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Ichnology of Early Cretaceous, cyclic bioturbated Ghuneri Member (Bhuj Formation) from the Kachchh Basin, western India

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The Early Cretaceous Ghuneri Member (Bhuj Formation) is a prominent sandstone unit outcropping along the Kachchh-Rift Basin. The post-rift sediments of Ghuneri Member comprised asymmetrical bioturbated cycles deposited in a wave-dominated deltaic environment. An ideal bioturbated cycle included coarsening-up thickening-up cycles, varying from shale/siltstone/fine-grained sandstone to medium/coarse-grained massive to cross-bedded sandstones. The basinal scale outcrops offer an excellent opportunity to analyze ichnological variations spanning proximal to the distal part of the wave-dominated delta in Ghuneri Member. The paper deals with trace fossil data from twenty-six sections of Ghuneri Member, with twenty-eight ichnospecies from twenty-two ichnogenera. Ichnological data shows a moderate to high diversity trace fossils corresponding to ichno-assemblages of regim between fair-weather and storm-wave bases. Integration of ichnological data with sedimentological data indicates fluctuating wave and storm energy within normal marine conditions. The bioturbation style signifies the availability of colonization window as a prime reason for preserving bioturbation in wave-dominated settings. Thus, the cyclic units of Ghuneri Member offer better insight into the ichnology of the Early Cretaceous wave-dominated deltaic environment.

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INTRODUCTION

Ichnology is an excellent tool to decipher the complex interplay of depositional processes. The deltaic environment possesses unique challenges as even a minor variation in the process may host different manifestations (MacEachern *et al*., 2005). The western Indian subcontinent witnessed several coeval episodes of deltaic progradation during Late Jurassic – Early Cretaceous period, namely Late Jurassic Jhuran Formation (Desai and Biswas, 2018), Bhuj Formation (Biswas, 1993; Desai, 2016; Desai and Chauhan, 2021), Wagad Sandstone (Alberti *et al*., 2019), Dhrangadhra Formation (Aslam, 1992), Himmatnagar Sandstone (Bhatt *et al*., 2016). The Kachchh deltaic sediments deposited in post-rift settings (Desai and Biswas, 2018) are excellently outcropped and contain multiple trace fossil-rich levels. The basin experienced a regressive cycle with the initiation of mega deltas, *viz.,* Jhuran Formation, Bhuj Formation and Wagad Sandstone from Late Jurassic – Early Cretaceous (Biswas, 1977; Desai and Biswas, 2018).

In the Kachchh Mainland, the older three Mesozoic formations, viz Jhurio, Jumara and Jhuran, have gained preference due to their richness of body fossils and trace fossils. These fossils have played a significant role in the reconstruction of palaeoecology, palaeogeography, palaeobiology, palaeobathymetry and faunal realms (Singh and Venkatchala, 1987; Pandey and Dave, 1993; Fürsich *et al*., 1991; Pandey and Fürsich, 1993; Pandey *et al*., 2013; Pandey and Pathak, 2015; Mukherjee, 2017). The Cretaceous Bhuj Formation lacks body fossils (Howard and Singh, 1985; Singh and Shukla, 1991). However, it is rich in trace fossils. In addition, previous workers have misinterpreted the Bhuj Formation's depositional environment.

Recent integrated approaches have resolved the depositional environment of the Bhuj Formation. The three members are re-interpreted as, wave-dominated delta for Ghuneri Member (Desai, 2016; Bhatt and Patel, 2017; Desai and Chauhan, 2021), transgressive unit for Ukra Member (Desai, 2013, 2016; Bansal *et al*., 2017) and fluvial dominated delta for Upper Member (Biswas, 1993). The Ghuneri Member offers an excellent outcrop of asymmetrical bioturbational clastic cycles. In addition, stratigraphically well-constrained proximal to distal variations offer exceptional insight to evaluate the ichnology of wave-dominated deltaic settings'. Thus, the purpose of the present work is to evaluate the proximal to distal ichnological and bioturbational variations in Early Cretaceous Ghuneri Member (Bhuj Formation).

GEOLOGICAL SETTING AND AGE

The break-up of India and Africa aided in creating the Kachchh-Rift Basin along pre-existing Precambrian lineaments. Nagar Parker Uplift and Kathiawar Uplift bound the basin in the north and the south, respectively, while the Randhapur-Barmer arch marks the eastern margin (Biswas, 2005). The sediments of the Kachchh Basin ranges from Triassic (Rhaetian) to Quaternary in age and are studied in three physiographic divisions *viz.,* Island Belt Uplift, Wagad Uplift and Kachchh Mainland Uplift (Biswas, 1993). The outcrops in Kachchh are dominated by Mesozoic (Jurassic-Cretaceous) sediments, while Deccan Traps and Tertiary sediments border the Mesozoic. Subsequently, salt marsh and other Quaternary age sediments cover them.

The Mesozoic lithostratigraphy of the Kachchh classifies the Kachchh Mainland succession into four formations, *i.e.,* Jhurio, Jumara, Jhuran and Bhuj in ascending order (Biswas, 1977). The Bhuj Formation is only exposed in the Kachchh Mainland and can be sub-divided into Ghuneri, Ukra and Upper Member in ascending order (Biswas, 1977). It extends from Bhachau in the east to areas beyond Ghuneri village in the west (Fig. 1). The Ukra Member is a marine transgressive unit, exposed only in the western part of the basin, while in the central and proximal part is manifested as an unconformity (Biswas, 1993; Desai, 2013). The Bhuj Formation is a diachronous unit based on geological field mapping of the stratigraphic units across the basin.

Ghuneri Member

The sandstone-dominated Bhuj Formation is divisible into three members: Ghuneri, Ukra, and Upper members (Biswas, 1977). Of these three members, the Ukra Member is a wedge-shaped transgressive unit, exposed only in the western part of the basin (Desai, 2013). In comparison, Ghuneri and Upper members are well exposed from the basins proximal to the distal part. The Ghuneri Member, when mapped from east to west, shows a considerable increase in thickness. The Ghuneri Member is 168 meters thick in the east and progressively thickens to 535 meters in its type area (Ghuneri Dome; Table 1) in the west (Biswas, 1977). The Ghuneri Member is dominantly unfossiliferous except for rare shell lenticels and few scattered plant-rich shales horizons. The member can easily pick up in the field based on its characteristic asymmetrical bioturbated cycles (Desai, 2012).

The gross lithology observed is laterally fluctuating, which mainly shows highly bioturbated, trough, and tabular, planar cross-bedded sandstone with thinly laminated siltstone/shale. The individual cycle starts with a poorly bioturbated shale or siltstone unit, which coarsens and thickness upward (Figs. 2 and 3). The bioturbation intensity increases upwards and reaches maximum bioturbation (Fig. 2). The Ghuneri Member consists of thick beds of sandstones alternating with laminated silts and shales. Sandstones are well-sorted medium to coarse-grained quartz arenites with occasionally micaceous, ferruginous or calcareous cement. Large-scale trough cross-bedded structures dominate the fine- to coarse-grained sandstones. The fine to medium-grained sandstones are hummocky cross-stratified. The bed tops contain medium and large-scaled wave ripples, linear wave ripples with crest bifurcations, or flat crests; substantial events of erosion with or without wave-winnowed lags are typical (Bose *et al.*, 1986).

In contrast, the shales are laminated and interleaved with thin rippled sand layers. These shales are carbonaceous, pyritiferous, rich in organic matter, and laterally grades into plant beds or coal seams (e.g. upper part of Ghuneri Mb-Coal Seam) (Fig. 3.1). The shales occasionally show syn-depositional inclination topped by horizontal bioturbated

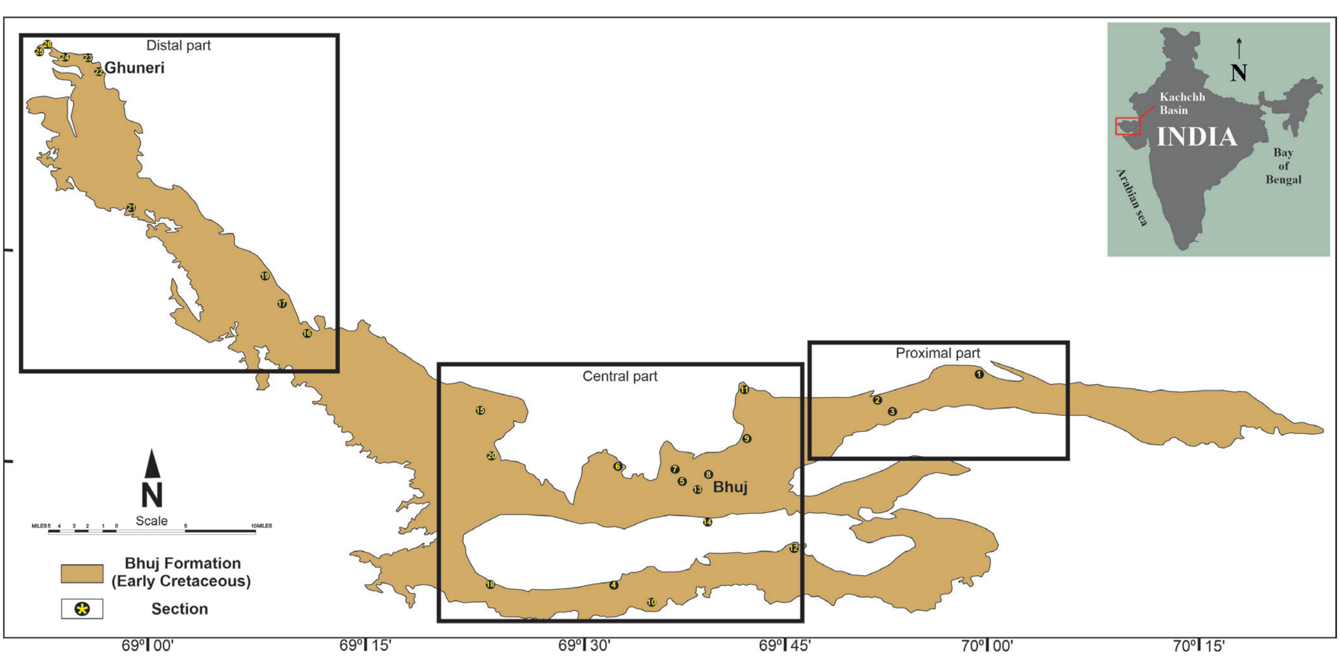


Figure 1. Location map of the Kachchh Basin along with outcrop exposures of Bhuj Formation.

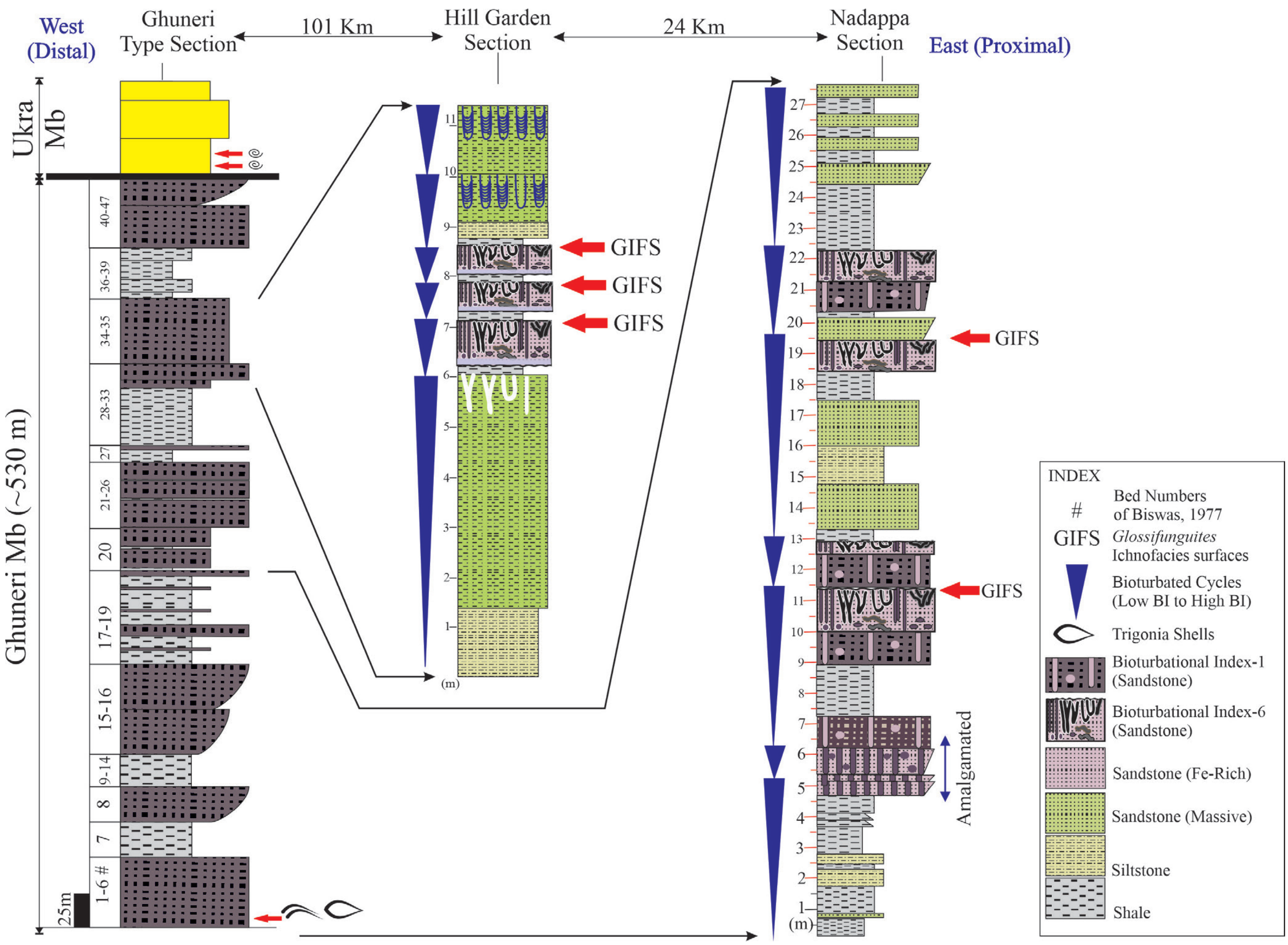


Fig. 2: Lithology and lithocolumn of the Ghuneri Member in its type section (Ghuneri) correlated with sections in the central and proximal sectors of the basin. Note the asymmetric bioturbation cyclicity and multiple occurrences of *Glossifungites* Ichnofacies surfaces.

sands (Fig. 3.2). Across the basin, several plant beds occur at different stratigraphic horizons within the Ghuneri Member. Along with the plant beds, a variety of shales are also commonly exposed. In many sections, the bioturbated cycle initiates with shale and grades up into the coarse-grained sandstone (Figs. 2 and 3.2). The shales and siltstones are frequently interrupted with channel shape sands wider than height (Fig. 3.4). The medium-coarse grained cross-bedded sands are highly bioturbated. They indicate two distinct types of colonization (a) completely bioturbation and (b) colonization after deposition of the sandbar (Figs. 3.3 and 3.6). The bioturbated sequence also displays various *Glossifungutes* ichnofacies surfaces (GIFS, Figs. 2 and 3.7). In its type section, Ghuneri Member sedimentary facies analysis suggest wave-dominated autocyclic transition of bar-lagoon depositional environment interrupted by allocyclic storm surges (Bose *et al*., 1986). Basinal scale mapping and overwhelming evidence of paleocurrent directions of the cross-stratification (Figs. 3.2, 3.5 and 3.8), channel axis (Fig. 3.4), wave-dominated sedimentary structures, bioturbation (Figs. 3.2, 3.3 and 3.6), and marine tongues in down-basin direction suggest deltaic deposits west and southwest, *i.e.* towards depocentre (Biswas, 1977).

Previous work on the ichnology of the Ghuneri Member suggests bioturbation cycles to be characteristics (Desai, 2016) and contains *Balanoglossites* from the *Glossofungites* ichnofacies (Desai and Saklani, 2012) and *Conichnus conicus* (Desai and Saklani, 2015). Other trace fossil discoveries include *Thalassinoides*, *Skolithos*, *Chondrites*, *Ophiomorpha*, *Rhizocorallium*, *Aulichinites* from the Umia formation (=Lower part Ghuneri Member) (Krishna, 1987). *Asteriacites quinquefolis* – starfish trace (Patel *et al*., 2008). Recently, Desai and Chauhan (2021) analyzed ichnological data from 24 sections of Ghuneri Member across the basin and suggested two major ichnoassemblages corresponding to below (a) fair-weather wave base and (b) storm-weather wave base.

Age of the Ghuneri Member

Age diagnostic fossils are absent in the Ghuneri Member; however, it is age bracketed by underlying and overlying ammonite bands. In previous literature, Ghuneri Member's age was considered Neocomian (Biswas, 1993, 2016). The Ghuneri Member disconformably overlies the Jhuran Formation; towards the top of the Jhuran succession, two Tithonian fossiliferous bands (1) three ammonite-rich

Table 1: Summary of the study location, rock type, bioturbation cycle and ichnofacies.

Section	Latitude (N)	Longitude (E)	Log Thickness (mt)	Traverse	Rock Type	Bioturbated cycles	Glossifunguite Ichnofacies surface
Jawahar Nagar	23°21'9.23"	69°59'22.07"	15.6	River channel	Calcareous and Ferruginous sst	4	Present
Nadappa (road side)	23°19'26.00"	69°53'23.00"	26.24	Road cutting	Amalgamated Bioturbated sst, siltstone,	9	Absent
nadappa 5 km (Before)	23°19'39.00"	69°52'18.00"	4.45	Road cutting	Ripple Laminated sst, siltstone, claystone	2	Absent
Godpar	23° 6'49.03"	69°32'32.87"	16.45	Road cutting, River channel	Calcareous and Ferruginous Biotrbated sst	7	Present
Hill Garden	23°14'24.34"	69°38'22.91"	18.7	Road cutting	Calcareous Sandstone	3	Present
Kodki	23°15'13.37"	69°33'33.05"	11.58	At Kodki-Makhana Village	Calcareous and Ferruginous Ripple Laminated sandstone	2	Absent
Khari Gorge	23°15'3.17"	69°37'48.90"	8	Road cutting, Gorge	Calcareous Sandstone	3	Absent
Leva Patel Hospital	23°13'58.64"	69°39'52.70"	10.2	Road cutting	Calcareous Sandstone	4	Present
Nagor	23°16'54.00"	69°43'0.00"	21.34	Road cutting	Ferruginous Bio. Sst, siltstone, Carbonaceous shale	6	Present
Naranpar	23° 5'53.90"	69°35'25.80"	18.28	Road cutting, River channel	Calcareous Sandstone	3	Present
Pur	23°19'38.11"	69°42'42.95"	20.5	River channel	Calcareous Ferruginous Sandstone, sitstone	3	Present
Reha	23° 8'38.90"	69°46'25.50"	22.35	River channel	Calcareous and Ferruginous sst	3	Present
Ring road	23°13'53.57"	69°39'19.79"	11.58	Road cutting	Calcareous and Ferruginous sst	4	Present
Tapkeshwari	23°10'48.23"	69°40'1.18"	18.2	At near Temple	Calcareous and Ferruginous sst	3	Present
Gangaji mandir	23°19'23.50"	69°23'24.70"	10.9	Road cutting	Calcareous and Ferruginous sst	6	Present
Mathal	23°24'29.64"	69°10'14.49"	3.1	Road cutting	Bioturbated sanstone	2	Absent
Moray Camp	23°26'18.79"	69° 8'58.21"	7.59	Road cutting	Shale, sitstone, Bio Sandstone	1	Absent
Rampar Vekra	23° 6'18.60"	69°28'13.30"	10.85	River channel	Calcareous and Ferruginous sst	4	Present
Ugedi	23°28'1.75"	69° 7'26.81"	12.5	Road cutting	Calcareous and Ferruginous sst	5	Present
Yaksh	23°17'26.29"	69°21'43.87"	13.2	Road cutting, River channel	Organic rich shale, sitstone. Sandstone	2	Absent
Mata no madh	23°32'0.53"	68°56'0.49"	17.5	Road cutting	Calcareous Sandstone	_	Absent
Siyot	23°19'23.50"	68°54'58.12"	3.6	Road cutting	Calcareous Sandstone, Bio. Siltstone	2	Present
Atada	23°44'52.96"	68°52'42.02"	13.1	River channel	Fe nodules and Organic rich Black shale. Bio. claystone, Sst	5	Absent
Near Katesar	23°46'5.00"	68°52'40.00"	13.25	River channel	Bio. sandstone, Shale, sitstone,	6	Present
Umarsar	23°46'16.98"	68°50'30.11"	7	along the flank of Ghuneri Dome	Maroon sandstone, siltstone, fe shale	2	Present
Ghuneri Type Section	23°47'6.03"	68°50'40.20"	73.12	Nr. Guneri Village	Bio. sandstone, Shale, Siltstone, claystone	10	Present

oolitic limestone bands (2) the Gryphaea band, along with a lower Cretaceous "Trigonia Ridge Sandstone" occurs (Fürsich and Pandey, 2003; Desai and Biswas, 2018; Fursich *et al*., 2021). Of the Three ammonite-rich oolite limestone bands, the lower two bands range in age from Frequens Zone (corresponds to *Durangites*) of Upper Tithonian age (Krishna *et al*., 2006; Pandey *et al*., 2016). While the youngest oolitic limestone band yielded *Argentiniceras* (= *Andesites*) *loncochensis* (Steuer), assigning Lower Berriasian age to pre-Ghuneri sediments (Krishna *et al*., 1994). Additionally, a *Trigonia*-shell bed also occurs approximately 2-3 meters below the base of Ghuneri Member. Thus, the western part of the Kachchh Mainland, the basal boundary of the Ghuneri Member can be placed in the Berriasian age. Similarly, in the Ghuneri Mb type area, fossiliferous Ukra Member, considered a short transgressive unit in deltaic progradation (Biswas, 1993; Desai, 2013), overlies the Ghuneri Member. The Ukra Member in its basal part contains ammonites *Australiceras*, *Cleoniceras*, and *Lemuroceras* (Krishna *et al*., 1983), belemnites *Neohibolithes ewaldi* and *Tetrabelus seculus* of Aptian age (Desai, 2013). Additionally, the basal part of the Upper Member (Bhuj Formation) was dated to Middle Albian based on nannoplankton (CC8 *Prediscosphaera columnata* zone to NC8 *Tranolithus orionatus* zone) (Rai, 2006). Thus, the Ghuneri Member can be age bracketed between Berriasian to Barremian age.

MATERIALS AND METHODS

We studied twenty-six outcrop sections of Ghuneri Member for their stratigraphical, sedimentological and ichnological content. The studied outcrops (Table 1) mainly cover domes (anticlines), river cliffs and road cross-sections. Sedimentary beds in all sections show low to moderate dips towards the south and southwest. We integrated, collated ichnological data with sedimentological data of grain size, bed geometry, bedform (symmetrical wave ripples) and cross-stratification (planar, trough, hummocky). In addition, we studied the trace fossil content (cross-section and on the bedding planes) to understand ichnoassemblage, along with statistical measurements like an abundance of each identified ichnotaxa (at ichnogenus level) at the outcrop. As a result, ichnotaxa are classified as abundant (above 100 individuals), common (50-100 individuals), rare (10-50 individuals) and very rare (less than ten individuals) (Table 2). We used the initiation of bioturbation cycles and associated substrates for lithostratigraphic correlation from the east (proximal) to the west (distal) parallel to the strike orientation (Figs. 1 and 2). The contacts between the sedimentary beds are marked as conformable unless the top of the bed exposes deep tier trace fossils. All the trace fossils were photographed and documented in the field, and selective samples are collected for further taxonomic studies.

SYSTEMATICS

In Ghuneri Member, a total of twenty-eight recurring ichnospecies corresponding to twenty-two ichnogenus are recorded. The recorded trace fossils are described as follows.

Ichnogenus Arenicolites Salter, 1857

Arenicolites variabilis Fürsich, 1974a
(P1. I. Fig. 1)

Description: Endichnial, U-shaped burrows, oriented vertically to incline to the bedding plane, lined burrows without spreite. The arms of the U-tubes are straight to curved and parallel to each other. In cross-sections, they also appear as varying J- shaped morphology. Burrowing depth varies between 15 to 27 cm, with burrow diameter between 9-30 mm, and distance between two arms between 20-40 mm.

Discussion: The burrows are highly variable in morphology with narrower width of U tube and greater depth. *Arenicolites* are considered a dwelling and feeding structure of suspension-feeding (Hakes, 1976) or crustacean-like organisms (Goldring, 1962). *Arenicolites* differ from *Diplocraterion* in the absence of spreiten (Fürsich, 1974a). Though known to occur in diverse environments, including non-marine (Guillette *et al*., 2003), it is typical of shallow-marine settings (Crimes, 1977). The trace fossils commonly occur as post-depositional features passively filled with coarse-grained sediments; however, the Kachchh specimens lack retrusive structures. *Arenicolites* are interpreted as work of suspension-feeding polychaetes (Fürsich, 1974a; Patel and Desai, 2009).

Ichnogenus Balanoglossites Mägdefrau, 1932

Balanoglossites triadicus Mägdefrau, 1932
(P1. I. Fig. 2)

Description: Irregularly oriented, branched tunnels forming a complex three-dimensional network, resembling U, J, Y, or I shape in a vertical section. All burrows are unlined with sharp margins, 10-28 mm in diameter. In the lower part of the burrows, a cross-section of the tunnels and galleries are circular to elliptical. The burrow widens in diameter towards the top of the bed, shaping into funnels, which merge, forming a wider irregular opening. The burrow contrasts with the host rock and is characterized by structureless medium- to coarse-grained sand grains, which are passively filled into the burrows. Locally burrow fills are encircled by purple to reddish coloured ferruginous rims or halos.

Discussion: *B. triadicus* (Mägdefrau, 1932) was first described from the Middle Triassic sediments of Germany, which Knaust (2008) re-described as a complex type trace encompassing both the burrowing and boring behaviour. Also, the ichnospecies *B. eurystomus* (Mägdefrau, 1932) included under *B. triadicus* as junior synonymy. The present specimens lack faecal pellets and give indications of firm-ground (Desai and Saklani, 2012). The irregular branching with a complex pattern of burrows is assigned to *B. triadicus*. The *B. triadicus* differs from *B. ramosus* in clear U- or Y-shaped tunnels and absence of faecal pellets.

Balanoglossites ramosus Knaust, 2008
(P1. I. Fig. 3)

Description: Complex three-dimensional burrow systems comprising of vertical to inclined shafts connected to horizontal tunnels. In cross-section, the tunnels and shafts are circular to elliptical and at places irregular. Tunnels are local blind-ended and show side branching. Shafts are curved or straight and may bifurcate and continue as inclined or horizontal tunnels. The tunnels and shafts are unlined, with clean and sharp margins. Burrows are filled with medium-grained, structureless and massive sand contrasting with the host sediment.

Discussion: For *B. triadicus and B. ramosus*: Recently Knaust, (2008) re-described this ichnogenus from the type area and re-described the ichnospecies. Stratigraphically, the trace fossils range from Ordovician (Knaust, 2008; Dronov, 2011) to Holocene and recent deposits (Patel and Desai, 2009). However, they are more abundant and widely reported from the Triassic carbonate successions of the German Basin (Kazmierczak and Pszczołkowski, 1969; Knaust, 2008). These trace fossils are reported from omission surface of shallow marine condition (Knaust, 2008), lower intertidal zone (Kazmierczak and Pszczołkowski, 1969), storm dominated shallow marine environment (Dronov, 2011), intertidal lagoon (Patel and Desai, 2009).

Ichnogenus Chondrites Sternberg, 1833

Chondrites intricatus Brongniart, 1823
(P1. I. Fig. 4)

Description: Dichotomously branched burrows bifurcating at an angle >45° with 1st or 2nd order of branching. Tunnels are straight with a rounded or tapering end with an elliptical cross-section. Tunnel diameter varies from 4 to 10 mm. Burrow fill is different from the host sediment.

Discussion: *C. intricatus* differs from other species in the angle of branching and diameter of the burrow. *C. intricatus* are more slender than other specimens. Mono-species occurrence of *Chondrites* is indicative of anoxic conditions (Bromley and Ekdale, 1984). *Chondrites* trace makers are also considered chemosymbiotic organisms (Seilacher, 1990; Fu, 1991). In recent intertidal zones of Mandvi, Gulf of Kachchh, the trace makers of *Chondrite*s shows changes in feeding strategies during reversal of flow during changing tidal condition (Patel and Desai, 2009).

Ichnogenus Conichnus Männil, 1966

Conichnus conicus Männil, 1966
(P1. I. Fig. 10)

Description: Endichnial burrows, typically conical in vertical cross-section, display steeply inclined lateral margins and a distinctly rounded basal terminus. Specimen length reaches up to 1000 mm, and length: width ratios are 2:1. The lateral laminae are steep and clear. In the upper parts, convex-down laminae reflect a uniform deflection of toe and foreset laminae.

Discussion: Buck and Goldring (2003) reviewed conical sedimentary structures and differentiated seven principle processes responsible for their formation. Based on the criteria described by Buck and Goldring (2003), the present conical structures can be classified as burrows made by sea anemones exhibiting (1) escape locomotion and (2) equilibrium movement. *Conichnus* is widely reported from shoreface deposits (MacEachern and Pemberton, 1992; Pemberton *et al*., 1992); cross-bedded and bioturbated sandstones of tidal environments (Savrda, 2002). Thirteen *Conichnus* specimens are reported from medium to coarse-grained sandstones representing episodic sedimentation in Ghuneri Member (Desai and Saklani, 2015).

Diplocraterion Parallelum Torell, 1870
(P1. I. Fig. 7)

Description: Vertical, unlined, U-shaped burrow with retrusive spreite, burrow fill, and spreite sediments are similar to the host sediments. The arms of the burrows are straight and parallel to each other; tube diameter varies between 1 to 3 mm, with inter-tube distance 7 to 10 mm. The depth of the burrow is up to 60 cm.

Discussion: *Diplocraterion parallelum* is characterized by straight and parallel arms of the burrow having little distance. *Diplocraterion* is described as the work of the suspension-feeding organism (Fursich, 1974b). *D. parallelum* is probably produced by worms which occurs commonly in Paleozoic, Mesozoic and Cenozoic sediments (Gerard and Bromley, 2008). The retrusive spreite structure is mainly related to the impermeability of sediments or perturbation in sediments.

Ichnogenus Gyrolithes Saprota, 1884

Gyrolithes saxonicus Häntzschel, 1934
(P1. I. Fig. 6)

Description: Endichnial preservation, circular helix burrow. Burrows are thinly lined, coiling dextrally and sinistrally, with an average radius of the whorl is about 25 mm or more, while the burrow radius is about 10-12 mm. Burrows are circular to elliptical in cross-section. Burrows form a system of sub-circular curves. Burrow fills are similar to the host sediment.

Discussion: The dimensions of the Kachchh specimens match well with *Gyrolithes saxonicus* range as Uchman and Hanssen (2013) suggested that the smaller forms are to be described under *G. saxonicus*, while larger forms under *G. cycloides*. Larger forms of *G. cycloides* are previously described from the Kachchh Basin from the younger Aptian Ukra Member from the same area. Additionally, thinly lined and similar burrow fill sediment indicates its formation during softer substrate conditions.

Ichnogenus Gyrochorte Heer, 1865

Gyrochorte comosa Heer, 1865
(P1. I. Fig. 8)

Description: Bilobed, horizontal burrows having straight to sinuous orientation consisting of smooth ridges with a median furrow. Burrows have positive and negative epirelief preservation. The maximum observed burrow width is up to 6 mm.

Discussion: *Gyrochorte* is the burrow of an animal that selects food from the sediment over the entire length of its body (Powell, 1992). The trace commonly occurs throughout the Mesozoic sediments of the Kachchh Basin. One of the most characteristic features of *Gyrochorte* is the vertical dimension of convex epirelief and their corresponding hypo reliefs in the same bed (Gibert and Benner, 2002). They are interpreted as the work of an opportunistic organism from a shallow marine environment (cf. Gibert and Benner, 2002).

Ichnogenus Gyrochorte Heer, 1865

Gyrochorte variabilis Fürsich, Alberti and Pandey, 2017
(P1. I. Fig. 9)

Description: Bilobate ribbon preserved as positive epirelief, curved to oblique pairs of elongated oblique bulges that are serially arranged along the axis of the ribbon and merged at the endpoint. Fan like arranged and closely aligned, separated by grooves split into the ribbon-like structure.

Discussion: *Gyrochorte variabilis* differs from other species of *Gyrochorte* by displaying fan-like arrangements of bilobed traces (Fürsich *et al*., 2017). In general, polychaetes or worm-like organisms to be its trace maker (Seilacher, 2007). The “brushes” forming fanning pattern is considered a behavioural variant of the trace makers (Weiss, 1949; Seilacher, 2007). *G. variabilis* show fan-like structure occurred not only in one direction but also sideways movement and is considered a behavioural variant for the exploitation of organic matter in the substrate (Fürsich *et al*., 2017).

Ichnogenus Lockeia James, 1879

Lockeia siliquaria James, 1879
(P1. II. Fig. 1)

Description: Almond-shaped, bilaterally symmetrical, a high standing mound with slightly rounded to subangular and straight crest, smooth-walled bulb tapering from one side. Two-dimension groups occur together, ranging from 14 to 18 mm and another from 4 to 9 mm.

Discussion: The Kachchh specimen of *Lockeia* represents cubichnia (resting trace of bivalves). The size variation indicates two groups of the population. *L. siliquaria* is interpreted as either cast of foot or shell itself (Mángano *et al*., 1998).

Ichnogenus Maiakarichnus Verde and Martinez, 2004

Maiakarichnus currani Verde and Martinez, 2004
(P1. II. Fig. 8)

Description: Sub spherical chamber with clay lining persevered in full relief with shaft radiating, exposed in vertical section with eight thin shafts. Slightly curved shaft radiating in an upward direction from the upper part of the chamber. The external diameter of the chamber is 30 mm. The length of the radiating shaft is 40 mm. The total length of the species is 55 mm. The thickness of the chamber wall lining is 1.2 mm. Chamber diameter measurement includes the clay lining. Host material and infill material are like each other.

Discussion: *Maiakarichnus* is a spherical chamber with shafts radiating upwards. It was considered a crustacean brooding chamber (Curran, 1976; Verde and Martinez, 2004). Callianassid crustaceans are considered to be their trace makers. They are frequently reported to make brooding chambers in their three-dimensional burrows like *Ophiomorpha* or *Thalassinoides* (Desai, 2016). *Maiakarichnus* specimen may or may not be clay lining (Verde and Martinez, 2004).

Ichnogenus Monocraterion Torell, 1870

Monocraterion tentaculatum Torell, 1870
(P1. II. Fig. 5)

Description: Elongated, unlined, vertically oriented burrow with a funnel at the top. The lower part of the burrow is not preserved. In cross-section, burrow sides are parallel to slightly converging, forming a weak cone. Funnel diameter ranges between 10-18 mm with tube diameter varying between 5-8 mm and length up to 35 mm.

Discussion: The association of funnel with the vertical tubes in *Monocrateion* functionally helps trace makers in suspension-feeding and irrigating the burrow. The burrow is a temporary dwelling burrow of suspension-feeding activities and irrigation of the burrow (Desai and Saklani, 2014).

Ichnogenus Ophiomorpha Lundgren, 1891

Ophiomorpha nodosa Lundgren, 1891
(P1. II. Fig. 4)

Description: Full relief three-dimensional, branched burrow systems, with vertical shafts and interconnected horizontal to inclined tunnels. Vertical shafts are straight, while horizontal tunnels may be straight to curve. Wall thickly lined with a smooth interior and outer wall with nodular structure. Burrow fill is similar to the host sediment. Diameter varies from 24 mm to 35 mm, a width of the outer wall of 5-6 mm thick. Sometimes the nature of the burrow wall changes vertically, from irregular to nodular outer wall. The species consists of well-developed and dominant vertical and horizontal galleries.

Discussion: The trace fossils are identified based on a thick-lined wall with nodular structures and interpreted as dwelling burrow or filter-feeding organisms. *Ophiomorpha* is a characteristic trace fossil for the clastic, shallow marine environment, typically belonging to a subtidal region (Chamberlain and Baer, 1973; Frey *et al*., 1978) or lower intertidal zone (Patel and Desai, 2001). They appear as dominantly vertically branched when associated with firmground *Glossifunguites* ichnofacies surface.

Ichnogenus Polykladichnus Fürsich, 1981

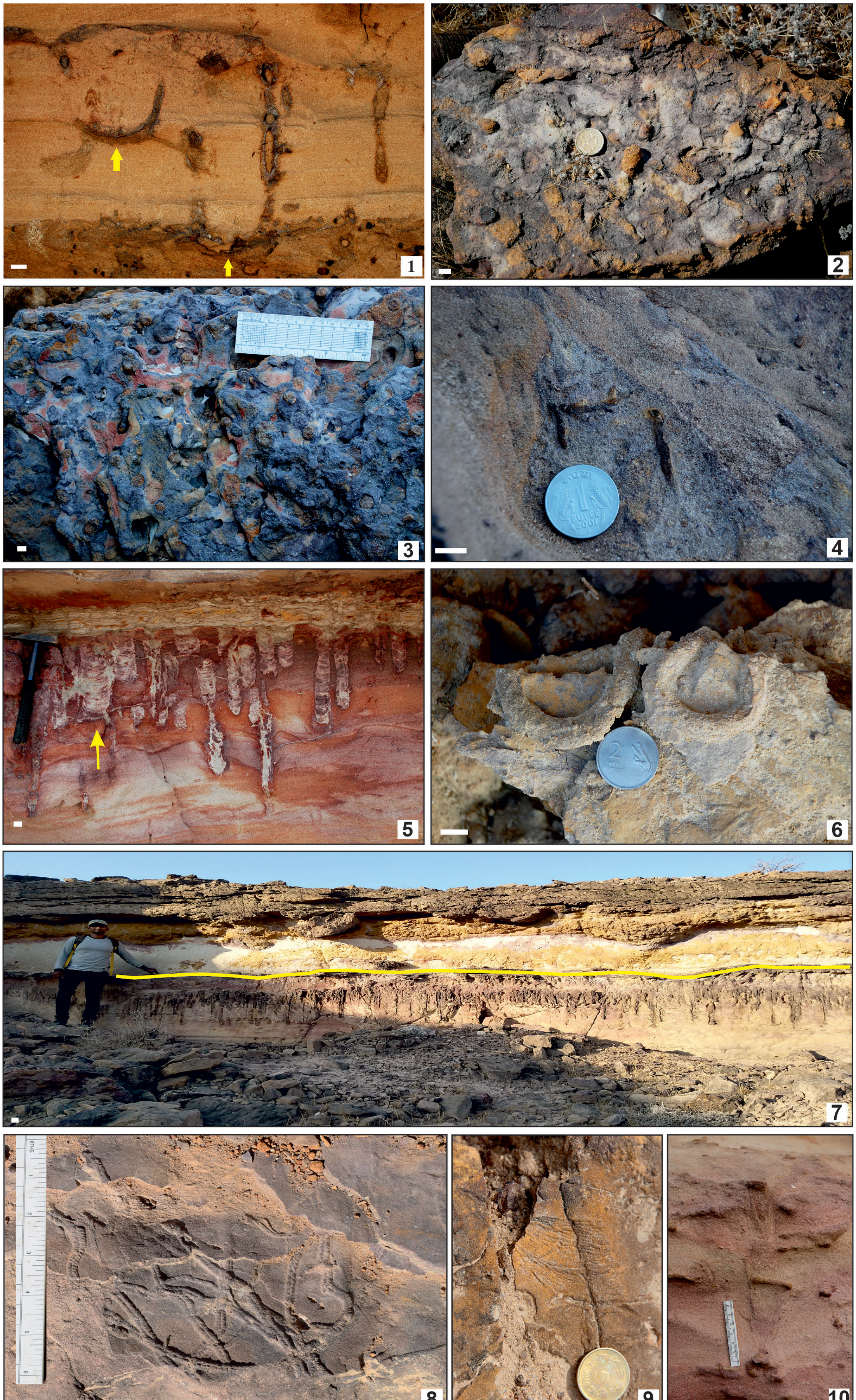
Polykladichnus irregularis Fürsich, 1981
(P1. II. Fig. 3)

Description: Simple, slender, vertically bifurcating burrow system comprising of vertically oriented tubes. Burrow is thinly lined, and branches in upward oriented Y. Burrow fill is different in texture and colour from the host sediment. Burrows are circular in cross-section with a maximum diameter of up to 20 mm, and a vertical burrow depth of up to 15 cm.

Discussion: In the study area, the *Polykladichnus* colonizes in two different substrates, i.e. muddy and sandy. In both cases, the thick-lined burrows are interpreted as a stabilizing mechanism in soft sediment. These are produced by polychaetes and are dwelling burrows. These were earlier reported from the recent intertidal zone of Mandvi and the Gulf of Kachchh (Patel and Desai, 2009).

EXPLANATION OF PLATE I →

Trace fossils from the Ghuneri Member, white bar in left bottom corner is one cm. (1) *Arenicolites variabilis* in medium-grained bioturbated sandstone in Pur Section (2) *Balanoglossites triadicus* in the highly bioturbated sandstones of Ghuneri Member type Section (3) *Balanoglossites ramosus* in highly bioturbated sandstones, both *Balanoglossites* occur as *Glossifunguites* ichnofacies surface horizons. (4) Mud-filled *Chondrites intricatus* in medium-grained ferruginous sandstone in the section near Katesar. (5) Post-depositional colonization of the *Diplocraterion* showing *D. bicalvatum* (arrow) and rest *Diplocraterion Parallelum*. (6) Cork-screw nature of *Gyrolithes saxonicus* in medium to coarse-grained sediment in Nagor section, note the coarse-grained sediments occurring as burrow fill. (7) Extensive colonization of the *Diplocraterion parallelum* occurring as a post-depositional event. Note the extent and depth of penetration. (8) *Gyrochorte comosa* occurring on the top of the fine-grained sandstone in Ugedi Section. (9) Fan-like structure of *Gyrochorte variabilis* occurring in ferruginous sandstones in Reha Section. (10) Equilibrium trace fossil *Conichnus conicus* in medium-grained bioturbated sandstone in Pur Section.



Ichnogenus Psilonichnus Fürsich, 1981

Psilonichnus tubiformis Fürsich, 1981
(P1. II. Fig. 2)

Description: Thickly lined, cylindrical burrows with vertically bifurcating Y or J-shaped components. A few specimens show irregular bifurcation that is different from burrow are cylindrical, straight to slightly curved, burrows thickly lined up to 4 mm. On a bedding plane, it appears as crowded protruding circular rims of tubes. Diameter ranges from 20 to 60 mm—burrow branches at angles ranging from 40° to 70°.

Discussion: The Kachchh specimen matches well with the material described by Fürsich (1981). It is interpreted as permanent dwelling burrows of crustaceans, showing an upper intertidal zone environment (Patel and Desai, 2009). *Psilonichnus* is produced by suspension-feeding crustaceans borrow (Fürsich, 1981).

Ichnogenus Palaeophycus Hall, 1847

Palaeophycus tubularis Hall, 1847
(P1. II. Fig. 6)

Description: Horizontal to sub-horizontal, lined and unbranched burrows. Cross-sections are circular to oval shapes varying between 6 to 15 mm in diameter with structureless passive fill. Burrow fill grain size coarser than host rocks.

Discussion: The thin lining, gently curved, smooth walls are consistent with *P. tubularis.* The burrow morphology is described by Fillion and Pickerill (1984). The trace is facies crossing and interpreted to be a dwelling structure. *Palaeophycus* are thin-walled with no striations, so the burrow morphology shows that the species is *P. tubularis*. *P. tubularis* produced probably by polychaetes, which occurs from the Precambrian to Recent (Pemberton and Frey, 1982).

Ichnogenus Planolites Nicholson, 1873

Planolites beverleyensis Billings, 1862
(P1. II. Fig. 7)

Description: Unlined, straight to gently curved, tubular unbranched burrow, cylindrical to elliptical in cross-section, oriented parallel to the bedding plane. Diameter ranges from 7 to 10 mm, the maximum observed length is up to 150 mm. Burrow fill is different from the host sediments.

Discussion: *P. beverleyensis* is distinguished from *P. montanus* in a larger size (Pemberton and Frey, 1982). *Planolites* is interpreted to be made by active backfilling of deposit feeder (Uchman, 1995).

Ichnogenus *Rhizocorallium* Zenker, 1836

Rhizocorallium irregulare Mayer, 1954
(Pl. III. Fig. 10)

Description: Epichnial, semi to full-relief preservation of U-shaped burrow. Trace fossils are more than 45 cm long, curved to slightly sinuous and occasionally branched, horizontally oriented with marginal burrow with crescent-shaped spreiten structures. The width of the U ranges from 70-80 mm, with a diameter of marginal tubes ranging from 10-20 mm. The spreiten are well preserved, and burrow fill is identical to the host rock.

Discussion: The *R. irregulare* differs from other species of *Rhizocorallium* in having long and curved to even bifurcating burrows. The Kachchh specimen characterized by its long and curved nature matches well with specimens described by *R. irregulare* (Fürsich, 1974c). These are considered deposit-feeding traces (Fürsich, 1974c) and are characteristic trace fossils indicating low energy hydrodynamic conditions (Rodríguez-Tovar and Pérez-Valera, 2008).

Rhizocorallium jenense Zenker, 1836
(Pl. III. Fig. 8)

Description: Epichnial, full relief, simple, horizontal to slightly inclined sprietien, U-shaped burrow tube. The width ranges from 80-100 mm with tubes parallel to each other. Tubes are relatively thick up to 25 mm with distinctly "Protrusive", with retrusive limbs. Distinct, curved packets of spreiten fill the inter-tube areas, each nearly 5-9 mm thick.

Discussion: The ichnospecies *R. jenense* differs from other species in having, short retrusive tube which is vertically retrusive. Seilacher (2007) extensively discussed the taxonomic status of *Rhizocorallium* and Fürsich (1974c), who concluded that short oblique, vertically retrusive forms should be interpreted as burrows of suspension feeders. It is typically found in Jurassic sediments deposited in high energy shallow marine conditions of Habo Dome (Patel *et al*., 2008) and from Lower Cambrian sediments (Jensen, 1997).

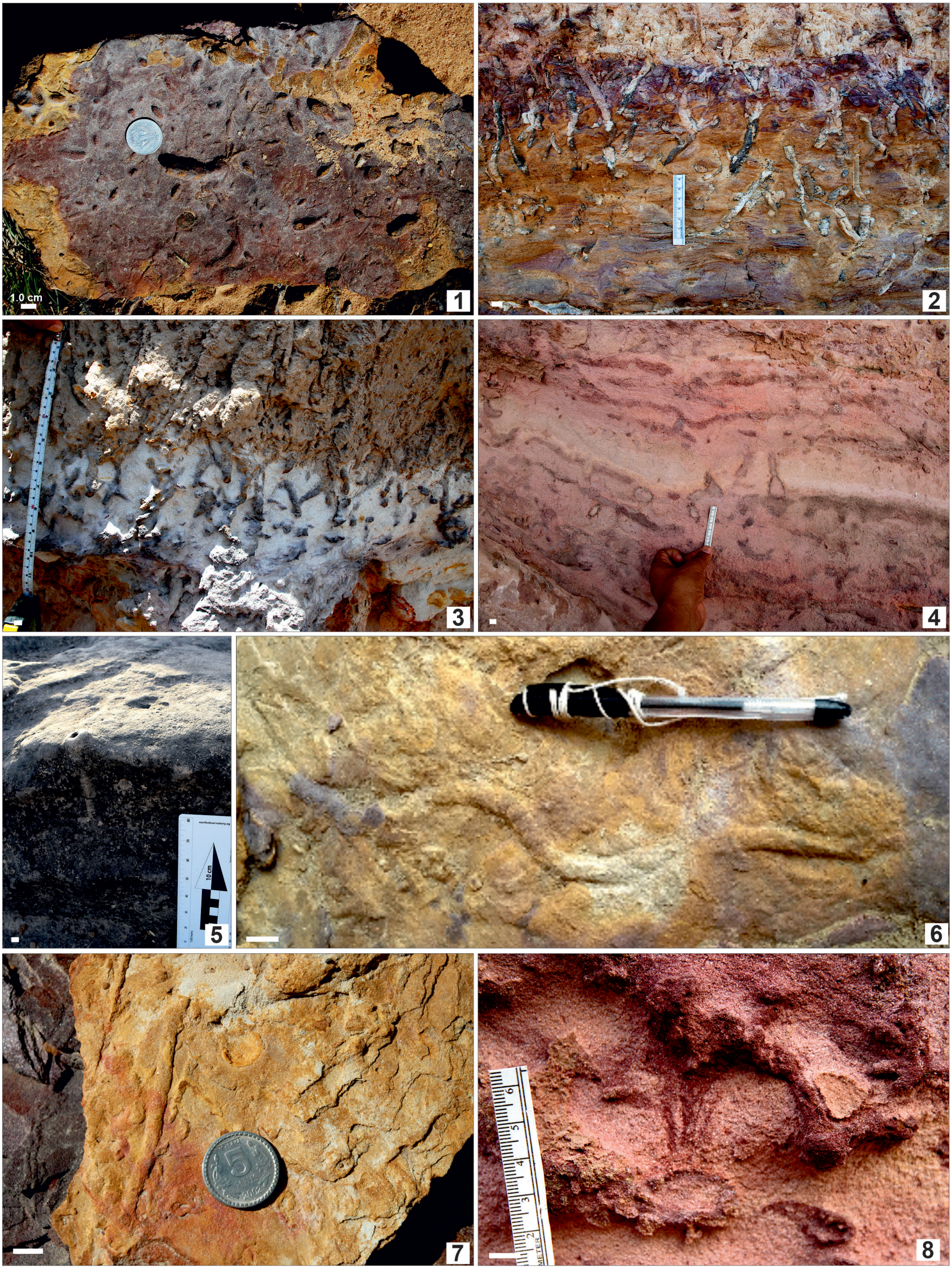
Ichnogenus Rosselia Dahmer, 1937

Rosselia rotates MacCarthy, 1979
(Pl. III. Fig. 1)

Description: Burrow oriented vertical to slightly inclined, conical to bulbous lined burrow with concentric backfill. The vertical section appears as wide "V". The bedding plane view of the burrow is circular to elliptical with 25 mm to 50 mm diameter. The centre of the circular structure shows a rotational pattern. The diameter of the central tube ranges from 10 to 13 mm.

EXPLANATION OF PLATE II ⟶

Trace fossils from Ghuneri Member (1) Almond-shaped *Lockeia siliquaria* occurring as hypechnia in the ferruginous siltstone near katesar Section (2) Y-shaped, branched *Psilonichnus tubiformis* occurring in bioturbated fine-grained sandstone in Rampar Vekra Section. (3) Slender-upward bifurcating *Polykladichnus irregularis* in claystone, penetrating from the top sandy horizon in Hill Garden Section (4) Moderately bioturbated sandstone containing *Ophiomorpha nodosa* occurring in Pur river Section (5) Vertically-oriented *Monocraterion tentaculatum* occurring in fine-grained sandstone. (6) Sub-horizontally oriented, sinous *Palaeophycus tubularis* in fine-grained sandstone. (7) Horizonally-oriented straight *Planolites beverleyensis* in fine-grained sandstone. (8) *Maiakarichnus currani* occurring in fine-grained ferruginous sandstone in Pur Section.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Discussion: *R. rotates are* characterized by a distinct pattern of rotational movement of the funnel burrow, while *R. socialis* is characterized by the central area is more systematically concentric. *Rosselia* is usually associated with environments experiencing high sedimentation rates and erosion (Nara, 1997; Netto *et al*., 2014). The actual morphology of the *Rosselia* is spindles-shaped, and the preservation of the only funnel-shaped forms suggests that the upper part of the trace might be eroded (Nara, 1997; Frieling, 2007). The trace fossils are a facies crossing dwelling structure, occurring in open marine to deltaic environments (Pemberton *et al*., 2001); formed by detritus-feeding polychaetes (Knaust, 2017).

Ichnogenus Skolithos Haldeman, 1840

Skolithos linearis Haldeman, 1840
(Pl. III. Fig. 4)

Description: Straight to slightly curved burrows occurring densely, unornamented, lined burrows with a diameter ranging from 10 to 17 mm. Length up to several decimeters. The burrow wall is distinct and appears as a small ring-like projection on the top of the bed. Burrow fill coarser than host rock.

Discussion: *Skolithos* commonly occurs in a shallow marine environment and is produced by annelids or phoronids (Alpert, 1974; Fillion and Pickerill, 1990). The dense occurrence of *Skolithos* may be interpreted to be a domichnion of a suspension-feeding organism like polychaetes (Alpert, 1974, Patel and Desai, 2009).

Skolithos verticalis Hall, 1943
(Pl. III. Fig. 3)

Description: Vertical to slightly inclined burrow with a diameter ranging from 6 to 10 mm and length up to 7 cm. Burrow wall distinct, smooth and sediment is similar to the host rock. Burrow fill is structureless and is similar to the host rock.

Discussion: *S. verticalis* is characterized by inclined burrows with shorter burrows, and the specimens from the study are similar to that described by Alpert (1974) for *S. verticalis*. It varies from another species like *S. linearis* in greater length. As compared to *S. verticalis*, *S. magnus* has indistinct burrow walls, *S. ingens* have slight bulges at irregular intervals, and *S. annulatus* have ring line annulations (Alpert, 1974). *Skolithos* are interpreted as dwelling burrows of suspension-feeding organisms (Patel and Desai, 2009), commonly occurring in high-energy shallow marine nearshore environments (Knaust, 2017).

Ichnogenus Teichichnus Seilacher, 1955

Teichichnus rectus Seilacher, 1955
(Pl. III. Fig. 9)

Description: Unbranched, straight, or slightly sinuous, irregular, horizontal burrow. Diameter ranging from 6 to 11 mm with broadly U-shaped. In lateral view, the burrow appears to have parallel, more-or-less horizontal to undulate lamina forming a spreite structure, topped by a tube. Burrows comprises convex up shaped lamina with a final tube, forming a retrusive spreiten structure in cross-section. Lamina are simple and convex, while tubes may be cylindrical to elliptical in cross-section. Burrow fill identical to a matrix.

Discussion: The described forms are arcuately lying horizontally on the bedding plane. Based on the morphology of the lamina, the present specimens can be placed under *T. rectus*. *T. rectus* has a retrusive, highly guide spreite burrow (Seilacher, 1955). It differs from *T. flexuosus,* which is a spiral burrow, while *T. palmatus* is a branched structure. *T. patens* have double gutter-shaped morphology of lamina (Schlirf, 2000). However, based on the photograph and description, it can be convincingly said that the described form does not belong to *Teichichnus*.

Ichnogenus Taenidium Heer, 1877

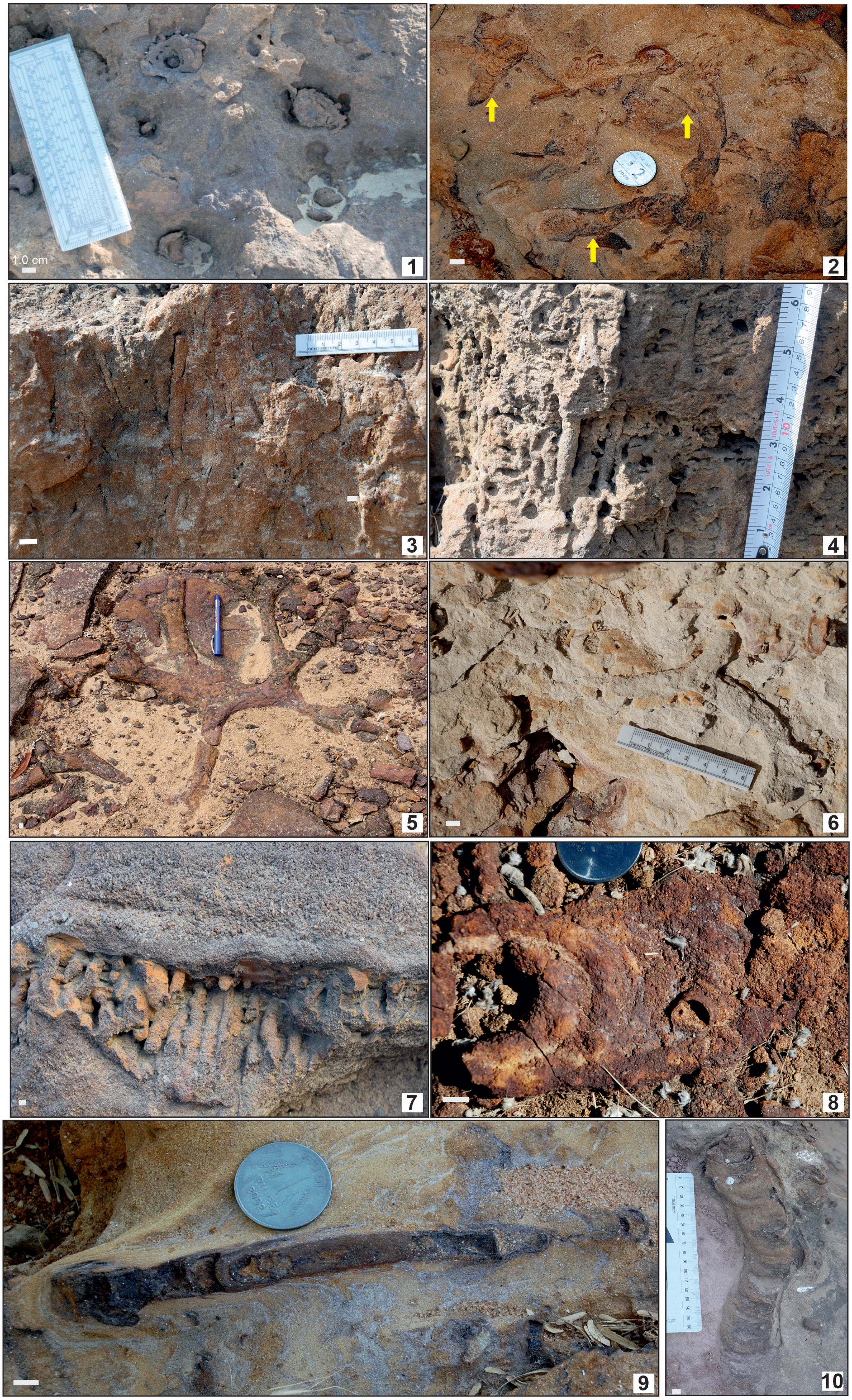
Taenidium serpentinium Brady, 1947
(Pl. III, Fig. 2)

Description: Cylindrical, unbranched, thinly lined, simple, parallel to inclined to the bedding plane, sinuous, burrow infill material meniscated. Burrow diameter is 10 to 17 mm wide. Burrow contains thick-segmented fills articulated by the meniscus. The filled material and host material may be identical and show contrasting filling. The menisci are about 1-3 mm thick, with inter-menisci segments being much wider (8-13 mm thickness) and are feebly concave.

Discussion: *Taenidium serpentinium* is characterized by sinuous burrows with distinct well-spaced arcuate menisci (D'Alessandro and Bromley, 1987). *Taenidium* is interpreted as pascichnia produced by vagile, deposit-feeding animals (D'Alessandro and Bromley, 1987). During Jurassic, the ichnospecies occurs in wide energy conditions in Kachchh, varying from the shallow marine storm-influenced environment (Fürsich *et al*. 2018); low-to-intermediate energy ramp (Fürsich, 1998) to inner shelf/ prodelta environment (Desai *et al*. 2008).

EXPLANATION OF PLATE III →

Trace fossils in the Ghuneri Member (1) Irregular bedding plane surface of ferruginous sandstone showing multiple trace fossils of *Rosselia rotatus,* Near Katesar Section. (2) Oblique view of *Taenidium serpentinium* in fine-grained sandstone in Ghuneri Member type Section. (3) *Skolithos verticalis* occurring in moderately bioturbated sandstones in Rampur Vekra Section. (4) Crowded occurrence of *Skolithos linearis* in bioturbated sandstone in Rampur vekra Section. (5) Box-work network of *Thalassinoides suévica* in ferrugenious sandstone. (6) Branching pattern in *Thalassinoides paradoxica* occurring in fine-grained sandstone. (7) Partially preserved *Teredolites calvatus* in coarse-grained sandstone, note the xylic substrate is decayed and eroded, only *Teredolites* borings are preserved. (8) *Rhizocorallium jenense* in coarse-grained ferruginous sandstone near Katesar Section (9) Slender and long *Teichichnus rectus* occurring in siltstone in Ghuneri type Section, the view is from the top (10) *Rhizocorallium irregulare* in fine-medium grained sandstone.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Ichnogenus Thalassinoides Ehrenberg, 1944

Thalassinoides suevicus Rieth, 1932
(Pl. III, Fig. 5)

Description: Three-dimensional system of lined burrows with smooth burrow walls. Burrow branching irregular to dichotomous, typically in Y and T shapes in a horizontal plane and enlargements at bifurcations, burrow bifurcation angle about 120°. Burrows are oriented parallel to the bedding plane, with dominating horizontal component and a minor vertical component. Cross-sections of the burrows are circular to elliptical, with a diameter ranging between 20 to 30 mm.

Discussion: *Thalassinoides suevicus* is distinguished from other species by its burrow enlargement at bifurcation dominance of horizontal components (Myrow, 1995 and reference therein). It occurs in a wide range of depositional environments ranging from marginal marine to deep marine (Fürsich, 1974a; Knaust, 2017 pg.160). Mainly crustaceans (Frey *et al*., 1984) make these burrows, and these burrows are regarded as a combined dwelling and feeding activity of crustaceans.

Thalassinoides paradoxica Woodward, 1830
(Pl. III, Fig. 6)

Description: Preserved specimen comprises of three-dimensional burrow system with horizontal component showing box work pattern of the network in a horizontal direction, burrow cross-section circular to elliptical with irregular branching burrow system. Burrow wall with indistinctly lined, burrow diameter is 11 to 13 mm wide and the angle between two branches is ~65°. Burrow fill is similar to the host rock.

Discussion: *T. paradoxica* is characterized by a box work network with varying size and geometry (Knaust, 2017). *T. paradoxica* are formed in firmground substrate or semi-consolidated substrate (Bromley, 1975; Myrow, 1995). *T. paradoxica* are produced by crustaceans (mainly shrimps) and indicate combined suspension-feeding and deposit-feeding behaviour (Knaust, 2017). *Thalassinoides* mainly occur in shallow- marine environments (Frey *et al*., 1984; Uchman, 1995).

Boring structures

Ichnogenus Teredolites Leymerie, 1842

Teredolites calvatus Leymerie, 1842
(Pl. III, Fig. 7)

Description: Calvate boring, oriented perpendicular to oblique to the woody substrate. Specimens were preserved essentially as complete relief and semi relief as incomplete to variably preserved clavate tubes. Borings are moderately lined with ferruginous material. In addition, burrow-fill consists of the same. In some samples, burrow lining was calcareous and burrow fill consist of glauconitic material. In some samples, because of the degrading of some woody material, the clavate borings are protruding out. Aperture in cross-section mainly circular to elliptical, a diameter of the neck region ranges from 3 to 5 mm, lining thickness up to 1 mm thick. The base of the boring is smooth with a turbinate shape.

Discussion: Ichnogenus *Teredolites* comprises two species, namely *T. calvatus* and *T. logissimus*. The species differ mainly in (1) the nature of the orientation regarding the grain/substrate, (2) it's width/length ratio. *T. calvatus* are mainly oriented perpendicular or slightly oblique to the substrate, with its width/length ratio less than 5 (Kelley and Bromley, 1984). The borings are considered permanent domicile structures of filter-feeding worms (Savrda and Smith, 1996).

GHUNERI MEMBER ICHNOASSEMBLAGES

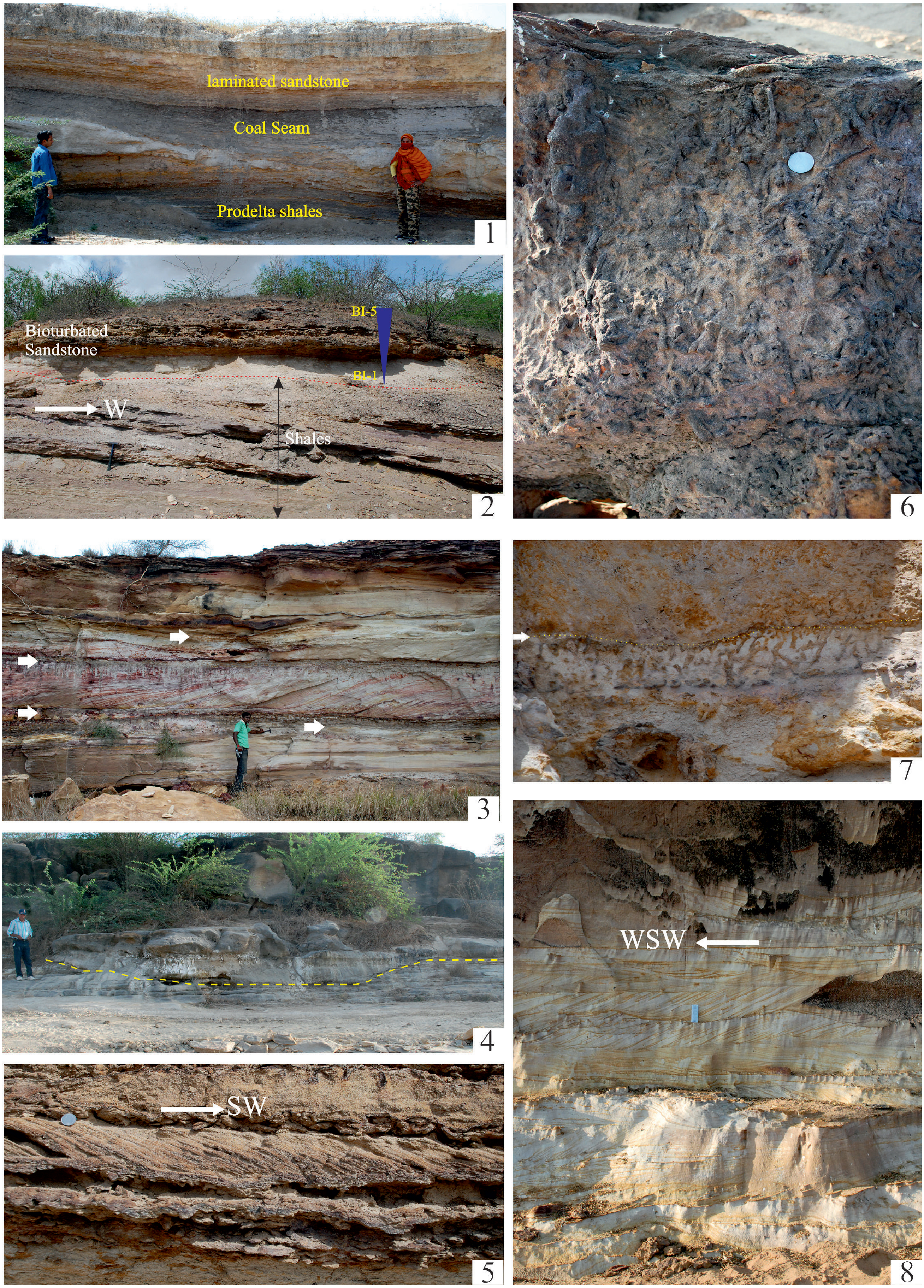
Bioturbated cycles

Ghuneri Member trace fossil data from all the twenty-six sections suggest moderate to a high diversity of recurring trace fossils, with a dominance of vertically dwelling burrows of suspension-feeding trace fossils. The ichnotaxa abundance from different sections is summarized in Table-2. The compiled data clearly indicates that the ichnogenera diversity from the highly bioturbated sandstones varies across the basin. Although the degree of bioturbation remains the same, the ichnogeneric diversity clearly varies. In the proximal part (east) of the basin, the diversity is low, and its maximum diversity is documented in the distal part (west) of the basin. The Ghuneri trace fossil content and suggested that the shallow tier is dominated by deposit-feeding traces, while the middle tier is most diverse with mixed opportunistic and climax communities, while the deep tier is composed of opportunistic suspension-feeding trace fossils. Such tiering results from controlling factors such as (a) timing, extend and availability of colonization window, (b) substrate conditions, and (c) intra-specific competition (Desai and Chauhan, 2021). The present ichnotaxa data was compared with the fair-weather and storm-weather ichnoassemblage of Desai and Chauhan (2021). Additionally, based on the ichnofabric analysis, they have identified six taphonomic pathways for the genesis of bioturbated units. These are (i) Type-1 Low bioturbated ichnofabric; (ii)Type-2 Ichnofabric of structureless sand; (iii) Type-3 Incomplete bioturbated top ichnofabric; (iv) Type-4 Bioturbated units with *Glossifunguites* ichnofabric; (v) Type-5 Firmground bypass ichnofabric; (vi) Type-6 Amalgamated bioturbated unit with resumed colonization. The bioturbated cycles typically display coarsening-up and upward increase in bioturbation intensity (Fig. 2). An ideal cycle starts with low bioturbated units, suggesting opportunistic organisms could rarely colonize because of the time-bounded availability of colonization window and high energy stress regime.

The thickness of these cycles are asymmetrical and varies across the basin. They are frequently interrupted by (a) *Glossifunguites* ichnofabric surfaces and (b) firmground bypass surfaces. The presence of such surfaces indicates a paucity of sedimentation followed by substrate change (Pemberton and Frey, 1985).

Table 2: Trace fossils diversity in each section of the Ghuneri Mamber (Bhuj Formation) (VR- Very rare <3, R- Rare 3-5, C-Common 5-10, A- Abundant >10).

Sec. no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Proximal Part							Central Part												Distal Part						
Section, Trace fossils	**Jawahar Nagar**	**Nadappa (road side)**	**nadappa 5 km (Before)**	**Godpar**	**Hill Garden**	**Kodki**	**Khari Gorge**	**Leva Patel Hospital (opposite)**	**Nagor**	**Naraypar**	**Pur**	**Reha**	**Ring road**	**Tapkeshwari**	**Gangaji mandir**	**Mathal**	**Moray camp**	**Rampar Vekra**	**Ugedi**	**Yaksh**	**Mata no Madh**	**Siyot**	**Atada**	**Katesar near.**	**Umarsar**	**Ghuneri TS**
Arenicolites	**R**	-	-	-	**C**	-	**VR**	**R**	**A**	-	**C**	**C**	**C**	**C**	**C**	-	**A**	**C**	-	-	-	-	**C**	-	**A**	**C**
Balanoglossites	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**A**
Bergaueria	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**R**
Chondrites	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**C**	-	**R**
Conichnus	-		-	-	-	-	-	-	-	-	**VR**	-	-	-	-	-	-	-	-	-	**A**	-	-	**C**	-	**C**
Diplocraterion	-	**C**	-	**A**	**A**	-	**A**	-	-	-	**A**	**A**	-	**A**	**A**	-	-	**VR**	-	-	-	**A**	**C**	-	**A**	**A**
Gyrollithes	-	-	-	-	**C**	-	-	-	**C**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**VR**
Gyrochorte	**A**	-	**C**	**C**	-	**A**	-	-	-	-	-	**A**	-	-	-	**A**	-	-	**A**	-	-	-	**VR**	-	**R**	**C**
Lockeia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**C**	-	**VR**
Maiakarichnus	-	-	-	-	-	-	-	-	-	-	**VR**	-	-	-	-	-	-	-	-		-	-	-	-	-	**VR**
Monocraterion	-	-	-	-	-	**C**	-	-	-	-	-	-	-	-	-	-	-	-	-	**C**	-	-	-	-	-	**VR**
Ophiomorpha	**R**	-	-	**C**	-	-	-	-	-	-	**C**	**C**	-	**R**	**R**	**A**	-	-	-	-	-	-	-	**A**	-	**C**
Palaeophycus	**C**	-	-	**C**	**C**	-	-	-	-	**VR**	**C**	**C**	**A**	**C**	-	**A**	-	**A**	**A**	**R**	-	-	**VR**	**A**	-	**A**
Planolites	**R**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**C**	**R**
Psilonichnus	**C**	**A**	-	**A**	-	-	-	**A**	**A**	**C**	**R**	**C**	**A**	**C**	**C**	-	-	**A**	**C**	-	-		**A**	**C**	**C**	**A**
Polykladichnus	-	-	-	-	-	-	**A**	**C**	**A**	**A**	**C**	**C**	-	**C**	-	-	**A**	**C**	-	-	-	-	**A**	-	**C**	**A**
Rhizocorallium	**VR**	-	**A**	-	-	-	-	-	-	-	**A**	-	-	**R**	**C**	-	**C**	-	-	-	-	-	**C**	-	**A**	**A**
Rossellia	-	-	-	-	-	-	-	-	**C**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**A**	-	**C**
Schaubcylindrichnus	-	-	**A**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**VR**
Skolithos	**C**	**A**	**R**	**A**	**A**	-	**R**	**C**	-	**C**	**C**	**C**	**A**	**C**	**C**	-	-	**A**	**C**	**C**	-	**A**	**C**	**C**	**C**	**C**
Taenidium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**A**	-	-	-	-	-	-	**A**	-	**R**
Teichichnus	-	-	-	**VR**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**R**	**A**	**R**
Teredolites	-	-	-	-	-	**VR**	-	-	**VR**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**VR**
Thalassinoides	**C**	**A**	-	-	**R**	-	-	-	-	-	-	**A**	-	-	-	-	-	**R**	**R**	-		-	**A**	**C**	**A**	**A**


laminated sandstone
Coal Seam
Prodelta shales
1
Bioturbated Sandstone
BI-5
BI-1
W
Shales
2
3
4
SW
5
6
7
WSW
8

Sector-wise trace fossil distribution

In proximal basins, the deltaic sediments significantly reduce the infaunal diversity; data from three sections suggest opportunistic suspension feeders dominated (Table-1, 2). The sedimentological data from these proximal sections suggested coarsening up-cycle of shales-siltstones grading up into medium-coarse grained sandstones. The sandstones indicated high bioturbation intensity (density) with limited infaunal diversity. This includes *Diplocraterion, Gyrochorte, Paleophycus, Psilonichnus, Rhizocorallium, Skolithos* and *Thalassinoides* as dominant ichnotaxa (abundant and common). The shallow tiers consisted of *Gyrochorte,* while *Paleophycus*, *Rhizocorallium*, occupied middle tiers; the shallow -middle-tier trace fossils assemblages agrees with fair-weather conditions. Deep tier ichnotaxa consist of *Diplocraterion, Psilonichnus, Skolithos,* and *Thalassinoides* and are related to storm-weather conditions.

Outcrops of the central basin showed maximum improved diversity. In total, eleven sections were studied (Table 1). The central basin sections showed the dominance of sands comprising massive thick sands topped by bioturbation. These sections also contained several channel structures (Fig. 3d) cutting thin to moderate bedded siltstone and fine-grained sandstones. The asymmetrical cycles in this sector display multiple levels of *Glossifunguites* ichnofacies surfaces (GIFS) (e.g. Nagor, Ring road and Tapkeshwari sections). Trace fossil data indicate *Arenicolites, Diplocraterion, Gyrolithes, Gyrochorte, Ophiomorpha, Paleophycus, Polykladichnus, Psilonichnus, Rhizocorallium, Skolithos, Taenidium* and *Thalassinoides* as common and abundant. *Gyrochorte* occupies the shallow tier while middle tiers are colonized by *Paleophycus, Polykladichnus, Rhizocorallium, Taenidium;* both tiers belong to fair-weather ichnoassemblages. In storm-weather ichnoassemblages, middle to deep tier traces (*Arenicolites, Diplocraterion, Gyrolithes, Skolithos, Ophiomorpha* and *Thalassinoides*) dominates. Few sections (six sections) towards the central-distal part show a reduction in fair-weather diversity and an abundance of storm-weather ichnoassemblage.

The section towards the distal end of the basins is expanded and shows maximum diversity. These sections have multiple levels of plant beds and organic-rich shales with bioturbated sandstones. One of the sections (Yaksh-Table-2) comprises three levels of *Ptillophyllum* rich beds alternating with highly bioturbated medium-grained sandstones. The shallow tiers (*Gyrochorte, Lockeia* and *Planolites*) are diversified compared with central and proximal sections. The middle tier comprises *Paleophycus*, *Polykladichnus*, *Rhizocorallium*, *Rosselia*, and *Taenidium*, while the *Chondrites* occupy the deep tier. All the tiers belong to fair-weather ichnoassemblages. In storm-weather ichnoassemblage, middle to deep tier traces (*Arenicolites, Diplocraterion, Psilonichnus, Skolithos, Ophiomorpha*, and *Thalassinoides*) along with occasional escape traces of *Conichnus conicus* occurs. Apart from these abundant and common recurring trace fossils, several ichnologically fascinating trace fossils are also recorded, including *Lockeia*, *Maikarichnus*, *Monocraterion* and *Teredolites*. Among these, *Maikarichnus* occurs in the central part of the basin, co-occurring with *Ophiomorpha* and *Diplocraterion*.

DISCUSSION

The ichnology of the deltaic environments helps in delineating and inferring various processes (MacEachern *et al*., 1995). In the case of the three end members in a deltaic environment, fluvial deltas are considered as most stressful, and the resultant ichnology is reflected in its depauperate ichnofacies (Buatois and Mángano, 2011; Tonkin, 2012). During the fluvial discharge in the deltas, the reduction in the salinity affects the epifaunal and infaunal bioturbators causing a serious reduction in diversity and size of the burrows (Pemberton and Whiteman, 1992; MacEachern *et al*., 2005). Additional stress on organisms are imparted by other factors, like the occurrence of hyperpycnal flows, frequency of high energy sedimentation, availability of colonization window, availability of oxygenation (MacEachern *et al*., 2005; Buatois and Mángano, 2011; Tonkin, 2012). In wave-dominated environments, stress is also imparted by the occurrence of storm events and de-colonization because of erosion. However, other stress factors, like salinity fluctuation, are negligible (Buatois and Mangano, 2011).

The Early Cretaceous sediments of the Kachchh Basin are dominantly unfossiliferous sandstone (except occurrence of fossiliferous bands in lower levels) that outcrops extensively in the basin. Recently, the Kachchh Basin has been declared as a petroliferous basin, with Early Cretaceous Bhuj Formation equivalent sediments forming excellent reservoirs (DGH website). Moreover, the present understanding of the depositional environment of the Bhuj Formation is varied and ranges from fluvial-deltaic to shallow marine to estuarine. The Ghuneri Member (Bhuj Formation) is rich in trace fossils yet of unfossiliferous nature (as far as body fossil is concerned). Thus, it becomes an excellent

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Figure 3: Lithological facies variations in the Ghuneri Member across the basin. (a) Alternation of shale-sandstone sandwiching the coal seam in the upper part of the Ghuneri Member exposed at the western flank of Ghuneri Dome. Scale- the height of the man is 173 cm (b) Example of the coarsening upcycle with syn-depositional, westerly dipping of the shales topped by horizontal, highly bioturbated sandstones, location Moray Camp, roadside section. The scale-height of the hammer is 40cm (c) Stacked deltaic lobes of medium to fine-grained sandstones with very thin shales. Sandstones indicates rapid deposition because of bioturbated tops exposed in the southern part of Ghuneri Dome Scale- the height of the man is 173 cm (d) Channel facies consisting of fining up sequences, note the pinching out of the lateral margin outcropping in the central sector. Scale- the height of the man is 167 cm (e) medium-scale cross-stratification in coarse-grained sandstone showing south-westerly paleocurrent direction, exposed in the proximal part of the basin. Scale-coin diameter 2.4 cm (f) Highly bioturbated unit showing overlapping and cross-cutting nature of *Skolithos*, *Arenicolites*. Scale-coin diameter 2.4 cm (g) Close-up of a *Glossifunguites* ichnofacies surface-exposed along the ring road section of Bhuj city. Note the contrasting ichnological nature along with the erosional surface. (h) Large-scale planner and trough cross-stratification showing west-southwest palaeocurrent direction in the medium-grained sandstones exposed in the central section.

case for integrating ichnology and sedimentology aimed at interpreting the depositional environment. Ichnology, a powerful tool, is an excellent aid in delineating complex depositional processes. Integrating ichnology and, sedimentology gives precise information regarding the processes responsible. The approach of the understanding depositional environment of highly bioturbated units dealt with extensive mapping and integrating ichnological data of 24 sections, with comprehending of trace fossils occurrences. Thus, ichnological data from Early Cretaceous, asymmetric bioturbated cycles of Ghuneri Member (Bhuj Formation) helps in understanding its wave-dominated deltaic environment.

Regionally, most prominent trace fossils are dominated by suspension-feeding like *Arenicolites*, *Diplocraterion*, *Psilonichnus*, *Polykladichnus*, and *Skolithos*. The dominance of suspension-feeding trace makers indicates agitated water that helps to keep organic matter in the water column. Additionally, these trace fossils are also in equilibrium with the aggrading substrate like *Diplocraterion, Conichnus,* which are common in most of the outcrop sections of the Ghuneri Member. For example, *Diplocraterion* occurs in a majority of sections. They are late colonizers, colonizing the top of the sandstones (Desai and Chauhan, 2021), while *Conichnus* occurs as equilibrium trace keeping pace with aggrading sediments (Desai and Saklani, 2012). In wave-dominated succession, preservation of such equilibrium surface indicates minor or negligible erosion. In addition, the *Glossifunguites* ichnofacies surfaces are also regionally mappable, which helps in correlating the bioturbated sequences across the basin. For example, the two firmground levels (*Balanoglossites*) at Ghuneri Dome described by Desai and Saklani (2012) are laterally well correlatable from the distal part in the west (type-section, Ghuneri Dome) to the proximal part in the east (Kas Hill). In the studied sections, few trace fossils are worth appraising and include an occurrence of *Chondrites, Lockeia, Maikarichnus, Rosselia, and Teredolites.* In the distal part of the basin, two species of *Chondrites* occur as deep tier opportunistic trace fossils along with middle-tier *Rosselia* and *Lockeia,* a shallow tier trace fossil of fair-weather ichnoassemblage. In contrast, *Maiakarichnus* is a callianassid brood structure (Curran, 1976; Verde and Martinez, 2004). In the Kachchh Basin, this is probably its first record, and it occurs in association with *Ophiomorpha* and *Diplocraterion*. It's occurrence indicates favourable conditions for juvenile callianassid to successfully habitat the substrate. Similarly, *Teredolites* also occurs in few localities, where the xylic substrate is decayed, and only the borings are preserved. The decaying of the xylix substance of wood logs is because the wood logs were preserved in sandstones. In sandstones, because of their porous nature, the organic matter often interacts with oxygen, increasing the rate of decaying and decomposition. Thus, the presence of *Teredolites* trace fossils suggests the possible locking of wood logs in coastal settings. Savrda (1991) suggested that the occurrence of allochthonous woods in the marine shelf environments indicates transgression. However, in the present case, the remains of boring wood logs in the deltaic settings is indicative of marine influence.

The Ghuneri Member ichnological data reveals moderate to high trace fossils diversity with a clear distinction between fair-weather and storm wave ichnoassemblages when compared with the other deltaic deposits (Jhuran Delta) in the same basin. The Ghuneri trace fossils suggest a wave-dominated deltaic environment. The Kimmeridgian-Tithonian Jhuran delta is river-dominated, showing overwhelming evidence of reduced trace fossil diversity because of salinity stress, high rate of sedimentation stress (Desai and Biswas, 2018). In the Jhuran delta, The *Teichichnus*, *Gyrolithes* ichnoassemblages of prodelta environment and *Siphonichnus*, *Gyrolithes* ichnoassemblages in the delta front environment indicate salinity fluctuations. In contrast, there is an absence of salinity stressed ichnoassemblage in the Ghuneri Member, along with highly bioturbated unit (BI-5 to 6) cycle tops. In addition, these asymmetrical bioturbated cycles are interrupted with multiple levels of *Glossifunguites* ichnofacies surfaces (Desai and Saklani, 2012; Desai, 2016; Desai and Chauhan, 2021). This indicates fluctuating energy conditions with normal marine conditions for successful colonization and bioturbation of the sediments. Several factors control fully or partially bioturbated sediments and include colonization window, variations in substrate conditions, along seasonal fluctuations. However, high-energy events like storms will lead to a shorter duration of colonization window, leading to partial bioturbation. Thus, the cyclic bioturbated units of Ghuneri Member offers better insight into bioturbated cycles.

CONCLUSIONS

The Early Cretaceous Ghuneri Member comprises asymmetrical bioturbated cycles deposited in a wave-dominated deltaic environment. Systematic analysis of twenty-six sections across the basin revealed moderate diversity of trace fossils with twenty-eight recurring ichnospecies. Trace fossils are dominated by suspension-feeding trace fossils, like *Arenicolites*, *Diplocraterion*, *Psilonichnus*, *Polykladichnus*, and *Skolithos,* and equilibrium trace fossil *Conichnus*. Regionally, the trace fossil diversity varies across the basin (proximal to distal); maximum diversity is noted in the distal part of the basin. Multiple levels of *Glossifunguites* ichnofacies surfaces are also common and can be regionally correlated. The trace fossils form two distinct fair-weather wave and storm-wave ichnoassemblages formed within a wave-dominated deltaic environment. Thus, asymmetrical cyclic bioturbated units of Ghuneri Member offers better insight into the Ichnology of the Early Cretaceous wave-dominated deltaic environment.

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