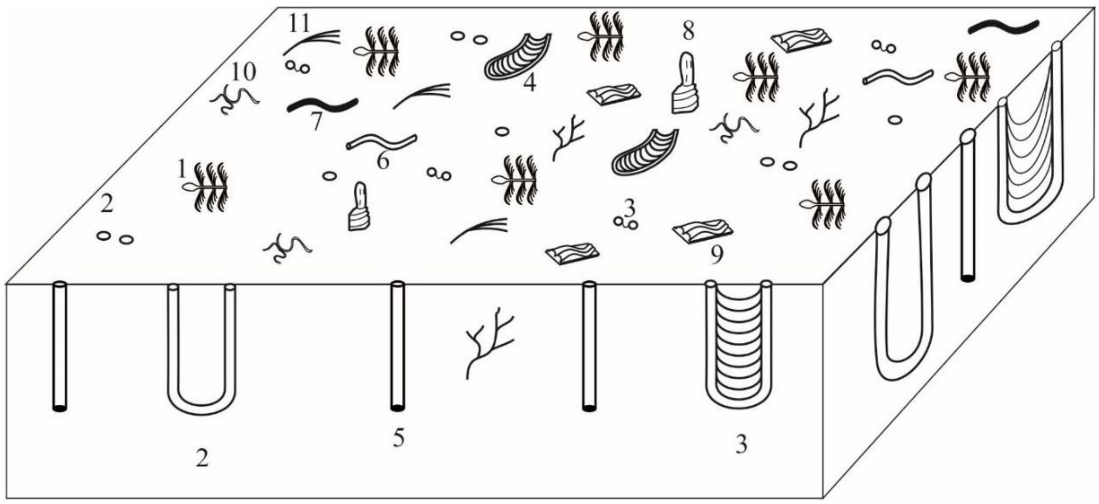

Fig. 6.9 Diagrammatic representation of *Hillichnus* assemblage. 1. *Hillichnus* 2. *Arenicolites,* 3. *Diplocraterion,* 4. *Rhizocorallium,* 5. *Skolithos,* 6. *Planolites,* 7. *Palaeophycus,* 8. *Protovirgularia,* 9. *Didymaulichnus,* 10. *Taenidium,* 11. *Phycodes.*

6.3.2.3 *Thalassinoides* Assemblage

Thalassinoides assemblage is observed in a thinly bedded micritic sandstone facies of Hadibhadang Shale Member of Khadir Formation in Bela Island. It occurs as monodominant ichnogenus at the shale-sandstone interface. *Thalassinoides* usually is interpreted as a fodinichnia burrow constructed by infaunal crustaceans or other kinds of arthropods, which are obligate or facultative deposit feeders (Ekdale, 1992). *Thalassinoides* is reported in a range of environments from salt marshes to outer shelf. The occurrence of individual ichnogenera in a thinly bedded micritic sandstone intercalated with shales suggest oxygenated soft but fairly cohesive substrate (Bromley and Frey, 1974; Bromley 1996). The dominance of horizontal feeding traces suggests fluctuating environmental conditions (Beynon et al., 1988; Beynon and Pemberton 1992; Pattison 1992).

Plate 6.10 Mono occurrence of *Thalassinoides* in micritic sandstone facies of Hadibhadang Shale Member in Bela Island.

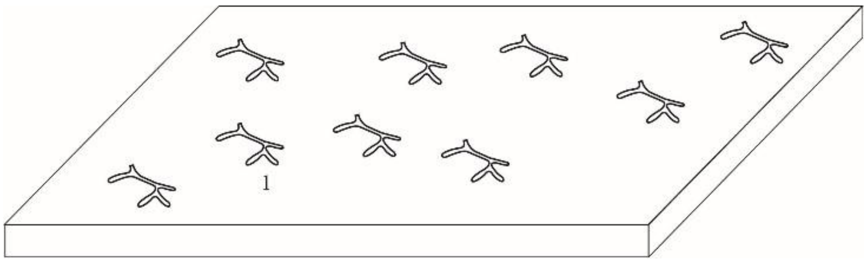

Fig. 6.10 Diagrammatic representation *Thalassinoides* assemblage. 1. *Thalassinoides*

6.3.3 Ichnoassemblage of Chorar Island

The Middle Jurassic succession of the Chorar Island consist 20 identifiable ichnospecies belonging to 16 ichnogenera. These trace fossils are Characterized by five recurring trace fossils assemblage which include *Hillichnus*, *Rhizocorallium*, *Gyrochorte*, *Thalassinoides* and *Skolithos* assemblages.

6.3.3.1 *Hillichnus* Assemblage

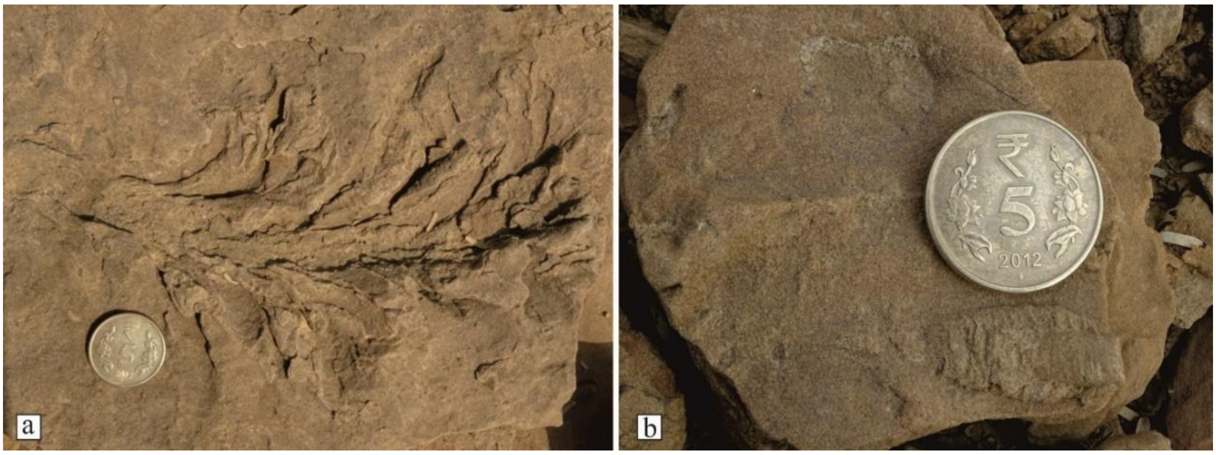

Plate 6.11 Trace fossils for *Hillichnus* assemblage (Scale: coin diameter = 2.3 cm). (a) Level C of *Hillichnus* and (b) *Protovirgularia* observed in sandy allochemic limestone of Hadibhadang Sandstone Member (Scale: coin diameter = 2.3 cm).

Hillichnus assemblage is observed in sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation in Chorar Island (Fig. 6.9). It comprises of abundant *Hillichnus lobosensis* (Plate 6.10a) and *Protovirgularia* (Plate 6.10b).

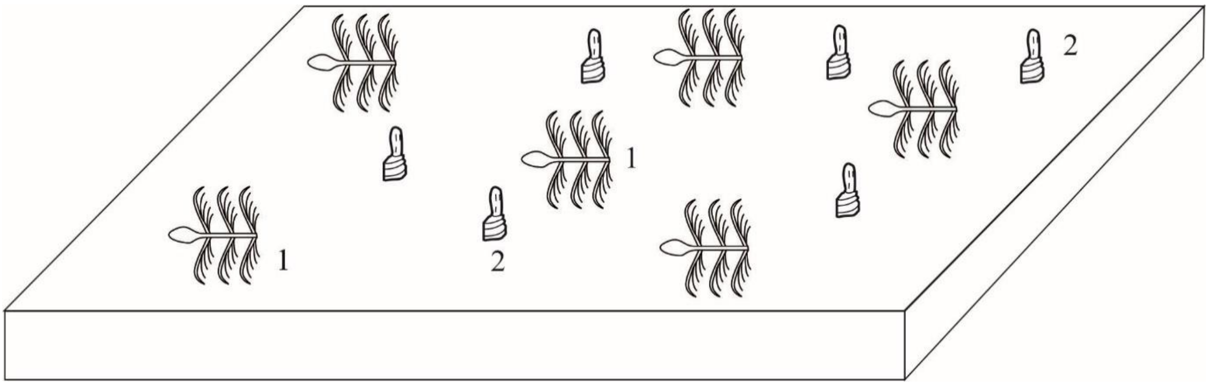

Fig. 6.11 Diagrammatic representation of *Hillichnus* assemblage. 1. *Hillichnus* 2. *Protovirgularia*.

Complex *Hillichnus* burrow suggest deposit feeding behaviour, where the siphon of the trace maker, tellinacean bivalves has made successive probes or excursions within the sediment, and exploited a high proportion of the chosen laminae for food (Bromley et al., 2003; Darngawn et al., 2018). The dominance of deposit feeders (Fig. 6.10) in sandy allochemic limestone characterized by fine grain, angular and moderately sorted quartz grains with micrites and allochems suggest nutrient-rich substrate in low energy condition of lower shoreface environment (Darngawn et al., 2018).

6.3.3.2 *Rhizocorallium* Assemblage

Plate 6.12 Trace fossils for *Rhizocorallium* assemblage. (a) *Rhizocorallium* (Scale: coin diameter = 2.3 cm) (b) *Curvolithus* in association with *Planolites* (Scale: coin diameter = 2.3 cm) (c) *Gyrochorte* in sandy allochemic limestone of Hadibhadang Sandstone Member of Chorar Island (Scale: coin diameter = 2.3 cm).

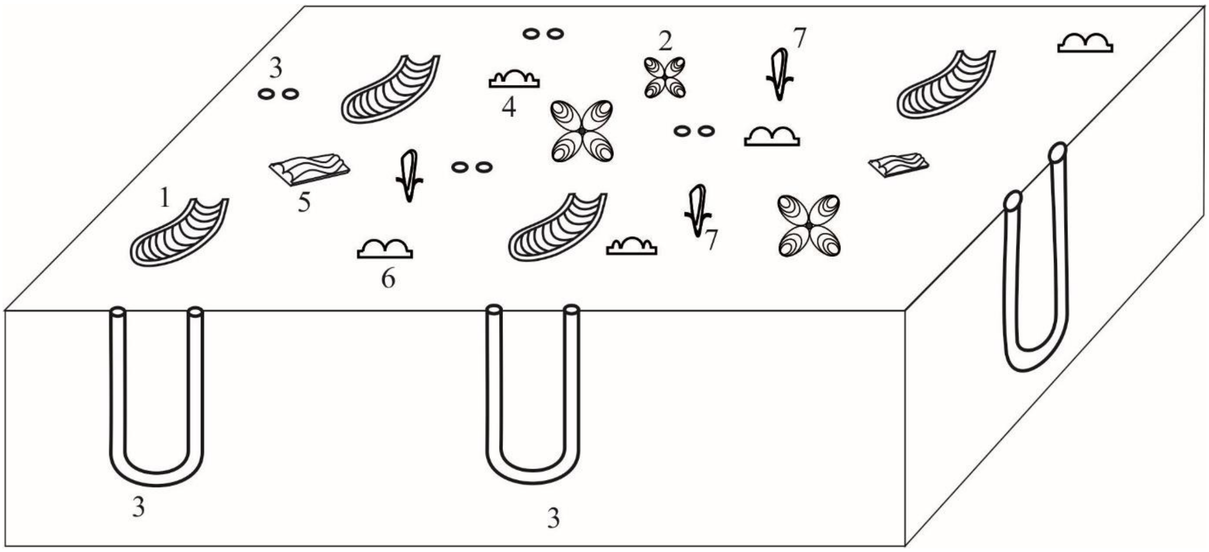

Fig. 6.12 Diagrammatic representation of *Rhizocorallium* assemblage. 1. *Rhizocorallium*, 2. *Asterosoma*, 3. *Arenicolites*, 4. *Curvolithus*, 5. *Didymaulichnus*, 6. *Gyrochorte* 7. *Lockeia*.

Rhizocorallium assemblage is observed in sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. This assemblage occurs in association with *Rhizocorallium* (Plate 6.11a), *Asterosoma* (Plate 5.1a), *Arenicolites* (5.11b), *Curvolithus* (Plate

6.11b), *Didymaulichnus* (Plate 5.2a), *Lockeia* (Plate 5.11b) *Planolites* (Plate 6.11b). and *Gyrochorte* (Plate 6.11c) The *Rhizocorallium commune* is a member of *Cruziana* Ichnofacies Knaust (2013) often observed in soft substrate with a Bathymetry between FWWB and SWB (MclLroy, 2004).

The *Rhizocorallium* assemblage (Fig. 6.10) is dominated by deposit feeders suggesting a well-oxygenated, nutrient-rich substrate. Its association with suspension feeding vertical traces like *Arenicolites* suggest fluctuating or agitating energy conditions in the middle shoreface environment (Häntzschel, 1975).

6.3.3.3 *Gyrochorte* Assemblage

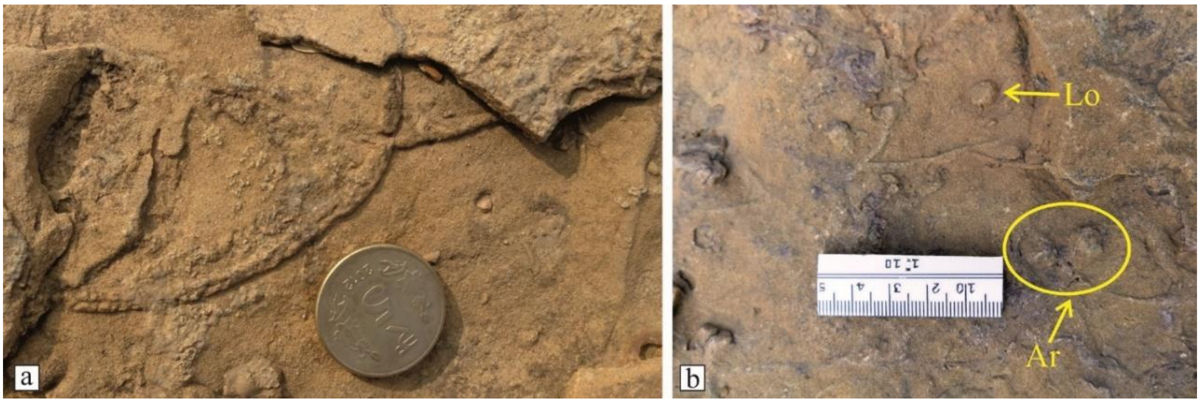

Plate 6.13 Trace fossils for *Gyrochote* assemblage. (a) *Gyrochorte* (Scale: coin diameter = 2.3 cm) (b) Paired tubes of *Arenicolites* (Ar) in association with *Lockeia* (Lo) and *Planolites*.

Gyrochorte assemblage is observed in sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. It is characterized by the occurrences of *Gyrochorte* (Plate 6.12a), *Arenicolites* (Plate 6.12b), *Megagrapton* (Plate 5.4a) and *Palaeophycus* (Fig. 5.5c). The occurrences of suspension feeders, grazing traces, and deposit feeders indicate nutrient-rich substrate, well-oxygenated bottom substrate, and agitating energy conditions. However, the occurrence of *Palaeophycus* which is a eurybathic form (Pemberton and Frey, 1982) in fine-grain with small ripples on the substrate indicates low energy condition thereby indicating fluctuating energy condition (Darngawn et al., 2018). The occurrences of *Gyrochorte* represents shallow storm-dominated shelf where it is abundantly developed in rippled mixed carbonate-siliciclastic grainstone (Picard and Uygur, 1982; Lord, 1985). The presence of *Arenicolites* (agitating condition), *Palaeophycus* (low energy condition) and *Gyrochorte* (storm-dominated shelf) suggest that the assemblage represent fluctuating energy condition in shoreface environment.

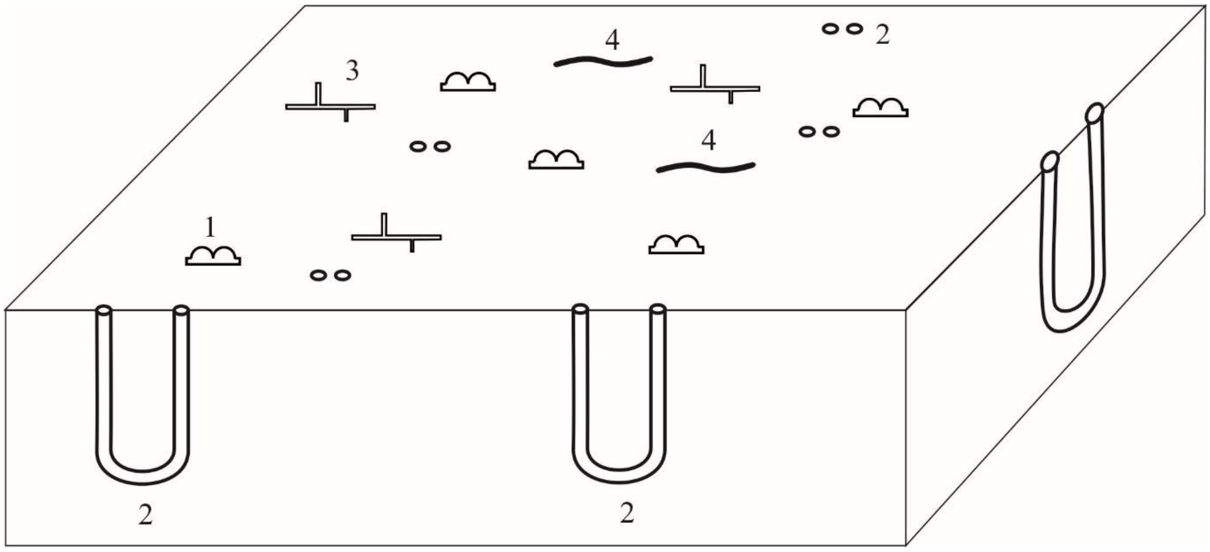

Fig. 6.13 Diagrammatic representation of *Gyrochorte* assemblage. 1. *Gyrochorte,* 2. *Arenicolites,* 3. *Megagrapton,* 4. *Palaeophycus*.

6.3.3.4 *Thalassinoides* Assemblage

Plate 6.14 *Thalassinoides* assemblage. (a) Predominant occurrence of *Thalassinoides* at the sediment-sediment interface of sandy allochemic limestone (Scale: hammer=15 cm). (b) Wrinkled with discontinuous striation of *Halopoa* in sandy allochemic limestone of Hadibhadang Sandstone Member in Chorar Island (Scale: coin diameter = 2.3 cm).

The *Thalassinoides* assemblage is a recur and observed as a monodominant ichnogenus occurring at the sediment-sediment interface of sandy allochemic limestone (Plate 6.13a) of Hadibhadang Sandstone Member of Khadir Formation. It is also observed in association with *Halopoa* (Plate 6.13b), *Palaeophycus* (Plate 5.4e-f) and *Thalassinoides* (Plate 5.18c) in micritic sandstone of Hadibhadang Sandstone Member in Chorar Island.

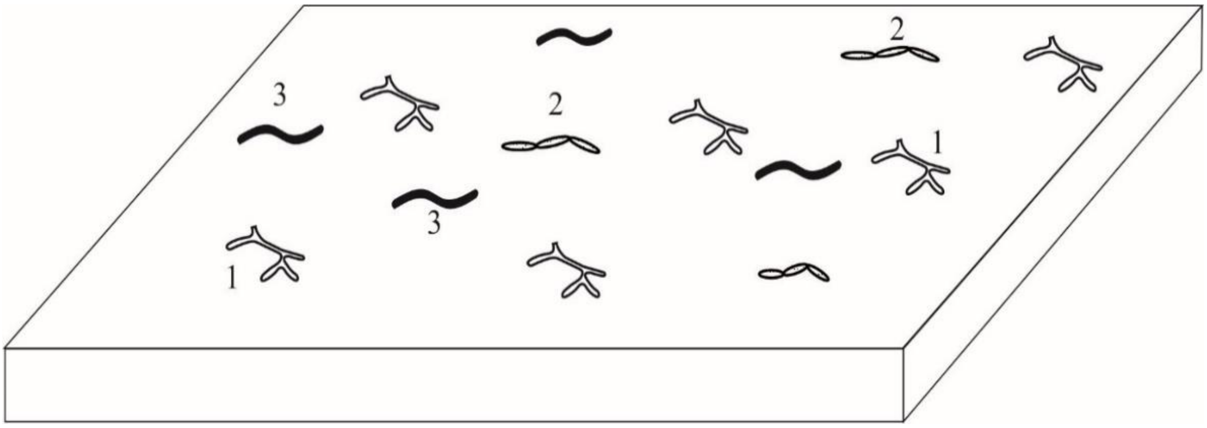

Fig. 6.14 Diagrammatic representation of *Thalassinoides* assemblage. 1. *Thalassinoides*, 2. *Halopoa*, 3. *Palaeophycus*.

Thalassinoides are frequently related to the oxygenated situations and soft but fairly cohesive substrates (Bromley and Frey, 1974; Kern and Warme, 1974) that supported the occurrence of a monodominant large size box-work burrows in sandy allochemic limestone. The dominance of horizontal feeding structures suggests low to moderate energy conditions, unstable, soft, unconsolidated substrate of the lower shoreface environment (Darngawn et al., 2018).

6.3.3.5 *Skolithos* Assemblage

Skolithos assemblage is a recur and observed in cross-bedded white sandstone and ferruginous sandstone facies of Ratanpur Sandstone Member of Gadhada Formation (Fig. 6.13). It is characterized by *Skolithos* (Plate 5.15 b, c), *Planolites* (Plate 6.14a) and *Thalassinoides* (Plate 6.14b) in cross-bedded white sandstone facies while it is also observed in association with *Arenicolites* (Plate 6.14c), *Diplocraterion* (Plate 6.14c), *Palaeophycus* (Plate 6.14d) and *Skolithos* (Plate 6.14c), in ferruginous sandstone facies of Ratanpur Sandstone Member of the Gadhada Formation.

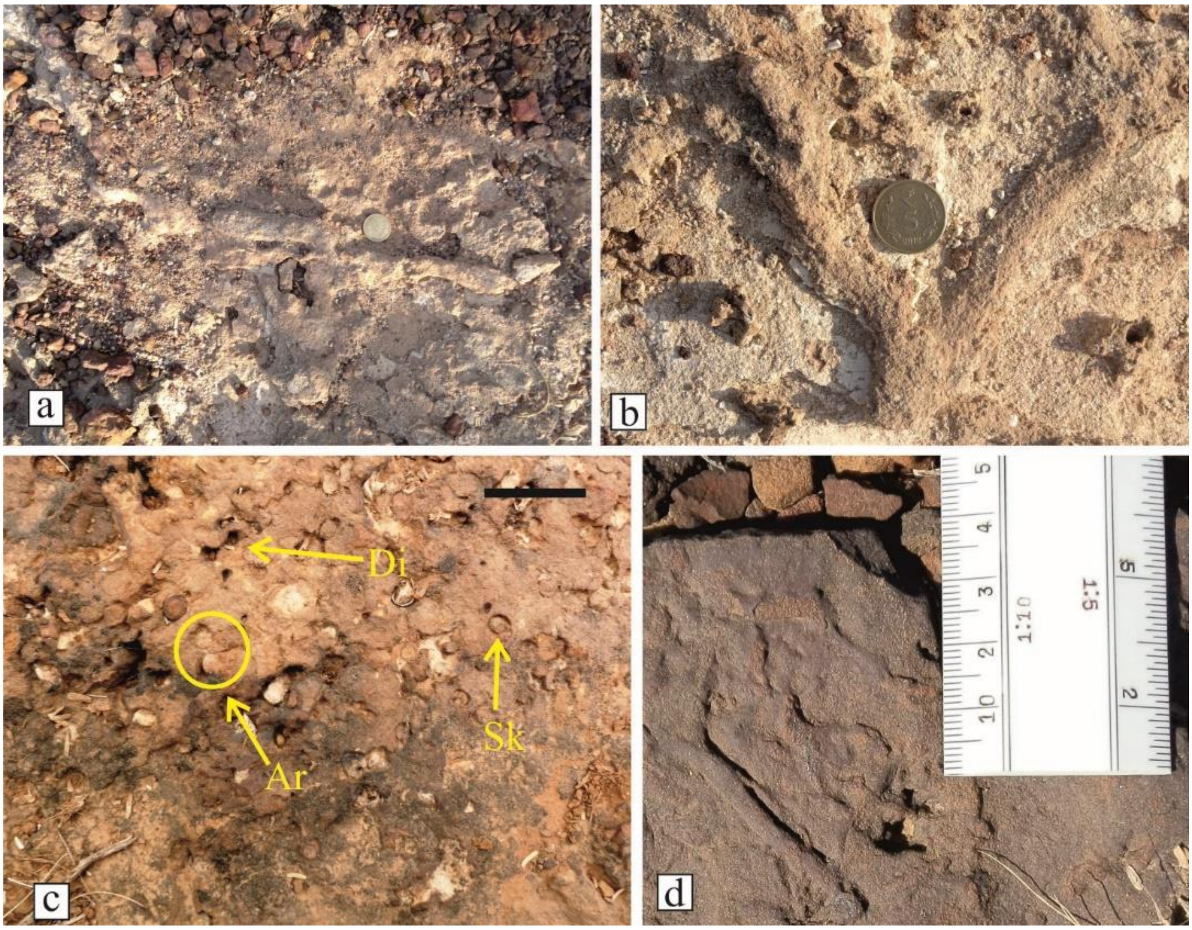

Plate 6.15 Trace fossils of *Skolithos* assemblage. (a) Highly weathered *Planolites* (Scale: coin diameter = 2.3 cm). (b) Highly weathered *Thalassinoides* burrows are observed in friable cross-bedded white sandstone facies of Ratanpur Sandstone Member (Scale: coin diameter = 2.3 cm). (c) *Skolithos* (Sk) in association with *Arenicolites* (Ar) (Scale: bar = 5 cm) and *Diplocraterion* (Di). (d) *Palaeophycus* observed in ferruginous facies of Ratanpur Sandstone Member in Chorar Island.

The ichnoassemblage is dominated by vertical dwelling burrows of opportunistic suspension feeders indicating unconsolidated, soft shifting substrate and high wave and current energy conditions of middle shoreface environment (Darngawn et al., 2018). The occurrence of *Planolites* and *Thalassinoides* in cross-bedded white sandstone facies suggest cohesive substrate with low to medium energy condition while the dominance of vertical traces like *Arenicolites, Diplocraterion* and *Skolithos* suggest agitating, medium to high energy condition with shifting substrate.

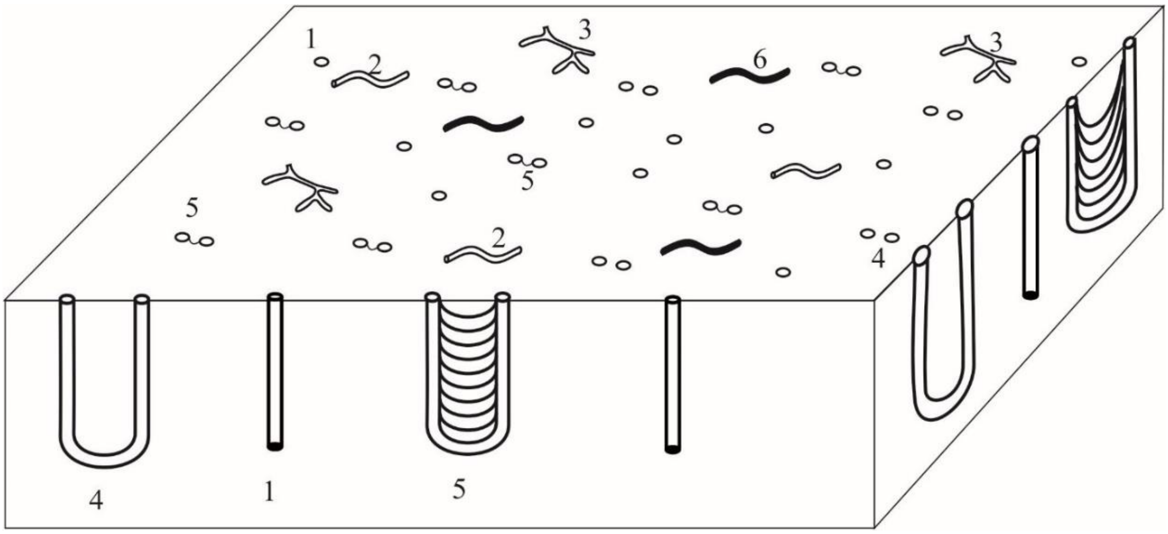

Fig. 6.15 Diagrammatic representation of *Skolithos* assemblage. 1. *Skolithos,* 2. *Planolites,* 3. *Thalassinoides,* 4. *Arenicolites,* 5. *Diplocraterion,* 6. *Palaeophycus.*

6.4 ICHNOFACIES

An ichnofacies is an association of trace fossils that is recurrent in time and space, and that directly reflects environmental conditions such as bathymetry, salinity and substrate character (Bromley, 1996). It differs from ichnocoenoses as the latter refers to a group of biogenic structures that result from the work of a single community (Buatois and Mángano, 2011). The ichnofacies model introduced by Seilacher (1964a) reflects specific combinations of organism behaviour (ethology) and constitutes the benchmark of animal-sediment responses to optimum environmental conditions (Miller, 2007). Seilacher (1964a) introduce six ichnofacies based on bathymetry (*Skolithos, Cruziana, Zoophycos* and *Nereites* Ichnofacies), omission surface reflecting hard to firm surface (*Glossifungites* Ichnofacies) and non-marine environments, *Scoyenia* Ichnofacies.

Subsequently, new ichnofacies were introduced by subsequent workers to encompass additional paradigm. Ichnofacies can be broadly divided into four main categories: soft ground marine ichnofacies, substrate controlled ichnofacies, continental invertebrate ichnofacies, and vertebrate ichnofacies. Soft ground marine ichnofacies include *Psilonichnus* (Frey and Pemberton, 1987), *Skolithos* (Seilacher, 1963, 1967a), *Cruziana* (Seilacher 1954), *Zoophycos* (Seilacher, 1954, 1967b), and *Nereites* (Seilacher 1954) Ichnofacies. Substrate controlled ichnofacies include *Glossifungites* (Seilacher, 1967a), *Trypanites* (Frey and Seilacher, 1980), *Gnathichnus* (Bromley and Asgaard, 1993), and *Teredolites* (Bromley et al., 1984) Ichnofacies. Continental archetypal ichnofacies comprises of six ichnofacies which include the *Scoyenia*

(Seilacher, 1967a), *Mermia* (Buatois and Mángano, 1995), *Coprinisphaera* (Genise et al., 2000), *Termitichnus* (Smith et al., 1993), *Celliforma* (Smith et al., 1993), and *Octopodichnus* (Hunt and Lucas 2007) *Entradichnus* (Ekdale et al., 2007) Ichnofacies. Hunt and Lucas (2007) five archetypal tetrapod ichnofacies for Vertebrate ichnofacies category for continental and coastal-plain environments include *Chelichnus, Grallator, Brontopodus, Batrachichnus* and *Characichichnos* Ichnofacies.

Ichnofacies	Predominant trace fossil types	Inferred control (Seilacher)
Skolithos	Vertical traces of suspension feeders	Bathymetry (above fair-weather wave base,
Cruziana	Cruziana Horizontal and vertical deposit feeders	Bathymetry (between FWWB and storm wave base, SWB)
Zoophycos	Pervasive deposit feeders	Bathymetry (shelf and slope below SWB)
Nereites	Shallow burrows with complex morphologies showing highly programmed behaviours	Bathymetry (basin-floor with turbidites)
Glossifungites	Traces characteristically preserving scratches, mostly of suspension feeders	Firm surfaces associated with incipient submarine lithification
Scoyenia	Non-marine traces	Freshwater conditions (red-bed deposition)

Table. 6.5 The archetypal Seilacherian ichnofacies (MclLroy, 2004)

The succession of Khadir Island, Bela and Chorar are bioturbated by abundant and recurring yet diverse groups of trace fossils at different stratigraphic levels representing a particular environmental condition. These groups of trace fossils form six ichnoassemblage which include *Diplocraterion, Hillichnus, Lockeia, Planolites-Palaeophycus, Rhizocorallium* and *Protovirgularia* assemblage in Khadir Island; *Monocraterion, Hillichnus* and *Thalassinoides,* assemblage in Bela Island while *Hillichnus, Rhizocorallium, Gyrochorte, Thalassinoides* and *Skolithos* assemblage in Chorar Island. These ichnoassemblage typically show shallow marine assemblages where the association represents agitating and shifting substrate above fair-weather wave base to moderate-low energy between storm weather wave base to fair weather wave base of *Skolithos* and *Cruziana* Ichnofacies respectively. These ichnofacies also suggest suggests marine loose and soft-ground where high and low energy traces were produced (Seilacher (1967). These assemblages also often occur together as a combined *Skolithos-Cruziana* Ichnofacies. The occurrence of mixed *Skolithos-Cruziana* Ichnofacies intermittently reflect poor substrate consistency and stressed environments. The Jurassic clastic, non-clastic and mixed siliciclastic-carbonate succession of Khadir, Bela and Chorar Islands display similar recurring ichnofacies at different stratigraphic levels which include *Skolithos, Cruziana* and a mixed *Skolithos-Cruziana* Ichnofacies (Fig. 6.14).

6.4.1 *Skolithos* Ichnofacies

The *Monocraterion, Diplocraterion* and *Skolithos* assemblages belong to the *Skolithos* Ichnofacies. This ichnofacies shows recurrence in space and time, and is characterized by the dominance of vertical traces which include *Arenicolites, Monocraterion, Diplocraterion* and *Skolithos* with fewer number of occurrences of *Rhizocorallium, Thalassinoides* and *Palaeophycus.* This ichnofacies is mostly observed in micritic sandstone facies at different stratigraphic levels in different islands. It is observed in thick to thinly bedded micritic sandstone facies of Hadibhadang Shale Member in Khadir Island, and in thinly bedded micritic sandstone in Ratanpur Sandstone Member of Gadhada Formation in Bela Island while in cross-bedded white sandstone and ferruginous sandstone facies of Ratanpur Sandstone Member in Chorar Island.

The occurrences of *Diplocraterion, Arenicolites, Skolithos* as a small structure in thinly bedded micritic sandstone represent traces of opportunistic organism in moderate to relatively high energy conditions. These trace fossils developed in muddy to clean shifting substrate during a short period of time and are subject to abrupt deposition and erosion (Buatois and Mángano, 2012). The occurrence of *Monocraterion* as a monodominant in a thickly bedded micritic sandstone in Bela Island indicate high energy, winnowed or shifting substrate with abundant sediment supply. Similarly, *Skolithos* also occur as a monodominant ichnogenus in friable cross bedded white sandstone facies while the diversity of trace fossils is relatively more in ferruginous sandstone of Chorar Island indicating sudden change in environmental conditions. The presence of horizontal burrow such as *Planolites* and *Thalassinoides* which normally occur few centimetres below the sediment-water interface, suggest unconsolidated substrate experiencing relatively moderate to low energy conditions and relatively protected zone in the middle shoreface environment (Darngawn et al., 2018).

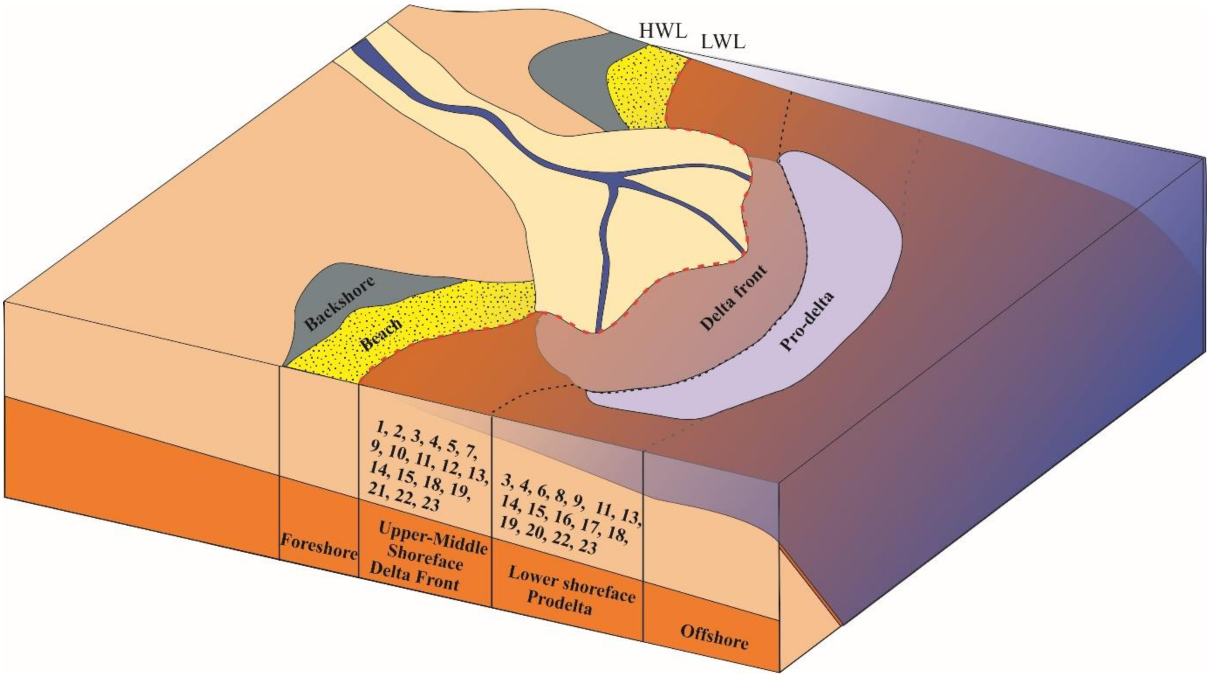

Fig. 6.16 Environmental distribution of trace fossils of Khadir, Bela and Chorar Islands. Upper-middle shoreface and lower shoreface-prodelta environment shows the either trace fossils of *Skolithos, Cruziana* Ichnofacies as well as mixed *Skolithos-Cruziana* Ichnofacies. 1. *Asterosoma*, 2. *Curvolithus*, 3. *Didymaulichnus*, 4. *Gyrochorte*, 5. *Halopoa*, 6. *Helicolithus*, 7. *Laevicyclus*, 8. *Megagrapton*, 9. *Palaeophycus*, 10. *Phycodes*, 11. *Planolites*, 12. *Protovirgularia*, 13. *Rhizocorallium*, 14. *Taenidium*, 15. *Arenicolites*, 16. *Chondrites*, 17. *Diplocraterion*, 18. *Lockeia*, 19. *Monocraterion*, 20. *Skolithos*, 21. *Hillichnus*, 22. *Ophiomorpha*, 23. *Thalassinoides*, LWL= Low water line, HWL=High water line.

6.4.2 *Cruziana* Ichnofacies

Cruziana ichnofacies is Characterized by ichnoassemblages which recur both vertically and laterally throughout the sequences of the Island Belt Zones. It is represented by *Lockeia, Rhizocorallium* and *Protovirgularia* assemblages in Khadir Island, *Thalassinoides* in Bela Island and *Rhizocorallium*, *Gyrochorte*, *Thalassinoides* and *Hillichnus* assemblages in Chorar Island. The ichnoassemblages representing *Cruziana* in Khadir Island are observed in micritic sandstone facies of Ratanpur Sandstone Member (*Lockeia* assemblage); peloidal packstone-grainstone facies of Ratanpur Sandstone Members (*Rhizocorallium* assemblage); thinly bedded micritic sandstone facies of Bambhanka Member in Kakinda Bet (*Protovirgularia* assemblage); micritic sandstone facies of Hadibhadang Shale Member in Bela Island and

Hadibhadang Sandstone Member of Chorar Island (*Thalassinoides*); sandy allochemic limestone of Hadibhadang Sandstone Member in Chorar Island (*Gyrochorte, Rhizocorallium*).

The closely spaced chevrons of *Protovirgularia*, observed in thinly bedded micritic sandstone may suggest that the substrate in which they were emplaced was stiff, resistant, dewatered and better consolidate (Paranjape et al., 2013) marking change in the substrate condition for a short period of time. The monodominant *Thalassinoides* occurs as a post depositional event at the sediment-sediment interface in thinly bedded micritic sandstone deposited by short-term events, probably storm below the fair-weather wave base in Bela Island. This trace fossil recurs as a monodominant trace fossil at a sediment-sediment interface in sandy allochemic limestone facies in Chorar Island. The occurrences of abundant *Hillichnus,* a complex deposit feeding trace fossils in association with *Protovirgularia* suggest nutrient-rich substrate. The dominance of horizontal feeding structures suggests low to moderate energy conditions, unstable, soft but fairly cohesive, unconsolidated substrate below the fair-weather wave base. (Darngawn et al., 2018).

6.4.3 Mixed *Skolithos - Cruziania* Ichnofacies

Cruziana Ichnofacies often occur in settings outside the zone specified in the original paradigm (Frey et al., 1990) and overlap with *Skolithos* Ichnofacies. This ichnofacies does not restrict to just bathymetry, it is rather dependent on the dynamic controlling factors such as substrate consistency, hydraulic energy, rates of deposition, turbidity, oxygen and salinity levels, toxic substances, the quality and quantity of available food, and the ecologic or ichnologic prowess of trace makers (Frey et al., 1990). The mixed *Skolithos-Cruziana* Ichnofacies is characterized by *Rhizocorallium, Hillichnus,* and *Planolites-Palaeophycus* assemblages. *Rhizocorallium* assemblage is observed thickly bedded micritic sandstone facies of Bambhanka Member.

The Mesozoic *Rhizocorallium commune* are restricted to the *Cruziana* Ichnofacies (Knaust, 2013). However, it occurs in association with suspension feeding *Arenicolites*, and *Diplocraterion* and detrital feeding *Monocraterion* which are the members of *Skolithos* Ichnofacies. The dominance of *R. commune* in micritic sandstone facies of Bambhanka Member in association with *Skolithos* Ichnofacies suggest nutrient rich, shallow-marine environments with fluctuating energy condition. The *Hillichnus* assemblage recurs spatially and vertically. It occurs in association with *Arenicolites, Chondrites, Diplocraterion, Taenidium, Laevicyclus, Planolites, Thalassinoides* and *Skolithos* in micritic sandstone facies of Khadir Island. It also occurs in association with *Arenicolites*, *Diplocraterion, Rhizocorallium, Skolithos, Planolites, Palaeophycus, Protovirgularia, Didymaulichnus, Taenidium,* and *Phycodes* in sandy allochemic limestone facies of Bela Island. The *Planolites-Palaeophycus* assemblage also occurs in association with *Planolites, Palaeophycus, Thalassinoides* and *Ophiomorpha, Chondrites, Arenicolites, Skolithos, Lockeia* and *Curvolithus* in sandy allochemic limestone facies of Ratanpur Sandstone Member in Khadir Island.

The mutual occurrences of both deposit and suspension feeding organisms suggest fluctuating eposidic and taphonomic conditions, such that nutrients may be obtained through both suspension and deposit-feeding, and thus support a community of trace makers with a variety of trophic styles (Ekdale et al., 1984b; Ekdale, 1985; Bjerstedt, 1988; Stanley and Feldmann, 1998). The mixed *Skolithos–Cruziana* Ichnofacies can also be produced by a seaward expansion of the *Skolithos* Ichnofacies into the *Cruziana* Ichnofacies as a result of localized reduced energy conditions (Davies et al., 2007).