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PALAEOECOLOGICAL SIGNIFICANCE OF TRACE FOSSILS OF CHORAR ISLAND, EASTERN KACHCHH BASIN, WESTERN INDIA

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ABSTRACT

The Middle Jurassic (Bajocian-Callovian) of Chorar Island in eastern Kachchh comprises of ~109 m thick sequence of mixed siliciclastic-carbonate sediments, limestone, ferruginous sandstone and shales; divided into Khadir and Gadhada formations. The sequence is further analysed and nine lithofacies namely, micritic sandstone, allochemic sandstone, sandy allochemic limestone, sandy micrite, cross-bedded white sandstone, ferruginous sandstone, shales, coralline limestone and mudstone are identified. The whole sequence is bioturbated in varying intensity and comprises of 19 identifiable ichnospecies (*Arenicolites carbonarius, Asterosoma* isp., *Curvolithus* isp., *Didymaulichnus lyelli, Diplocraterion* cf *parallelum, Gyrochorte comosa, Halopoa imbricata, Hillichnus lobosensis, Lockeia silliquaria, Megagrapton irregulare, Palaeophycus tubularis, Planolites beverleyensis, Protovirgularia rugosa, Rhizocorallium commune* var *irregulare, Skolithos linearis, S. verticalis, Skolithos* isp., *Thalassinoides horizontalis* and *T. paradoxicus*.) of 16 ichnogenera which are further analysed for ichnodisparity. The sequence is characterised by ethologically less diverse groups, mainly of dwelling and feeding structures. Presence of *Hillichnus lobosensis* in sandy allochemic limestone facies shows different feeding strategies adopted by tellinacean bivalves indicating a complex organism–sediment interaction. The characteristic set of environmentally related group of trace fossil reveals five ichnoassemblages (*Gyrochorte*, *Hillichnus*, *Rhizocorallium, Skolithos* and *Thalassinoides*) which represent *Skolithos* and *Cruziana* Ichnofacies. The sedimentological and ichnological analysis of the Middle Jurassic sequence of Chorar Island reveals that the sediments were deposited in middle shoreface to offshore zone in a fluctuating sea-level.

Keywords: Trace fossils, Ichnodisparity, Palaeoecology, Middle Jurassic, Chorar Island.

INTRODUCTION

The Jurassic sequence of the Kachchh basin is adorned abundantly with body fossils as well as trace fossils. These Jurassic sequences are exposed in disconnect outcrops in northern part of the Kachchh mainland, along the domes and the Island Belt that include Pachchham, Khadir, Bela and Chorar Islands. The well preserved biotic signatures of Kachchh attracted several geologists (Fürsich *et al*., 2004; Joseph *et al*., 2012; Patel *et al*., 2008, 2014; Patel and Patel, 2015). However, Chorar Island remains greatly neglected due to its isolated location, patchy outcrop and devoid of ammonites as compared to other coeval sequence of the Kachchh basin. Biswas (2016) has made an attempt to lithostratigraphically classify the Eastern Kachchh sequence including the Chorar Island; however, the detailed stratigraphic and sedimentological information of Chorar Island is provided by Patel *et al.* (2018).

The fossilized work of an animal reflects the past life activity of an individual organism as well as the resultant modification of the substrate. The present study focuses on trace fossils of Chorar Island which is a home for extraordinarily well preserved and diverse trace fossils. Trace fossils are collected and photograph at different locality; a composite litholog has been prepared and marked the stratigraphic position of each trace fossils. The main objectives of the present study is to describe the systematic taxonomy, ichnodisparity, ethology, ichnoassemblage and ichnofacies of the Jurassic succession of Chorar Island to throw light on the past depositional environment.

GEOLOGICAL SETTING

Kachchh is a peri-cratonic east-west trending rift basin bounded by Nagar Parker in the north, North Kathiawar uplift (Saurashtra Horst) in the south, Radhanpur-Barmer arch in the east and Arabian Sea in the west (Biswas, 2005). The Mesozoic sediments are deposited in isolated and discontinuous sub basin and display distinct characteristics due to which the Mesozoic stratigraphy of the Kachchh basin is broadly classified into four divisions, viz. Kachchh mainland, Pachchham Island, Eastern Kachchh and Wagad highland.

Chorar Island is the eastern-most island of the Kachchh basin and lies between latitude N 23°41’06” to N 23°57’00”and longitude E 71°00’55” to E71°18’36” in Patan district (Fig. 1) of Gujarat. The Jurassic sequence in Chorar Island is exposed in isolated patches, where the maximum thickness is exposed in an elliptical dome southwest of Aaval village. Sediments range in age from Bajocian to Callovian belonging to Khadir Formation and Gadhada Formation which are rift filled sediments (Biswas, 2016).

The total sequence comprises of ~109 m thick sediments which is characterised by shale dominated Hadibhadang Shale Member of Khadir Formation at the base of exposed succession. These shales are overlain by Hadibhadang Sandstone Member which is characterized by intercalated thinly bedded shales and mixed siliciclastic-carbonate rocks. The intercalated mixed siliciclastic-carbonate rocks are capped by coralline limestone marking the top of Hadibhadang Sandstone Member of Khadir Formation. Top of the Hadibhadang Sandstone Member of Khadir Formation is equivalent to Raimalro Limestone Member of the Goradongar Formation (Biswas, 2016) and Patcham Formation of Fürsich *et al*. (2013). The Hadibhadang Sandstone Member of Khadir Formation is overlain by Ratanpur Sandstone Member of Gadhada Formation which comprises of thinly bedded mudstone and allochemic sandstone with thickly bedded bioturbated cross-bedded white sandstone and ferruginous sandstone. The sequence is finally capped by thick bedded

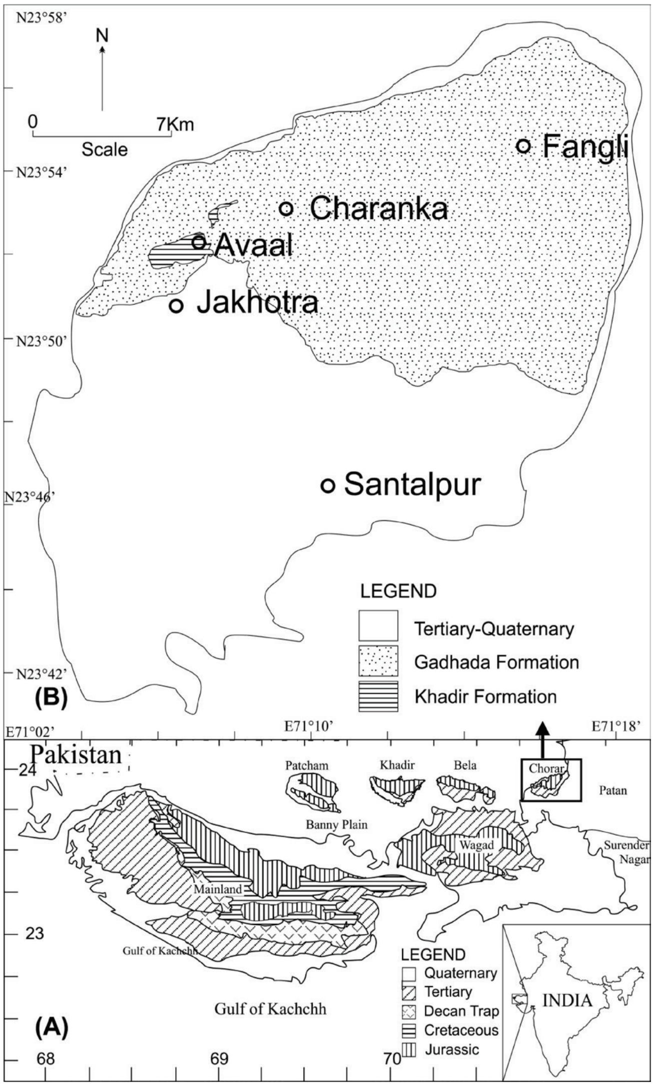


Fig.1: (A) General geological map of Kachchh shows the position of Chorar Island in Kachchh Basin and (B) detailed geological map of Chroar Island (Modified after Biswas and Deshpande, 1975).

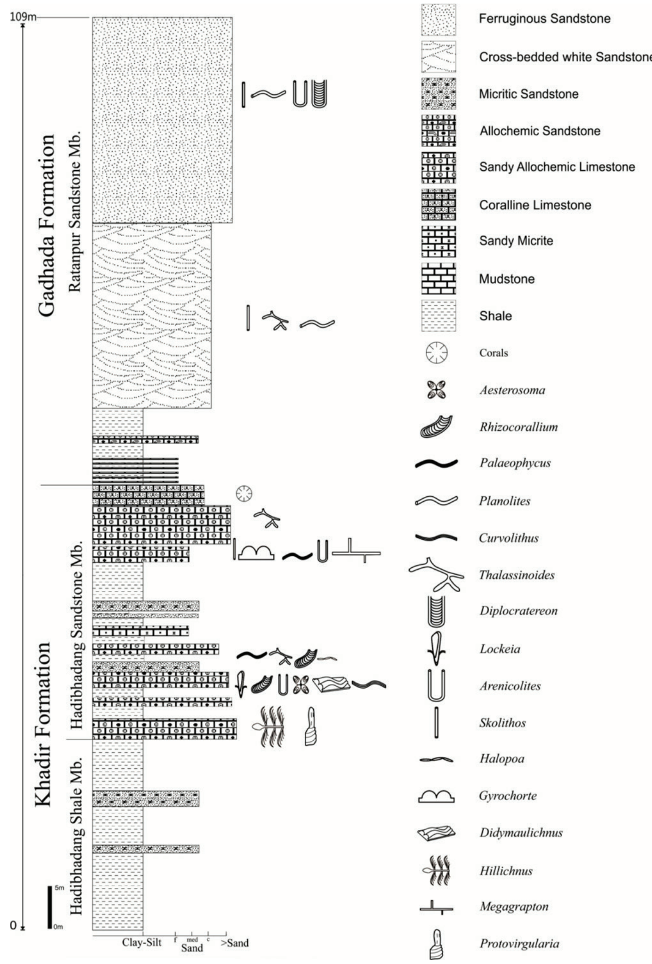


Fig. 2. Composite litholog of Middle Jurassic succession of Chorar Island showing lithofacies and associated trace fossils.

weathered, friable and rusty brown ferruginous sandstone on the top.

LITHOFACIES

Lithofacies are bodies of sedimentary rocks with distinctive lithologic characteristics including grain size, composition, sedimentary structures, and bedding characteristics representing an individual depositional event (Miall, 2000). Field observation and petrographic studies of the Jurassic succession Chorar Island reveals nine lithofacies which includes ferruginous sandstone, cross-bedded white sandstone, micritic sandstone, allochemic sandstone, sandy micrite, mudstone, sandy allochemic limestone, coralline limestone and shale facies (Fig. 2). The field observation along with their associated trace fossils and petrographic data are given in the table -1.

TRACE FOSSILS DESCRIPTION

The Middle Jurassic sequence of the Chorar Island consist 20 identifiable ichnospecies of 16 ichnogenera which are named according to binomial system of ICZN. These ichnogenera are further categorized according to Knaust (2012) scheme. It is mainly grouped into subhorizontal, subvertical and complex burrows which are further assign according to shape and lining characteristics. Each ichnogenera is described alphabetically in each category as under.

I. Subvertical Burrows

Branching: Unbranch
Shape: U - Shape
Fill: Passive Fill

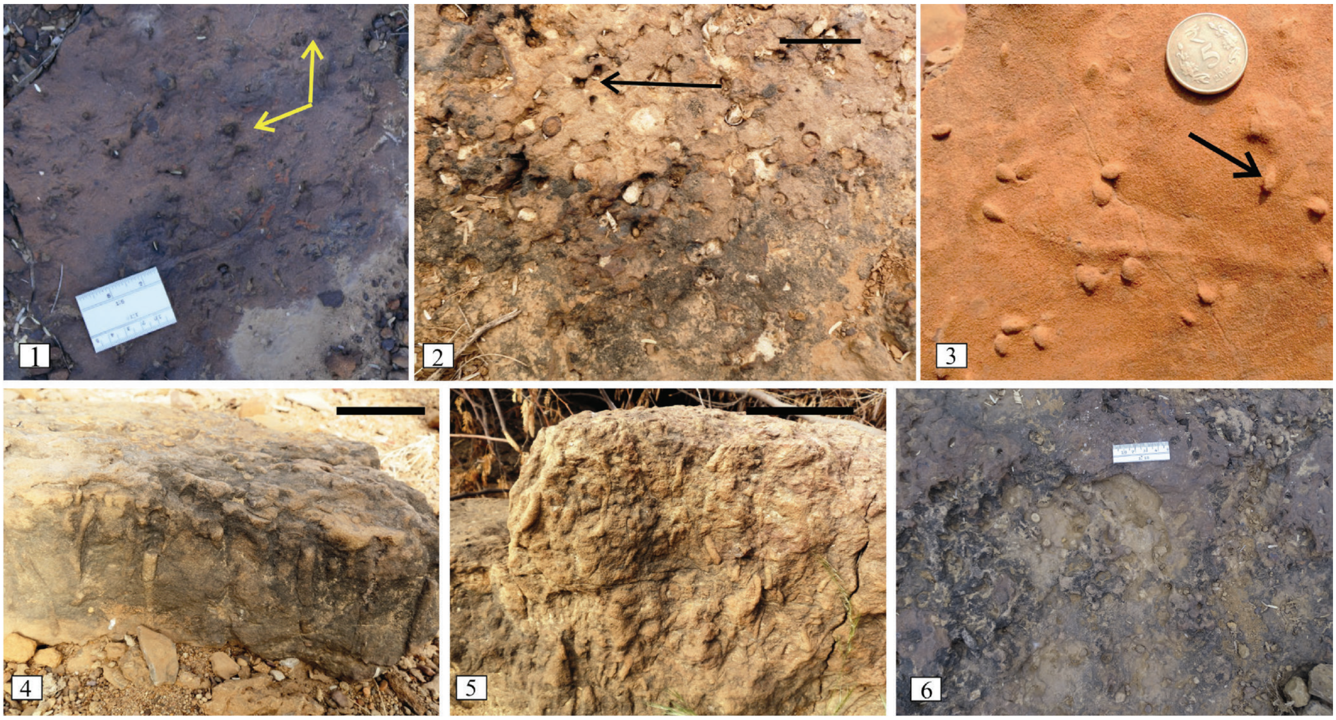
Ichnogenus ***Arenicolites*** Salter, 1857
Arenicolites carbonarius Binney, 1852
(Pl. I, fig. 1)

Description: U-shaped lined burrows with distinct walls, inclined or vertical to the bedding plane. Opening is circular. Diameter of the burrow is 0.57 to 0.76 cm and burrow arms are about 0.11 to 0.41 cm apart.

Occurrence: Ferruginous sandstone facies of Ratanpur Member, Gadhada Formation and sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: Arenicolites represents dwelling and feeding burrows of suspension-feeders (Fürsich, 1975; Hakes, 1977;

Plate I



EXPLANATION OF PLATE I

Fig. 1. U-shaped ***Arenicolites carbonarius*** appearing as pair tubes on bedding surface in ferruginous sandstone facies of Ratanpur Sandstone Member. Fig. 2. U-shaped spreiten burrow ***Diplocraterion* cf. *parallelum*** with tubes connected with biogenic lamina (groove) at the top of bedding surface, in ferruginous sandstone facies of Ratanpur Sandstone Member (Scale bar length= 2 cm). Fig. 3. Resting traces of ***Lockeia siliquaria*** in sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation (Coin diameter= 2.2 cm). Fig. 4. Vertical, ***Skolithos linearis*** in highly bioturbated cross-bedded white sandstone facies of Ratanpur Sandstone Member (Scale bar length= 5 cm). Fig. 5. Inclined to curved ***Skolithos verticalis*** in highly bioturbated cross-bedded white sandstone facies of Ratanpur Sandstone Member (Scale bar length= 5 cm). Fig. 6. ***Skolithos*** isp., appearing as circular opening on the bedding surface, in ferruginous sandstone facies of Ratanpur Sandstone Member.

Howard and Frey, 1984; Fillion and Pickerill, 1984). The lining of the burrows give more stability to the burrows.

Branching: Unbranch
Shape: U Shaped
Fill: Active

Ichnogenus ***Diplocraterion*** Torell, 1870
Diplocraterion cf. *parallelum* Richter, 1926
(Pl. I, fig. 2)

Description: Straight and uniform U-tubes with spreiten structures, perpendicular to bedding plane. Both the tubes are parallel with narrow opening on surface. Tube diameter is about 0.41 to 0.50 cm and tubes are 0.55 to 0.63 cm apart from each other.

Occurrence: Ferruginous sandstone facies of Ratanpur Sandstone Member, Gadhada Formation.

Discussion: It is the dwelling burrow of polychaete annelids, crustaceans, or other suspension feeding animal (Fillion and Pickerill, 1990), probably living in environment of high wave energy. *Diplocraterion* cf. *parallelum*.

Branching: Unbranch
Shape: Plug Shaped
Fill: Passive

Ichnogenus ***Lockeia*** James, 1879

Lockeia siliquaria James, 1879
(Pl. I, fig. 3)

Description: Convex, hypichnial, relatively small, almond shaped, oblong parallel to sub parallel bodies; with tapering to sharp. They occur as isolated and their dimension varies in different burrow populations, with observed length 0.5 cm and width is 0.3 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: *Lockeia siliquaria* differs from the other ichnospecies of *Lockeia* by lack of plump nature of *L. amygdaloides* (Seilacher, 1953); or *L. avalonensis* (Fillion and Pickerill, 1990); thin and elongate as *L. elongata*, (Yang, 1984); and asymmetrical as *L. czarnockii* (Karaszewski, 1975).

Branching: Unbranched
Shape: Cylindrical
Fill: Passive

Ichnogenus ***Skolithos*** Haldeman, 1840
Skolithos linearis Howel, 1943
(Pl. I, fig. 4)

Description: Burrows are straight, vertical to slightly curved and perpendicular to the bedding plane. Burrows wall are distinct measuring about 1cm in diameter and length of about 8.5 cm

Table 1. Facies characteristic and associated trace fossils in Chorar Island.

Lithofacies	**Characteristics**	**Trace Fossils**
Shale	Light grey, argillaceous material with gypsum crystals	NA
Micritic Sandstone	Dirty yellow to dark brown colour; cross-bedded; planar laminated; symmetrical-, asymmetrical-, linguoid- and micro-ripples. Petrography: siliciclast component quartz -80%, Micrite - 20% with few sparitized shell fragments.	*Palaeophycus, Thalassinoides, Halopoa, Rhizocorallium.*
Sandy Micrite	Dark colored fine grain rock; cross-bedding and planar lamination. Petrography: 30-40% siliciclast component; allochems 10-20%; micrite 40-50%.	NA
Sandy Allochemic Limestone	Light yellow or dark brown in colour, hard and massive, intercalated with greyish shale. Petrography: 20-30% siliciclast component with allochems - 40-60%; micrite 15-20%	*Arenicolites, Asterosoma, Curvolithus, Didymaulichnus, Gyrochorte, Hillichnus, Lockeia, Megagrapton, Palaeophycus, Protovirgularia, Rhizocorallium, Skolithos, Thalassinoides.*
Coralline Limestone	Well cemented, dirty yellow; abundant mushroom shaped corals Petrography: 95-90% carbonate (sparite and micrite), completely sparitized & lost internal structures; with 5-10% quartz.	NA
Mudstone	Well cemented greyish to yellowish brown colour, very fine grained, thinly bedded with fine lamination Petrography: textureless micrite (lime mud) with < 5% micritized shell fragments	NA
Allochemic Sandstone	Thinly bedded, dirty yellow to brown color intercalated with shales. Petrography: siliciclast component – 60%; allochems 30%; micrite 10%	NA
Cross-bedded white sandstone	White, dirty yellow to red colored, soft, highly friable sandstone with faint planar- & trough- cross-stratification. Petrography: Siliciclastic component –50% to 70% with ferruginous matrix in the western margin of Chorar dome.	*Planolites, Skolithos, Thalassinoides*
Ferruginous Sandstone	Dark red to blackish/rusty brown in color; cross-bedding, ripple marks and concretionary structures Petrography: Textural fabrics are masked by ferruginous material.	*Arenicolites, Skolithos, Planolites, Diplocraterion*

Occurrence: Cross-bedded white sandstone facies of Ratanpur Sandstone Member, Gadhada Formation.

Discussion: *Skolithos linearis* includes various forms that include straight and crowded to slightly curve and less crowded (Alpert, 1974).

Skolithos verticalis Hall, 1843
(Pl. I, fig. 5)

Description: These are cylindrical, curved, seldom straight burrows generally inclined to the bedding plane. The tubes are unbranched with smooth walls. Diameter of the tubes varies from 0.57 to 0.67 cm. Length of the tube is 15.22 cm.

Occurrence: Cross-bedded white sandstone facies of Ratanpur Member, Gadhada Formation.

Discussion: The *Skolithos verticalis* burrows are generally shorter and smaller, and more commonly inclined and curved (and to a greater extent) than *S. linearis*, and never are extremely crowded (Alpert, 1974); considered as dwelling burrow of annelids or phoronids (Alpert, 1974).

Skolithos isp.
(Pl. I, fig. 6)

Description: Cylindrical to sub-cylindrical burrow with oval to circular on surface occurring in large numbers. Burrow wall is distinct and it appears as small ring like projections on the bedding plane ranging in diameter from 0.6 to 1.03 cm.

Occurrence: Ferruginous sandstone facies of Ratanpur Member, Gadhada Formation.

Discussion: The sediment in the burrows tends to weather out readily, leaving the burrows as holes in the rock. The crowded nature of the present specimen of *Skolithos* suggests it to be *Skolithos linearis* however due to non visible vertical sections it cannot be refrained from the other ichnospecies of *Skolithos* and thus kept under open nomenclature.

II. Subhorizontal Burrows

Branching: Branched
Shape: Radial
Fill: Passive

Ichnogenus ***Asterosoma*** Von Otto, 1854.
Asterosoma isp.
(Pl. II, fig. 1)

Description: Sub-horizontal bulbs showing radial or star like orientation with tapering ends; preserved as full relief; walls show longitudinal furrows and striae. The bulb length varies from 3.3 cm to 3.5 cm; width is 0.7 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: The finger like protruding resembles *Phycodes,* however the bulbous nature of the petal restrict it to *Asterosoma*. The present specimen shows sub horizontal bulbs radiating but the five usually common petals of *Asterosoma radiciforme* is not visible due to lack of complete preservation, therefore the nomenclature for species has been kept open and the specimen is described here as *Asterosoma* isp. The tubular nature and manner of sediment working in *Asterosoma* are generally considered as the feeding structures of deposit feeders (Dawson, 1890).

Plate II

EXPLANATION OF PLATE II

Fig. 1. ***Asterosoma*** isp., in sandy allochemic limestone facies of Hadibhadang Sandstone Member (Coin diameter= 2.2 cm). Fig. 2. Faintly visible trilobate structure (arrow) ***Curvolithus*** isp. in sandy allochemic limestone facies of Hadibhadang Sandstone Member, (Coin diameter= 2.2 cm). Fig. 3. ***Didymaulichnus lyelli***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member. Fig. 4. ***Gyrochorte comosa***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member (Coin diameter= 2.2 cm). Fig. 5. ***Halopoa imbricata***, in micritic sandstone facies of Hadibhadang Sandstone Member(Coin diameter= 2.2 cm). Fig. 6. ***Palaeophycus tubularis***, in ferruginous sandstone facies of Ratanpur Sandstone Member. Fig. 7. ***Planolites beverleyensis***, in ferruginous sandstone facies of Ratanpur Sandstone Member. Fig. 8. ***Protovirgularia* cf. *rugosa***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member (Coin diameter= 2.2 cm). Figs. 9-11. ***Rhizocorallium commune* var *irregulare*** in sandy allochemic limestone facies of Hadibhadang Sandstone Member.

Branching: Unbranched

Shape: Trilobate

Fill: Active

Ichnogenus ***Curvolithus*** Fritsch, 1908
Curvolithus isp.
(Pl. II, fig. 2)

*Description***:** Slightly curved, trilobate subhorizontal, ribbon like structure. The trilobate structure is faintly visible due to lack of preservation, eroded burrows or the burrows are poorly developed due to thixotropic conditions.

*Occurrence***:** The specimen is observed sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: *Curvolithus* is interpreted as repichnia (locomotion trace) produced probably by carnivorous gastropods (Heinberg, 1973). *Curvolithus* are formed in shifting sediments with little cohesion, thus have a little preservation potential (Buatois *et al*., 2017). Its occurance is significant for palaeoenvironmental interpretation as it is restricted to shelf environment between fair which is the characteristic feature of *Cruziana* Ichnofacies (Buatois *et al*., 2017).

Branching: Unbranch
Shape: Bilobate
Fill: Passive

Ichnogenus ***Didymaulichnus*** Young, 1972
Didymaulichnus lyelli Rouault, 1850
(Pl. II, fig. 3)

Description: Long, straight to gently curved trails, usually preserved as convex hyporelief. It consists of two distinct smooth lobes separated by median depression. Lobes are simple and smooth with no ornamentation and parallel to bedding plane. Length of the trail is 8.0 cm and width is 0.4 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: This ichnospecies is assigned *Didymaulichnus lyelli* due to its lack of a) marginal bevels characteristics of *D. miettensis*, (Young, 1972); b) alternating burrow depths characteristic of *D. alternates*, (Pickerill *et al.*, 1984); c) lateral ridges characteristics of *D. rouaulti* (Lebesconte, 1883) and d) marginal bevels and larger size characteristics of *D. tirasensis* with repeated deepening and shallowing and exhibit overlap and imbrication (Palij, 1974). *Didymaulichnus lyelli* represents the crawling trail of molluscan origin (Häntzschel, 1975).

Branching: Unbranched
Shape: Bilobate
Fill: Active

Ichnogenus ***Gyrochorte*** Heer, 1865
Gyrochorte comosa Heer, 1865
(Pl. II, fig. 4)

Description: Winding ridges and tunnels, bilobate trails consist of two lobes showing biserial arrangement separated by median furrow. Each lobe consist uniformly developed obliquely aligned pads. The angle between the pads and the main furrow is 86°. The trails are winding to straight and crossing over each other frequently in such a way that the earlier formed ridges are not destroyed. Length is 10 cm. and width is 0.37 cm.

Occurrence: Micritic sandstone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: *Gyrochorte comosa* can be distinguished from other ichnospecies of *Gyrochorte* through its lack of a) oblique incisions characteristics of *G. burtani*, b) imbricate asymmetrical riblets characteristics of *G. imbricate* and c), densely spaced irregular incisions characteristic of *G. obliterate* (Książkiewicz, 1977). *Gyrochorte* producer must have been a detritus-feeding worm-like animal, probably an annelid that created a bilobed, vertically penetrating and sometime plaited meandering trace (Gibert and Benner, 2002).

Branching: Unbranched
Shape: Cylindrical ridge like
Fill: Active

Ichnogenus ***Halopoa*** Torell, 1870
Halopoa imbricata Torell, 1870
(Pl. II, fig. 5)

Description: Hypichnial cylindrical full burrows, with hardly any terminations, 12cm long, straight, 0.83cm wide, covered with wrinkles irregularly along the length. The wrinkles are thin, continuous along the length of the burrows. They are then replaced by other wrinkles, not necessarily prolongation. The diameter of the tube is not constant.

Occurrence: Sandy micrite facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: The specimen appears similar to *Palaeophycus striatus,* however it lacks distinct wall and burrow opening. Therefore it does not conform to the idea of *Palaeophycus* of Pemberton and Frey (1982). The burrow shows continuous horizontal furrows and wrinkles which is the characteristics of *Halopoa imbricata* (Uchman, 1998), produced by deposit feeding annelids (Birkenmajer, 1959).

Branching: Unbranched
Shape: Cylindrical ridge like
Fill: Passive

Ichnogenus ***Palaeophycus*** Hall, 1847
Palaeophycus tubularis Hall, 1847
(Pl. II, fig. 6)

Description: Straight, smooth, unbranched, long, unornamented and thinly lined burrows which occur as parallel to slightly oblique to the bedding plane. Length of burrows varies from 5 to 12 cm and diameter remains constant throughout the burrow length.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation

Discussion: The given ichnospecies *Palaeophycus tubularis* is distinguished from *P. striatus* and *P. annulatus* by its thin wall-lining and absence of continuous parallel, anastomosing or alternate and annulate striae (Pemberton and Frey, 1982).

Branching: Unbranched
Shape: Cylindrical ridge like
Fill: Active

Ichnogenus ***Planolites*** Nicholson, 1873
Planolites beverleyensis Billings, 1862
(Pl. II, fig. 7)

Description: Cylindrical, smooth, unbranched, unlined burrows typically oriented more or less parallel with bedding. Length of burrow is 3.8 cm and diameter is 0.5 cm.

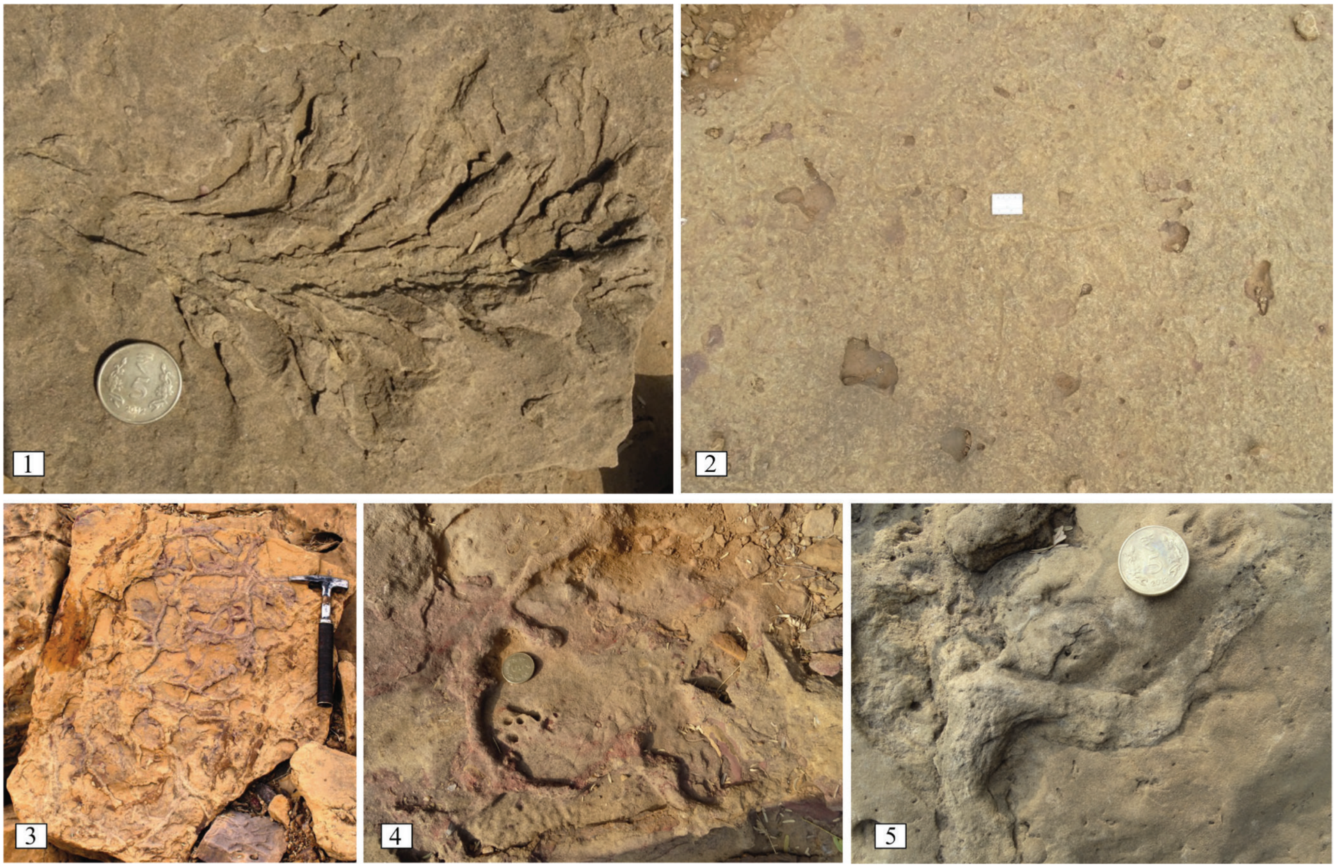
Occurrence: Sandy allochemic limestone facies of Hadibhdang Sandstone Member of Khadir Formation and Ratanpur Sandstone Member of Gadhada Formation

Discussion: *Planolites* is a broad ichnogenus ranging from Precambrian to Recent (Häntzschel, 1962; Crimes and Anderson, 1985). It is interpreted as pascichnion and referred to polyphyletic vermiform deposit-feeders producing active backfilling (Rodríguez-Tovar and Uchman, 2004).

Branching: Unbranched
Shape: Cylindrical ridge like
Fill: Active

Ichnogenus ***Protovirgularia*** M'Coy, 1850
Protovirgularia cf. *rugosa* Miller and Dyer, 1878
(Pl. II, fig. 8)

Plate III



EXPLANATION OF PLATE III

Fig. 1. ***Hillichnus lobosensis***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member (Coin diameter= 2.2 cm). Fig. 2. ***Megagrapton irregulare***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member. Fig. 3. Large and small boxwork burrow system of ***Thalassinoides horizontalis***, in sandy allochemic limestone facies of Hadibhadang Sandstone Member (hammer length= 32 cm). Fig. 4. Curved burrow tubes of ***Thalassinoides horizontalis*** with T-shaped branch, in sandy allochemic limestone facies of Hadibhadang Sandstone Member (Coin diameter= 2.2 cm). Fig. 5. Curved and inclined burrow ***Thalassinoides paradoxicus*** with swelling at bifurcation in micritic sandstone facies of Hadibhadang Sandstone Member (Coin diameter = 2.2 cm).

Description: Straight, unbranched, hypichnial transverse ridges slightly inclined to the bedding plane. The trace is 1.4 cm in diameter in the wider part and is about 1cm in relatively smooth and narrower, tapering part. The total length is about 2.6 cm. The central tube is smooth and surrounded by thick layer.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: The burrow lacks chevron appendages which are commonly seen in *Protovirgularia rugosa* rather the ridges are parallel and closely spaced. Similar structures is also reported by Fürsich (1998) arguing the need for more detail studies for the group.

Branching:Unbranched
Shape: U-, J-shaped/ laminar
Fill: Active

Ichnogenus ***Rhizocorallium*** Zenker, 1836.
Rhizocorallium commune Schmid, 1876
Rhizocorallium commune var. *irregulare* Mayer, 1954
(Pl. II, fig. 9-11)

Description: Long, slightly curved, horizontal, U-shaped spreiten burrows. Tubes are positive epirelief separated by spreiten structure. Total length of the structure observed is 11.5 cm. Diameter of the tube is about 0.5 to 1.0 cm and the distance between two tubes is about 3.9 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: The specimen is lacking pellets which is usually common however the slender and long nature of the horizontal U-shaped burrow of the present *R. commune* var. *irregular*e distinguishes it from the straight and parallel with abundant scratches nature of *R. jenense* and trochospiral nature of *R. commune* var. *uliarense* (Knaust, 2013). The trace maker is a deposit feeder probably crustacean (Rodríguez-Tovar and Pérez-Valera 2008).

Complex Burrows
Branching: Complex
Shape: Tunnel with serial shafts
Fill: Active

Ichnogenus ***Hillichnus*** Bromley *et al*., 2003
Hillichnus lobosensis Bromley *et al*., 2003
(Pl. III, fig. 1)

Description: Complex trace fossil having leaf like structure with spreite like lateral lamellae, extended, feather-like and curving and distally more slender. The developed structure may be called lateral tubules. The proximal end of the tubules is truncated by the basal tube, which is rough and wrinkling. The length of the structure varies from 13.2 to 26.4 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: The Chorar specimen belongs to complex *Hillichnus lobosensis* showing successive probes or excursion in the sediments suggesting deposit feeding activity of tellenecean bivalves (Bromley *et al*., 2003).

Branching: Complex
Shape: Network
Fill: Passive

Ichnogenus ***Megagrapton*** Książkiewicž, 1968
Megagrapton irregulare Książkiewicž, 1968
(Pl. III, fig. 2)

Description: Networks consisting of irregular polygons and rectangles which are never closed, formed by slightly curved or straight cylindrical strings 0.2 cm wide; branching at regular intervals at nearly right angles.

Occurance: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: *Megagrapton irregulare* can be easily differentiated from *M. submontanum* as the later branch in acute angles with winding strings (Uchman, 1998).

Branching: Complex
Shape: Boxwork
Fill: Passive

Ichnogenus ***Thalassinoides*** Ehrenberg, 1944
Thalassinoides horizontalis Myrow, 1995
(Pl. III, fig. 3 and 4)

Description: Horizontal cylindrical burrows which are Y- or T- shaped with no vertically oriented offshoot. Burrow walls are smooth and the angle of branching is 72°. Length of burrows is 1.86 cm and diameter ranges from 0.33 to 0.45 cm.

Occurrence: Sandy allochemic limestone facies of Hadibhadang Sandstone Member of Khadir Formation.

Discussion: It is characterized by absence of vertical component, by which it differs from the other species of the *Thalassinoides*.

Thalassinoides paradoxicus Kennedy, 1967
(Pl. III, fig. 5)

Description: Smooth, irregularly branched burrow systems spreading over bedding plane, bifurcated in different dimensions. The angle of branching is 86.5° and swelling at the point of bifurcation. Burrow fill is identical to host sediments. Diameter of the burrow is about 1.24 cm and near the point of bifurcation is about 1.67 cm.

Occurrence: Micritic sandstone facies of Hadibhadang Sandstone Member, Khadir Formation.

Discussion: *Thalassinoides paradoxicus* is characterized by enlargement at point of bifurcation, by which it is distinguished from the other ichnospecies and is interpreted as feeding and dwelling burrows of crustaceans (Myrow 1995).

ICHNODISPARITY

The concept of disparity has been adapted to ichnology which provides a measure of the variability of morphological plans in biogenic structures revealing innovations in body plan, locomotary system and/or behavioural program (Buatois and Mángano 2011, 2013; Buatois *et al.*, 2017). In a given geological time, the diversity and abundance of a particular evolved group of organism varies with latitude and bathymetry, and they are also responsive to the local environmental factors. The Middle Jurassic succession of Chorar Island, a part of eastern fringe of Kachchh basin, consisting of basin margin succession characterizes high morphological variation of biogenic structures. The sequence comprises of 16 identifiable ichnogenera which falls under 15 architectural categories of Buatois *et al.* (2017) which is given in the table 2.

The Chorar Island sequence represent sediments ranging in age from Bajocian to Callovian, deposited in tidally influenced (shoreface/offshore) shallow marine environments (Patel *et al*., 2018). The Bajocian succession mainly comprise of fine grain sediments with few thin hard bands of micritic sandstone. This sequence surprisingly lacks biogenic structures indicating non-conducive conditions for the trace makers. In contrast, the Bathonian sequence is comprised of highly bioturbated mixed siliciclastic-carbonate sediments with few bands of non-clastic sediments. This sequence show sudden increase in morphological variation reflecting the maximum ichnodisparity (Table 2), that indicate high potential for preservation of varied behavioural traces, high diversified body plan structures and suitable substrate conditions such as mixed siliciclastic-carbonate sediments. Similar conditions resulting in the maximum diversity and abundance of trace fossils in the Bathonian sequence of Chorar Island are also observed in Mainland Kachchh (Patel and Patel, 2015) and Pachchham Island (Patel *et al*., 2010) of the Kachchh basin. The Callovian sequence is mainly characterised by terrigenous sediments shows less morphologic variation of bioturbation structures and hence reflect low ichnodisparity (Table 2). The sequence is deposited in high energy shoreface environment which has eliminated vast variety of deposit feeders and invited some opportunistic suspension feeders which can sustain in shifting unconsolidated substrates by making mainly vertical burrows (Table 2). Thus, low ichnodisparity reflects change in environmental conditions as compared to Bathonian sequence. Nonetheless, the ichnodisparity observed in condense sequence of the Chorar Island is motivated by shoreface-offshore environmental set up with mixed siliciclasic-carbonate substrate preference.

ETHOLOGY

Trace fossils convey information about the past biological activities which are classified into various behavioural categories (Seilacher, 1953; Frey, 1973; Ekdale *et al*., 1984; Ekdale, 1985; Genise and Bown, 1994; Gibert *et al*., 2004 and Bromley, 1996). Some trace fossils are placed under different categories by different authors, for example, Frey and Pemberton (1985) classify *Planolites* under fodinichnia whereas Ekdale (1985) place the same ichnogenera in pascichnia.

Chorar Island displays various types of behavioral activities including dwelling, feeding, crawling and grazing. The Hadibhadang Sandstone Member of Khadir Formation is dominated by dwelling (*Diplocraterion, Lockeia, Palaeophycus,*

Table 2. Categorisation of trace fossils of Chorar Island based on the architectural design of Buatois *et al.* (2017).

Age	Architectural Design	Trace fossils
Callovian	Vertical unbranched burrows	*Skolithos linearis, S. verticalis, S.* isp.
	Simple actively filled (massive) horizontal to oblique structures	*Planolites beverleyensis*
	Vertical single U- and Y-shaped burrows	*Arenicolites carbonarius*; *Diplocraterion* cf. *parallelum*
Bathonian	Trilobate flattened trails	*Curvolithus* isp.
	Chevronate trails	*Protovirgularia* cf. *rugosa*
	Bilobate trails and paired grooves	*Didymaulichnus lyelli*
	Passively filled horizontal burrows	*Palaeophycus tubularis*
	Horizontal burrows with simple vertically oriented spreiten	*Halopoa imbricata*
	Burrows with complex vertically oriented spreiten	*Gyrochorte comosa*
	Burrows with horizontal spreiten	*Rhizocorallium commune* var. *irregulare*
	Basal axial tubes with feather-like and spreite-like structures	*Hillichnus lobosensis*
	Isolated and serial oval to almond-shaped burrows	*Lockeia siliquaria*
	Vertical unbranched burrows	*Skolithos linearis, S. verticalis, S.* isp.
	Vertical single U- and Y-shaped burrows	*Arenicolites carbonarius*
	Horizontal, branched concentrically filled burrows	*Asterosoma* isp.
	Regular to irregular network graphoglyptids	*Megagrapton irregulare*
	Boxwork burrows	*Thalassinoides horizontalis*; *T. paradoxicus*

Hillichnus), feeding (*Asterosoma, Rhizocorallium, Halopoa, Hillichnus,* and *Thalassinoides)* and crawling (*Curvolithus, Didymaulichnus, Gyrochorte, Protovirgularia*) traces along with grazing trails (*Megagrapton, Planolites*), in sandy allochemic limestone and micritic sandstone facies. *Hillichnus* and *Protovirgularia* are horizontal structures chiefly observed in allochemic limestone and presence of resting burrow *Lockeia* in sandy allochemic limestone are made by deposit-feeding bivalves. The presence of *Gyrochorte* and *Curvolithus* indicate activity of worms (Heinberg, 1973) and carnivore gastropods, flat worms or nemerteans (Buatois *et al.*, 1998), respectively, made while moving from one place to other place. *Planolites*, *Palaeophycus* and *Halopoa* are essentially horizontal endichnial structures and occur at sediment-sediment interface, suggesting unconsolidated substrate exploited by the deposit feeding polychaetes. The T-shape and curved Y-shaped branch burrows of *Thalassinoides* observed in sandy allochemic limestone are the dwelling-feeding combined activities of the crustaceans.

The Ratanpur Sandstone Member of Gadhada Formation is characterized by the occurrence of abundant vertical dwelling burrows of *Skolithos* associated with U-shaped *Arenicolites* and U-shaped, spreiten structures, *Diplocraterion*. The dominance of vertical burrows indicates opportunistic behavoir of polychaetes in higher energy condition.

ICHNOASSEMBLAGE

Ichnoassemblage is the basic collective term, embracing all the trace fossils occurring within a single unit of rock and is non-committal to the origin of the collection of trace fossils; may have been emplaced simultaneously as a single ecologically-related group, or may represent several overprinted events of bioturbation (Bromley, 1996). The Middle Jurassic sequence of Chorar Island is characterised by five recurring trace fossils assemblage which include *Hillichnus, Rhizocorallium, Gyrochorte, Thalassinoides* and *Skolithos* assemblages. These assemblages are characterized by a particular association of trace fossils in a particular bed which indicate hydrodynamic condition, mode of food supply, oxygenation conditions, substrate conditions and bathymetry (Joseph *et al*., 2012).

Hillichnus Assemblage

Hillichnus assemblage is characterized by abundant *Hillichnus lobosensis* in association with *protovirgularia.* It is observed in sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. Complex *Hillichnus* burrow suggest deposit feeding behaviour, where an organ of the tracemaker 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). The occurrence of *Hillichnus* in sandy allochemic limestone characterised by fine grain, angular and moderately sorted quartz grains with micrites and allochems indicating low energy condition of lower shoreface environment.

Rhizocorallium Assemblage

Rhizocorallium assemblage is characterized by the presence of *Rhizocorallium, Asterosoma, Lockeia, Arenicolites* and *Didymaulichnus.* It is observed in sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. *Rhizocorallium* assemblage shows dominance of deposit feeders which indicate well oxygenated nutrient rich substrates. Thus the *Rhizocorallium* assemblage is envisaged to be developed in fluctuating energy condition in middle shoreface environment.

Gyrochorte Assembalge

Gyrochorte assemblage is characterized by the presence of *Arenicolites, Gyrochorte, Megagrapton, Planolites* and *Palaeophycus. Gyrochorte* assemblage is found in sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. *Gyrochorte* assemblage shows predominance of deposit feeders indicating nutrient-rich substrate. *Palaeophycus* is a eurybathic form (Pemberton and Frey, 1982) however the fine grain with small ripples on the substrate indicates low energy condition. *Gyrochorte* represents shallow storm-dominated shelf where it is abundantly developed in rippled mixed carbonate-siliciclastic grainstones (Picard and Uygur, 1982; Lord, 1985). The presence of *Gyrochorte* in rippled sandy allochemic limestone indicates low energy conditions in lower shoreface environment.

***Thalassinoides* Assemblage**

This ichnoassemblage is characterized by *Thalassinoides horizontalis* and *T. paradoxicus.* It is observed at the bedding interface of sandy allochemic limestone of Hadibhadang Sandstone Member of Khadir Formation. This assemblage is also observed in micritic sandstone of the same member where it is associated with *Rhizocorallium, Halopoa* and *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 large size box-work burrows in sandy allochemic limestone. The dominance of horizontal feeding structures suggest low to moderate energy conditions, unstable, soft, unconsolidated substrate of the lower shoreface environment.

***Skolithos* assemblage**

Skolithos assemblage is characterized by *Skolithos, Planolites* and *Thalassinoides* in cross-bedded white sandstone facies of Ratanpur Sandstone Member of Gadhada Formation. This assemblage is also observed in association with *Arenicolites, Diplocraterion,* and *Palaeophycus* in the rippled ferruginous sandstone facies of the same member. The ichnoassemblage is mainly characterised by vertical dwelling burrows of opportunistic suspension feeders indicating unconsolidated, soft shifting substrate and high wave and current energy conditions of middle shoreface environment.

ICHNOFACIES

The Middle Jurassic sediments of Chorar Island show an excellent preservation of trace fossils which are grouped into number of ichnoassemblages. These ichnoassemblages are further analysed, which shows the *Skolithos* and *Cruziana* Ichnofacies coupled with sediment characteristics useful in the reconstruction of palaeodepositional environments.

***Skolithos* Ichnofacies**

The Ratanpur Sandstone Member of Gadhada Formation comprises of highly bioturbated cross-bedded white sandstone and ferruginous sandstone facies which consist of abundant vertical endichnial structures chiefly of suspension feederss. The cross-bedded white sandstone facies consisting abundant burrows of *Skolithos* with *Planolites* and *Thalassinoides*, and ferruginous sandstone facies consisting of *Arenicolites, Diplocraterion,Planolites* and *Skolithos* trace fossils, are typically members of *Skolithos* ichnofacies. The diversity of trace fossils is relatively more in ferruginous sandstone indicating sudden change in environmental conditions. The fine to coarse grained clastic sediments and presence of cross-bedding and dominance of vertical burrows indicates moderate to high wave and current energy condition and shifting substrate exploited by the opportunistic animals in the middle shoreface environment (Pemberton *et al.,* 2001). The presence of horizontal burrow such as *Planolites* and *Thalassinoides* which normally occur few centimeters below the sediment-water interface, suggest unconsolidated substrate experiencing relatively moderate to low energy conditions and relatively protected zone in middle shoreface environment. The ichnoassemblages of Ratanpur Sandstone Member is strongly influenced by energy conditions, substrate properties and distribution of particulate organic matter.

***Cruziana* Ichnofacies**

Cruziana Ichnofacies is characterized by *Thalassinoides, Gyrochorte*, *Rhizocorallium* and *Hillichnus* assemblages, occurring in sandy allochemic limestone and micritic sandstone facies of Hadibhadang Sandstone Member of Khadir Formation. This ichnofacies is dominated by cylindrical, branched to unbranched, large size horizontal endichnial structures of *Asterosoma, Curvolithus, Didymaulichnus, Gyrochorte, Halopoa, Lockeia, Ophiomorpha, Planolites, Palaeophycus, Protovirgularia, Rhizocorallium* and *Thalassinoides*, probably made by deposit feeders. Degree of bioturbation varies within the individual beds of sandy allochemic limestone and micritic sandstone facies and also shows varying mutual occurrences.

The deposit feeding endichnial structures (*Asterosoma, Halopoa, Hillichnus, Gyrochorte, Ophiomorpha, Planolites, Palaeophycus, Rhizocorallium* and *Thalassinoides*) and epichnial structures (*Curvolithus, Didymaulichnus, Lockeia,* and *Protovirgularia*) occurred at sediment-sediment interface and sediment-water interface respectively. The T-shape or curved Y-shaped branched *Thalassinoides* is considered as typical member of the *Cruziana* ichnofacies (Seilacher, 1967) colonizing in the reduced energy conditions of the shallow marine environments.

The presence of trace fossils in sandy allochemic limestone and micritic sandstone facies display that the most probable trace makers are crustaceans, bivalves, gastropods and polychaetes which are the elements of shallow marine environments. Sediment characteristic and presence of abundant feeding structures suggest normal salinity in the fully marine shoreface-offshore environmental conditions. The *Cruziana* Ichnofacies indicates low to moderate energy condition, unconsolidated substrate and plenty of detritus organic matters in shallow water marine environments.

CONCLUSIONS

~109 m thick Bajocian to Callovian succession of Chorar Island comprising Khadir and Gadhada formations are studied and the following conclusions had been drawn:

Sixteen ichnogenera have been identified which reflects four ethological (dwelling, feeding, grazing and crawling) and fifteen architectural (ichnodisparity) categories.

Five ichnoassemblages shows environmental gradients reflecting *Skolithos* and *Cruziana* Ichnofacies developed in shoreface-offshore environment.

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