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Palaeoecologic significance of the Callovian-Oxfordian trace fossils of Gangeshwar Dome, Southeast of Bhuj, Mainland Kachchh, India

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Key words: trace fossils, Late-Middle Jurassic, ichnocoenose, Gangeshwar Dome, Mainland Kachchh, India.

Abstract. The shallow marine deposits of the Late-Middle Jurassic (Callovian–Oxfordian) Jumara Formation of the Gangeshwar Dome of Mainland Kachchh, India, comprise a succession of ~247 m thick clastic sediments with few non-clastic bands and contain a diverse group of ichnofauna. The succession is subdivided into seven lithofacies, *viz.*, laminated shale-siltstone facies (LSS), sheet sandstone facies (SS), herringbone sandstone facies (HS), bivalve sandstone facies (BS), bioclastic limestone facies (BL), intraformational conglomerate facies (IC) and oolitic limestone facies (OL). The ichnofaunal study shows 29 ichnospecies of 23 ichnogenera including *Arenicolites*, *Bifungites*, *Bolonia*, *Chondrites*, *Didymaulichnus*, *Diplocraterion*, *Gyrochorte*, *Helminthopsis*, *Isopodichnus*, *Laevicyclus*, *Lockeia*, *Monocraterion*, *Taenidium*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Phycodes*, *Protopalaeodictyon*, *Rhizocorallium*, *Skolithos*, *Thalassinoides*, *Tisoa*, and *Zoophycos*. These trace fossils are distributed among nine ichnocoenose, characterized by *Chondrites*, *Diplocraterion*, *Gyrochorte*, *Ophiomorpha*, *Rhizocorallium*, *Skolithos*, *Taenidium*, *Thalassinoides* and *Zoophycos*. Their occurrence in the facies corresponds to their trophic and ethological properties. The colonisation of the opportunistic *Diplocraterion* and the *Skolithos* ichnocoenose shows a high density and marks foreshore/nearshore environmental conditions. The *Gyrochorte*, the *Rhizocorallium*, the *Taenidium* and the *Thalassinoides* ichnocoenose indicate the typically lower energy zone of the shoreface-offshore region. The *Chondrite*s ichnocoenosis indicates fluctuation in bottom water oxygen while the *Zoophycos* ichnocoenosis typically exploited a calm water niche in the offshore region. These ichnocoenose recur throughout the sequence and belong to the *Skolithos* and the *Cruziana* ichnofacies which marked changes in energy gradient, substrate stability, water depth and mode of life of invertebrate organisms. The study of trace fossil assemblages with sediment characteristics gives a detailed and accurate picture of foreshore to offshore palaeoenvironmental conditions.

GEOLOGICAL SETTING AND FACIES CHARACTERISTICS

The Charwar Range is a denudational remnant of half cut uplifted domes and anticlines parallel to the Katrol Hill Fault, Kachchh, western India. The Amundra-Ler Anticline (Biswas, 1980) is one among these uplifted anticlines, where rocks of the Jumara Formation are directly in contact with the Bhuj Formation across the Katrol Hill Fault, about 5 km south of Madhapar village and 8 km southeast of Bhuj. The study area, the Gangeshwar Dome, is a stretched brachyanticline covering small east-west extending anticlines and synclines, and is a part of the Amundra-Ler Anticline. The Gangeshwar Dome is bounded by the Katrol Hill Fault on the north, the Dhosa Oolite limestone bands on the east and south, while the west part is bounded by a northwest-southeast running fault filled with a dolerite dyke and by a northeast-southwest running fault. Here, middle Jhuran rocks are in direct contact with rocks of members I to IV of the Jumara Formation to the west (Fig. 1).

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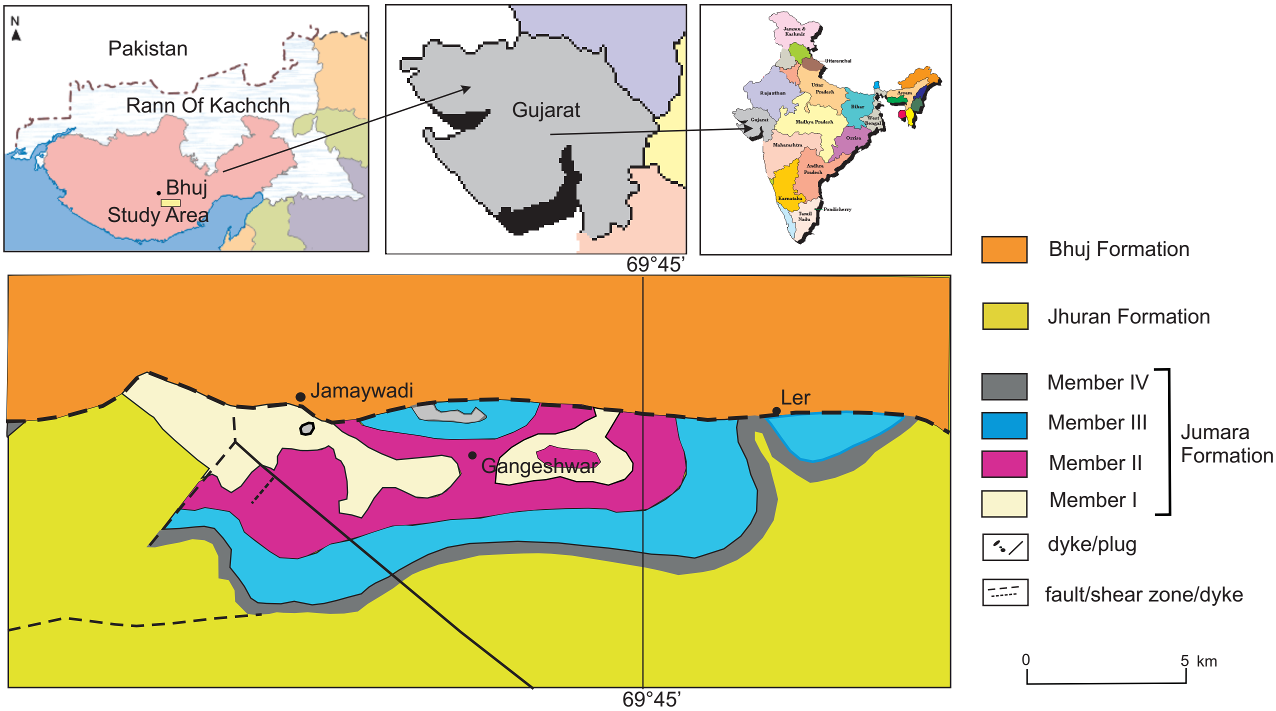

Fig. 1. Location and geological map of the study area

The area comprises fine to medium grained clastic sediments with a few bands of coarse clastic and non-clastic sediments (limestones) of members I, II, III and IV of the Jumara Formation (Biswas, 1977, 1993) of Jurassic age (Callovian to Oxfordian). The present investigation details the trace fossils and lithofacies of the area based on which the palaeoecological significance of the Jumara Formation is interpreted.

The Gangeshwar Dome exposes rocks of the Jumara Formation which is ~247 m thick and which is subdivided into four informal members I to IV (Biswas, 1977, 1993). They mainly consist of alternations of sandstones, shales and limestones. The base (member I) of the Jumara Formation is exposed near Jamaywadi, south of Madhapar village (Fig. 1), while the top is marked by oolitic limestone (member IV), which is unconformably overlain by the rocks of the Jhuran Formation. The age of the Jumara Formation is considered by Spath (1933) and Rajnath (1942) as Callovian and partly Oxfordian, while Pandey and Dave (1993) ascribed it to the Callovian (member I to III) and the Oxfordian (member IV) on the basis of the foraminiferal zonation.

MEMBER I

The member I (136 m thick) is exposed south of Madhapar village in the banks of a stream and comprises mainly siltstone-shale intercalations. In its lower part, it is characterized by a succession of silty-argillaceous sediments with hard calcareous siltstones/fine sandstones at regularly decreasing intervals, which gradually grades upwards into thick sandstone bands with thin shale intercalations. Many of these thick sandstone bands host small channel structures filled with extrabasinal angular to sub-angular gritty quartz grains and reworked angular pebbles. Intraformational limonitic flat pebbles are present at the bottom of some of the siltstone and fine sandstone bands in the lower part. The sandstone beds are characterised by ripplemarks (*e.g.*, symmetrical, interference, microripples), parting lineation and hummocky cross stratification; the shales are silty, micaceous with thin micritic to ferruginous silty lenses and gypsum layers/lenses (Pl. 1:1). Scattered occurrences of bivalves, gastropods, ammonoids and belemnoids are noted throughout the sequence but their abundance increases in the upper thick sandstone unit. The rocks are moderately bioturbated with trace fossils *Thalassinoides*, *Gyrochorte* (Pl. 1: 2), *Rhizocorallium*, *Palaeophycus*, *Zoophycos*, *Chondrites*, *Ophiomorpha*, *Cylindricum*, *Taenidium* (Pl. 1: 3) and *Helminthopsis*. Spath (1924, 1933), Pascoe (1959), Rajnath (1932, 1942), Krishnan (1968) and Biswas (1977) have assigned a Lower to Middle Callovian age to these rocks based on their fossil content. Pandey and Dave (1993) assigned a Callovian age to member I based on the presence of *Tewaria kachchhensis* – a foraminiferal partial range zone.

MEMBER II

The member II is best exposed in the central axial part of the Amundra Ler Anticline around the Gangeshwar Mahadev Temple, south of Bhuj, west of Jogi Timba and SSE of Jamaywadi. This member is ~39.55 m thick and comprises in the lower part massive to horizontally stratified sandstone beds with hard, rounded to subrounded concretions (small 5 cm, to large more than 2 m in diameter). These concretions - mostly rounded, sometimes subrounded - are texturally and lithologically slightly different from the host rock. The upper part of the member contains cross stratified vertically and laterally graded sandstones (Pl. 1:4). The lower part has a uniform grain size but it is also characterised by inverse grading, ripplemarks, parting lineations *etc.*; and also contains fossils of rhynchonellids, terebratulids, bivalves, gastropods (*Turritella*) and plant fossils. The upper cross-stratified sandstones on the other hand display normal graded bedding with ripplemarks (*e.g.*, symmetrical, interference and microripples), parting lineations, planar and trough cross-stratification, festoon bedding, herringbone structure, rivulrites *etc*. This member is poorly bioturbated and contains trace fossils such as *Skolithos*, *Gyrochorte* and *Diplocraterion*.

Pascoe (1959), Krishnan (1968) and Rajnath (1932, 1942) have assigned a Middle Callovian age to the member. Biswas (1977) placed it in the lower part of the *Proteonina difflugiformis* – foraminiferal assemblage zone of the Upper Callovian (after Pandey and Dave, 1993).

MEMBER III

The member III is best exposed in the Gunawari river section near Ler village and attains thickness of about 59.4 m. It is also exposed along the axis of the Amundra Ler Anticline, at the top of Jogi Timba hill and near the Gangeshwar Temple. It mainly comprises in the lower part shales, siltstones, sandstones (Pl. 1:5), conglomerates and fossiliferous, silty-sandy bioclastic limestones along with inverse graded 2.5 m thick siltstone-sandstone intercalations. The bioclastic limestones contain densely packed bivalves, brachiopods, cephalopods, and echinoids as well as abundant shells fragments (Pl. 1:6). The upper part is characterised by rhythmic sequences of thin partings of grey, yellow, red, silty shale-siltstone and gypsum with intraformational conglomerates and mega-rippled fossiliferous gritty limestones. This unit is highly fossiliferous in nature and contains bivalves (*e.g.*, *Astarte* and *Trigonia*), belemnite guards, cephalopods, brachiopods, bryozoans and foraminifers. In places convex up and concave up *Astarte* shells form are encountered. Primary sedimentary structures like ripplemarks (*e.g.*, wave, symmetrical and current), graded bedding, planar- and trough-cross-stratifications and herringbone structures are visible. This unit is highly bioturbated and contains trace fossils such as *Arenicolites*, *Monocraterion*, *Chondrites*, *Diplocraterion*, *Gyrochorte*, *Planolites*, *Rhizocorallium*, *Thalassinoids* and *Skolithos.* Pascoe (1959) assigned an Upper Callovian age to the member based on ammonoids, bivalves and brachiopods fossils and its position under the Dhosa Oolite (member IV). The member represents the Upper Callovian Athleta zone (Spath 1933), and corresponds approximately to the universal transgression phase of Haq *et al.* (1987, 1988).

MEMBER IV

The member IV forms the topmost part of the Jumara Formation. The base of the member is defined by its red/brown colour, ferruginous nature, silt to sand size quartz grains, limonite to marl pebbles, and the presence of fossils - bioclasts and gypsum. It is followed by 12 to 26 m thick, grey, silty shale with thin ferruginous silty layers and 5 mm thick gypsum layered separate crystals at intervals of 20 to 200 cm. Silty ferruginous layers show lenses of ripple lamination to flaser bedding and contain belemnoids, terebratulids and bivalves. The grey silty shale is overlain by 3.5 to 9 m of mixed siliciclastic-carbonate sediments which characteristically consist of oolite. Three prominent beds of sandy oolitic limestones are noticed alternating with silty shales; the lower two beds are brownish and the upper greenish. These are popularly known as the Dhosa Oolites, one of the distinctive marker horizons of the top part of the Mesozoic sequence of mainland Kachchh. The thickness of individual oolitic limestone beds varies from 10 to 50 cm (Pl. 1:7). They also contain abundant bivalves, brachiopods, bryozoans and foraminifers with ferruginous vertebrate bones and wood fossils. The topmost part of the member consists of a 30 cm thick bioclastic intraformational conglomerate with a ferruginous mud drape crust on the top (Pl. 1:8). It contains reworked rounded to elongated pebbles of oolitic limestone with abundant shells of bivalves, brachiopods, belemnites and foraminifers. Some boulders contain ammonoid / echinoderm fossils at their core (Pl. 1:8). The oolitic limestone is bioturbated and contains ichnogenera including *Thalassinoides*, *Planolites*, *Zoophycos*, *Chondrites* and *Arenicolites*. The member is considered to be Oxfordian age by Spath (1933), Rajnath (1932, 1942), Pascoe (1959) and Krishnan (1968) based on biostratigraphic correlation. Fürsich *et al.* (1992) suggest a Middle Oxfordian age of the sediments based on the presence *Perisphinctes orientalis*, indicating the Antecedens Zone. These beds are overlain by sediments of Lower Kimmeridgian age at Ler.

According to Miall (1985), descriptive facies include certain observable attributes of sedimentary rock bodies, which can be interpreted in terms of depositional processes. Each lithofacies represents an individual depositional event, which is characteristic of a particular depositional environment. These are commonly cyclic and form the basis for defining sedimentation models (Miall, 1985).

In the present study an individual lithofacies is considered to be a rock unit defined on the basis of its observable rock types, geometry, biota and sedimentary (physical and biological) structures. In order to gain detailed facies information, stratigraphic sections were measured at different localities. The Mesozoic (the Jumara) sequence in the study area consists of seven principal lithofacies based on occurrence, geometry and stratigraphic position, distinctive lithological features, including composition, grain size, bedding characteristics, lateral and vertical continuity, physical and biogenic sedimentary structures and on the pattern of the vertical sequence. Representative lithofacies are summarised in Table 1 with extended information.

ICHNOFOSSILS

In the present study, ichnogenera and ichnospecies are named according to I.C.Z.N. rules using the binomial system of nomenclature. These are further classified according to the scheme of Książkiewicz (1977), modified by Uchman

Table 1

Summary of lithofacies of the study area

Lithofacies and member	Description	Associated trace fossils	Palaeo-environments
Lithofacies 1: laminated shale siltstone (Plate 1.1) Member I, III and IV.	Thinly laminated shales with thin siltstone bands contains linguoid-, or current-, or symmetrical straight crested-, or interference-, or oscillatory influence ripple marks and/or parting lineations, high density of bioturbation	*Arenicolites*, *Chondrites*, *Calycraterion*, *Cylindrichnus*, *Diplocraterion*, *Lockeia*, *Gyrochorte*, *Helminthopsis*, *Cruziana*, *Ophiomorpha*, *Palaeophycus*, *Phycodes*, *Treptichnus*, *Planolites*, *Rhizocorallium*, *Thalassinoides* and *Tisoa*	Wave and storm influenced upper shoreface to offshore and protected zone
Lithofacies 2: sheet sandstone (Plate 1.5) Member I, II and III.	Gradational contact with LSS, fine to medium grained sandstones; normal graded to inverse graded or massive and also contains symmetrical oscillatory and interference ripples, flaser or lensoid bedding, hummocky cross stratification etc. and high degree of bioturbation	*Thalassinoides*, *Chondrites*, *Planolites*, *Palaeophycus*, *Gyrochorte*, *Skolithos and Ophiomorpha*, *Diplocraterion*, *Cruziana*	Tide dominated shoreface; bars and barriers
Lithofacies 3: herringbone sandstone (Plate 1.4) Member II	Submature to mature fine to medium grained sandstone contain planar- and trough- cross stratification, climbing ripple cross stratification, flaser bedding, festoon bedding, hummocky cross stratification and herringbone structure; unfossiliferous, only upper part is bioturbated	*Skolithos*, *Diplocraterion and Monocraterion*	Current and wave dominated shoreface under meso-, macro-tidal range
Lithofacies 4: bivalve sandstone Member I and III	The characteristics of the facies are (1) sharp (scoured) based sandstone with imbricate intra-, and extra-basinal grains and clasts; (2) bimodal cross stratified nature; (3) symmetrical mega ripples on top; (4) local poor gradation; (5) much lateral extent (except in Member I); (6) mainly concave upward bioclasts (bivalves) with several convex up bioclasts. Low bioturbation	*Skolithos* and *Thalassinoides*	Wave and tide influenced shoreface
Lithofacies 5: bioclastic limestone (Plate 1.6) Member III	Bioclasts of of bivalves, brachiopods, cephalopods, echinoids, foraminifers, gasteropods, bryozoans etc. Top and bottom shows wave ripples. No bioturbation	–	Wave influenced shoreface
Lithofacies 6: intraformational conglomerate (Plate 1.8) Member I, III & IV	Matrix supported consists of rounded/ elongated and flat pebbles, occasional reworked fragmented *Thalassinoides* burrow. No bioturbation	–	Storm influenced shoreface
Lithofacies 7: oolitic limestone (Plate 1.7) Member IV	Oolitic bioclastic calcareous sandstone siltstone to oolitic micritic or sparitic limestone, moderately to highly bioturbated in upper part	*Arenicolites carbonarius*, *Chondrites isp.*, *Palaeophycus sulcatus*, *Planolites annularis*, *Rhizocorallium irregulare*, *Zoophycos brianteus*	Tide, wave and storm influenced transition zone between shoreface offshore.

(1995) in combination with other classification schemes (Seilacher 1953; Chamberlain 1971, 1977). Altogether 29 ichnospecies assigned to 23 ichnogenera were identified and their stratigraphic and lithofacies occurrence and assemblages are represented in tabular form (Tab. 1, 2).

PALAEOICHNOCOENOSES

The term 'ichnocoenosis' is understood as an equivalent of 'palaeobiocoenosis' or 'life assemblage' (Bromley, 1996). It is an objective term and can be related to the use of suite and assemblage. Various authors have adopted the "community" approach (*e.g.*, Bromley, Asgaard, 1979), or even a "simultaneous community" approach (Ekdale *et al.*, 1984; Ekdale, 1985) and "single depositional setting" approach to the definition (Frey, Pemberton, 1985; Pickerill, 1992), although Pickerill (1992) noted that a community can never be conclusively demonstrated in the fossil record. Moreover, Vossler and Pemberton (1988b) also state that one needs to consider innate dynamic controlling factors such as substrate consistency, hydraulic energy, rate of deposition, turbidity, oxygen and salinity levels, toxic substances, quality and quantity of available food, and the ecologic and ichnologic prowess of the trace makers themselves.

The Mesozoic sequence of the Gangeshwar dome contains a rich and varied trace fossil fauna that demonstrate a wide range of animal behaviours. The maximum development of trace fossils are found in rhythmic or alternating sequences of shale, siltstone and sandstone. Differences in trace fossil assemblages among the various lithofacies can also be attributed to the preservational factors that are related to the parameters (*e.g.*, grain size) of the original sediments. Naming the individual ichnocoenosis is necessary for their identification as recurring entities and the simplest method is to name after the dominant ichnogenus. The present group of trace fossils occurring together constitutes nine ichnocoenose. The ichnocoenose and their associated trace fossils as depicted in different members are provided in the Table 3.

CHONDRITES ICHNOCOENOSIS

This ichnocoenosis is characterised by *Chondrites* (Pl. 2:1) along with the frequent occurrence of *Planolites* and the infrequent occurrence of *Zoophycos*. The ichnocoenosis has been observed in member III (SS, LSS and in exhumed pebbles of IC facies) and member IV (OL facies). According to Seilacher (1990) and Fu (1991), the tracemaker of *Chondrites* may be able to live in the aerobic/anoxic interface as a chemosymbiotic organism that pumps methane and hydrogen sulphide from the sediments. The monospecific *Chondrites* assemblage suggests poorly oxygenated bottom waters (*e.g*., Fu, 1991; Bromley, 1996). One of the main environmental controls of this ichnoassemblage is lowered oxygen levels associated with abundant organic material in quiet-water settings (Frey, Seilacher, 1980). The occurrence of *Chondrites* in OL facies indicates very low oxygen levels in the interstitial waters within the sediment at the site and time of burrow emplacement (Bromley, Ekdale, 1984). Thus, oxygen deficient conditions influence the distribution of *Chondrites*, which normally occurs alone and in association with unbioturbated sediments, commonly laminated dark sediments. *Chondrites* trace makers were characterized by a tolerance of a lower oxygen level - lower than producers of other ichnogenera. Its occurrence is related to chemically reducing conditions deep within the sediment and is only indirectly dependent on sea floor conditions. According to Frey *et al.* (1990), the ichnocoenosis develops in circatidal to bathyal conditions or protected intracoastal to epeiric sites with poor water circulation. It typically occurs in mud or muddy sands rich in organic matter and somewhat deficient in oxygen. Ekdale (1985) considered *Chondrites* as an opportunist, where its strategy reveals opportunism in severely oxygen depleted environments, in which it may occur alone (Bromley, Ekdale, 1984; Vossler, Pemberton, 1988b). The presence of *Chondrites* and the low ichnodiversity reveals poorly oxygenated bottom waters (Encinas *et al.*, 2008).

DIPLOCRATERION ICHNOCOENOSIS

The characteristic members of this ichnocoenosis are *Diplocraterion parallelum* (Pl. 2:2) and *Diplocraterion* isp., which occur in members I, II and III with low density eponymous forms. The *Diplocraterion* ichnocoenosis constitutes an assemblage of different types of dwelling tubes of suspension feeding organisms, which inhabited different types of substrate. It is associated with *Laevicyclus* (Pl. 2: 3), *Bifungites* (Pl. 2: 4), *Ophiomorpha*, *Planolites*, *Palaeophycus*, *Lockeia* (Pl. 3: 7) and *Tisoa* of SS facies (member I); *Skolithos* and *Monocraterion* of SS and HS facies (member II) and *Skolithos*, *Ophiomorpha*, *Tisoa* and *Planolites* of LSS facies (member III).

Diplocraterion is classified as a domichnial permanent dwelling structure (Bromley, 1996) produced by suspension feeders or benthic predators (Fürsich, 1975). It is also known as an "equilibrium structure" (*e.g.*, D'Alessandro, Bromley, 1986; Bromley, 1996) responding to sedimentation and erosion (yoyo-like behaviour by Goldring, 1964). The *Diplocraterion* ichnocoenosis can be interpreted as a relatively high energy environment, with moderate to insufficient sedi-

Table 2

Trace fossils are tabulated based on morphologic features and considering their behaviour, preservation, mode of life, producer and association; and also marked are their stratigraphic position and occurrences (lithofacies)

Ichnospecies	Ethology	Stratinomic	Feeding Behaviour	Possible producer	Occurrence	Associations
Simple structures – vertical form						
Laevicyclus isp.	Domichnia	Endogenic; full relief	Suspension and deposit feeder	Annelids (*Scolecopis*)/ ephemerid	LSS and SS in Member I	*Cruziana*, *Planolites*, *Bifungites*, *Helminthopsis*
Lockeia amygdaloides	Cubichnia	Epirelief	Suspension and deposit feeder	Bivalve	LSS and SS in Member I	*Gyrochorte*, *Cochlichnus*, *Planolites*
Skolithos linearis	Domichnia	Endogenic; full relief	Suspension feeder	Polychaetes, annelids or phoronids	SS in Member II and III	*Arenicolites*, *Diplocraterion*, *Monocraterion*
Skolithos isp.	Domichnia	Endogenic; full relief	Suspension feeder	Polychaetes, annelids or Phoronids	SS of Member II	*Arenicolites*, *Monocraterion*
Simple structures – plug shape form						
Monocraterion tentaculatum	Domichnia	Endogenic; full relief	Suspension feeder	“Worm”	SS in Member II & LSS and SS in Member III	*Skolithos*, *Arenicolites*, *Ophiomorpha*, *Cylindrichnus*
Simple structures – U-shaped form						
Arenicolites carbonarius	Domichnia	Endogenic; full relief	Suspension-feeder	Polychaetes	OL in Member IV; SS in Member II	*Chondrites*, *Zoophycos*, *Diplocraterion*, *Monocraterion*, *Skolithos*
Tisoa siphonalis	Domichnia	Endogenic; full relief	Suspension-feeder	Polychaete	LSS of Member I and III	*Arenicolites*, *Rhizocorallium*, *Planolites*, *Thalassinoides*, *Ophiomorpha*
Simple structures – horizontal form						
Palaeophycus sulcatus	Domichnia/? Fodinichnia	Intergenic, hypo-, epi-relief	Deposit-, suspension-feeder, predator	Polychaete	LSS in Member I, III and IV	*Planolites*, *Ophiomorpha*, *Thalassinoides*, *Gyrochorte*
Planolites annularis	Fodinichnia /Pascichnia	Intergenic, hypo-, epi-relief	Deposit-feeder	Various vermiform animals	LSS and SS in Member I and III and OL in Member IV	*Phycodes*, *Gyrochorte*, *Thalassinoides*
Branched structure – dichotomously branched form						
Chondrites isp.	Fodinichnia	Endogenic, full relief	Deposit-feeder	Sipunculids, polychaete	SS in Member III; OL in Member IV	*Zoophycos*
Branched structure – Y and T-shaped form						
Ophiomorpha nodosa	Domichnia/ Fodinichnia	Endogenic, full relief	Deposit-, suspension-feeder, scavenger, predator	Crustacean-shrimp	LSS and SS of Member I and III.	
Protopaleodictyon incompositum	Pascichnia	Endogenic, hypo relief	Agrichnia, deposit feeder	Annelids, polychaete	SS of Member I	*Palaeophycus*, *Gyrochorte*, *Rhizocorallium*
Thalassinoides paradoxicus	Domichnia/ fodinichnia	Endogenic, full relief	Deposit-, suspension-feeder, scavenger, predator	Crustacean	LSS in Member I and III and SS of Member II	*Thalassinoides* isp., *Planolites*, *Palaeophycus*, *Bifungites*, *Ophiomorpha*
Thalassinoides isp.	Domichnia/ fodinichnia	Endogenic, full relief	Deposit-, suspension-feeder, scavenger, predator	Crustacean	LSS in Member I	*Thalassinoides paradoxicus*, *Planolites*, *Palaeophycus*, *Bifungites*, *Ophiomorpha*

Table 2 cont.

Ichnospecies	Ethology	Stratinomic	Feeding Behaviour	Possible producer	Occurrence	Associations
Branched structure – bundled form						
Phycodes palmatum	Fodinichnia	Intergenic, hyporelief	Deposit-feeder	Annelids	LSS and SS in Member I	*Planolites*, *Palaeophycus*, *Gyrochorte*
Phycodes circinnatum	Fodinichnia	Intergenic, hyporelief	Deposit-feeder	Annelids	LSS of Member I	*Planolites*, *Palaeophycus*, *Helminthopsis*
Phycodes isp.	Fodinichnia	Intergenic, hyporelief	Deposit-feeder	Annelids	LSS in Member I	*Bifungites*, *Gyrochorte*, *Laevicyclus*, *Planolites*, *Palaeophycus*
Treptichnus pedum	Fodinichnia	Intergenic, hyporelief	Deposit-feeder	Vermiform animals, Annelids	LSS of Member I	*Planolites*, *Palaeophycus*, *Phycodes* isp., *Helminthopsis*
Meniscate structures						
Bolonia lata	Pascichnia/ repichnia	Epi-, endo-, inter-genic; epi-, hypo-relief	?Detritus feeder, scavenger	Polychaete, gastropods?	SS in Member I and III	*Palaeophycus*, *Cruziana*, *Taenidium*, *Ophiomorpha*
Taenidium isp.	Pascichnia	Inter-, endo-genic; epi-, hypo-relief	Deposit-feeder	Annelid worm	LSS and SS of Member I	*Ophiomorpha*, *Bolonia*, *Palaeophycus*, *Planolites*
Winding and meandering structures – winding structures						
Helminthopsis hieroglyphica	Pascichnia	Intergenic; epi-, hypo-relief		Annelids, polychaete	LSS and SS in Member I	*Bifungites*, *Planolites*, *Phycodes*, *Laevicyclus*, *Diplocraterion*
Winding and meandering structures – plaited structures						
Didymaulichnus lyelli	Repichnia	Intergenic; hypo-relief		Gastropod	LSS in Member I	*Gyrochorte*, *Planolites*, *Cruziana*
Gyrochorte comosa	Pascichnia/ repichnia	Positive-, negative-epirelief	deposit-feeder, scavenger, carnivore	Arthropods	LSS and SS in Member I, II and III	*Didymaulichnus*, *Circulichnus*, *Rhizocorallium*, *Thalassinoides*
Cruziana problematica	Repichnia	Intergenic; hypo-relief		Arthropod	LSS in Member I; SS in Member II.	*Didymaulichnus*, *Gyrochorte*, *Palaeophycus*
Spreiten structures – U-shaped forms						
Diplocraterion parallelum	Domichnia	Endogenic, full relief	Suspension-feeder	Annelids, crustacean	SS of Member I, II and III	*Arenicolites*, *Cylindrichnus*, *Monocraterion*, *Skolithos*, *Planolites*, *Palaeophycus*
Rhizocorallium jenense	Domichnia/ fodinichnia	Endogenic, full relief	Deposit-, suspension-feeder	?possible crustacean, polychaete	SS and LSS in Member I and III	*Palaeophycus*, *Planolites*, *Phycodes*, *Ophiomorpha*, *Skolithos*, *Thalassinoides*, *Gyrochorte*
Rhizocorallium irregulare	Fodinichnia	Endogenic, full relief	Deposit-feeder	?possible crustacean, polychaete	LSS and SS in Member I, III and IV	*Palaeophycus*, *Planolites*, *Skolithos*, *Thalassinoides*
Zoophycos brianteus	Fodinichnia / pascichnia	Endogenic, full relief	Deposit-feeder	Polychaetes, arthropods, hemichordates	OL of the Member IV	*Chondrites*, *Arenicolites*
Dumbbell-shaped structure						
Bifungites isp.	Fodinichnia	Epigenic; epi-relief	Deposit-feeder	"Worm"	LSS and SS Member I	*Planolites*, *Laevicyclus*, *Helminthopsis*

Table 3

Stratigraphic distributions of ichnocoenose, and their occurrence in the facies, associated trace fossils and probable palaeoecological interpretation

Ichnocoenoses	Member and facies	Trace fossils	Palaeoecology
Chondrites ichnocoenosis	Member III, IV; LSS, SS, OL, IC	*Chondrites*, *Planolites*, *Zoophycos*	Calm water, fine grained sediment, deposit feeding organism, oxygen deficient condition produce within the sediments
Diplocraterion ichnocoenosis	Member I, II, III; SS, HS, BS	*Diplocraterion*, *Laevicyclus*, *Bifungites*, *Ophiomorpha*, *Planolites*, *Palaeophycus*, *Tisoa*, *Skolithos*, *Monocraterion*	High energy, shifting substrate, suspension feeding organism, produce at sediment water interface
Gyrochorte ichnocoenosis	Member I, III; LSS, SS	*Gyrochorte*, *Didymaulichnus*, *Cruziana*, *Bolonia*, *Planolites*	Low energy, nil to negligible sedimentation-omission surface, crawling activity, produce at sediment-water interface as post-depositional ichnocoenosis
Ophiomorpha ichnocoenosis	Member I, III; LSS, SS, BS	*Ophiomorpha* (monodominant, inclined to horizontal)	Moderate to relatively low energy conditions, unstable sandy substrates, moderate to high sediment influx, low rate of reworking, dwelling structure produced by suspension feeding organism at or near water sediment interface
Rhizocorallium ichnocoenosis	Member I, III, IV; LSS, SS	*Rhizocorallium*, *Laevicyclus*, *Palaeophycus*, *Phycodes*, *Planolites*, *Ophiomorpha*, *Chondrites*	Low energy less protected lower foreshore - shoreface areas, fine to medium grained sediments, very low rate of deposition, activity of shallow, burrowing deposit feeders
Skolithos ichnocoenosis	Member II, III; LSS, HS	*Arenicolites*, *Diplocraterion*, *Monocraterion*, *Ophiomorpha*, *Tisoa*, *Palaeophycus*, *Planolites*	High energy, shifting substrate, suspension feeding organism, produce at sediment water interface, abrupt erosion and deposition
Taenidium ichnocoenosis	Member I; SS	*Taenidium*, *Planolites*, *Helminthopsis*, *Protopalaeodictyon*, *Bolonia*	Calm and oxygenated water, stable and slowly accreting substrates, vagile deposit feeder organism, produce within the sediment, climax trace fossils under equilibrium environments
Thalassinoides ichnocoenosis	Member I, II, III; LSS, BS, IC	*Thalassinoides*, *Phycodes*, *Rhizocorallium*, *Ophiomorpha*, *Planolites*	Extremely quiet water conditions, little reworking, lowest energy level, less abrupt shifting of sediments and change in temperature and salinity, semivagile and vagile, middle level deposit feeder structures, oxygenated situations, intermediate to equilibrium or climax trace fossils
Zoophycos ichnocoenosis	Member IV; OL	*Zoophycos*, *Chondrites*	Opportunistic in low resource oxygen depleted conditions; once in a life time structure; the epitome of slow, stable and specialized reworking of sediment for food lacks characteristics of an opportunist form; non-vagile, deepest tier structures

mentation of fine grained particles to support deposit feeders. Physical reworking is frequent, as indicated by the presence of tapering against erosional surfaces in numerous horizons of SS facies of member II. It is probable that the long tubes could have served as a protective shelter against unstable conditions on the sea floor depicting agitating water conditions. The low ichno-diversity and low density of the ichnocoenosis suggest the scarce presence of opportunistic ichnotaxa. Sedimentological data (sedimentary structures, erosional and reactivation surfaces, in the members) indicate that the burrows were produced over a short period of time in a depositional environment inhospitable to most life forms due to uneven sedimentation rates and newly deposited substrate. In sequence stratigraphy, assemblages of trace fossils (*Diplocraterion*, *Arenicolites*, *Skolithos*) often indicate transgressive and regressive surfaces (Dam, 1990; Olóriz, Rodríguez-Tovar, 2000). Eustatic changes of sea level and tidal activity, shallow water environment conditions, and loose-ground to firm-ground substrates are characteristic environmental conditions for producers of *Diplocraterion* and other similar U-shaped and vertical trace fossils (Šimo, Olšavský, 2007). *Diplocraterion* ichnofabrics are typical of intertidal shallow water environments (Fürsich, 1974b). The studied trace fossils should be attributed to opportunistic trophic generalists (Vossler, Pemberton, 1988a).

Considering the above facts, it is postulated that the depositional environments varied from lower foreshore to upper shoreface and tidal flats with moderate to relatively high energy conditions. Such conditions are normally formed in slightly muddy to clean well-sorted, shifting sediment subjected to abrupt erosion or deposition. Episodic erosion and deposition could have resulted in producing protrusive and retrusive spreiten structures respectively (Fürsich, 1974b; Bromley, Hanken, 1991).

GYROCHORTE ICHNOCOENOSIS

The ichnocoenosis is characterised by dominance of the ichnospecies *Gyrochorte comosa* (Pl. 2:5) in association with other larger crawling and feeding trails and it occurs in Jurassic shelf siliciclastics (Weiss, 1940; Schlirf, 2000; Uchman, Tchoumatchenco, 2003). It is observed in LSS and SS facies of member I associated with *Didymaulichnus*, *Isopodichnus*, *Bolonia*, *Planolites*; SS facies of member II associated with *Gyrochorte*, *Isopodichnus* and bilobe trails and, BS and LSS facies of member III associated with *Bolonia* and *Planolites*. The ichnocoenosis generally shows a high degree of bioturbation indicating relatively slow sedimentation and little physical reworking. The small-scale ripple laminated sandstones with the *Gyrochorte* assemblage very often found in the Jamaywadi stream sections indicate small scale sediment transport, but not necessarily an increase of sediment influx.

It is regarded as the trace of a polychaete-like worm (Heinberg, 1973) or aplacophoran mollusc (Heinberg, Birkelund, 1984), but Schlirf (2000) criticised this view and regarded it as the feeding trace of an arthropod. According to Gibert and Benner (2002), the *Gyrochorte* trace-maker must have been a worm shape animal with bilateral symmetry and bearing some sort of organs along the body that enable it to manipulate and move the sediment. An annelid is a good candidate supported by many authors (Weiss, 1941; Heinberg, 1973; Karaszewski, 1973), as most other worms lack any external anatomical elements that could be used to move grains around their bodies. The vermiform morphology of the burrower is also supported by Stanley and Pickerill (1998). The *Gyrochorte* ichnocoenosis represents a feeding and locomotion trace which is similar to amphipod trails. The very good preservation of crawling trails mostly in the form of epirelief and intrastratal suggest low energy conditions, with low to negligible rate of sedimentation at the time of comission and early diagenesis or hardening. The ichnocoenosis occurs in shelf sequences, commonly lower foreshore to transitional substrates, below daily wave base but not below storm wave base, to somewhat quieter conditions offshore. From a taphonomic point of view, this situation profoundly increases the preservational potential of the ichnocoenose. It normally occurs in well-sorted silts and sands and in interbedded muddy and clean sands, and is moderately to intensely bioturbated, and depicts negligible sedimentation. Howard and Reineck (1981) have commonly observed storm deposition in which this assemblage is found, producing repeated laminated to scrambled units, bioturbated at the top.

In Kachchh, the ichnocoenosis occurs in silts and sands and in interbedded muddy and clean sands mostly containing ripplemarks with moderate bioturbation. It occurs in tidal flats to lagoonal, foreshore and shallow shelf deposits, and represents a community of opportunists intermediate in between opportunists and equilibrium trace fossils producing a post-depositional ichnocoenose.

OPHIOMORPHA ICHNOCOENOSIS

The *Ophiomorpha* ichnocoenosis consists of monodominant *Ophiomorpha* (Pl. 3:1) in a particular bed and can be observed in LSS and SS facies (member I) and LSS facies (member III). The density of *Ophiomorpha* is low to moderate in different members and lithofacies, and can be interpreted to indicate conditions of moderate to instantaneously high sediment influx. It is further suggested that a low rate of reworking seems to be a precondition for the construction of structures since the delicate clay-ball lined walls in *Ophiomorpha* are wholly preserved. On the other hand, the regular nature of the tube swellings along certain bedding planes reveals that these were brought by some events affecting all the burrow individuals at the same time. Periodic additions of new layer of sediments causing successive upward extensions of the shafts as suggested by Howard (1971) seem to be a reasonable explanation. It is considered as an ichnocoenosis of unstable sand substrates in hydrodynamically energetic environments which is mainly found in the form of shafts (Bromley, 1990). It is produced in modern environments by callianassid crustaceans such as the recent *Callichirus major* (former *Callianassa major*), which usually produce a system of shafts and galleries in sandy sediments (Frey *et al.*, 1984; Uchman, Gaździcki, 2006). Claw elements of *Callichirus* were found in infillings of *Ophiomorpha* from Eocene erratic blocks of East Antarctica (Schweitzer, Feldmann, 2000). The ethology of this trace fossil is not fully understood: deposit and/or suspension feeding are considered for its tracemakers (Uchman, Gaździcki, 2006). *Diplocraterion*, *Ophiomorpha nodosa* and *Skolithos* are typical members of the *Skolithos* ichnofacies, which typifies foreshore–middle shoreface environments with a sandy substrate (Uchman, Gaździcki, 2006). *Ophiomorpha* is common in marine sandy substrates, and elaborate burrow systems often are prolific in shoreface environments (Frey *et al.*, 1978).

Irregularly inclined to horizontal structures in member I and member III in LSS lithofacies depict moderate to relatively low energy conditions below daily wave base. The *Ophiomorpha* ichnocoenosis in Kachchh thus represents suspension feeders and occurs in well sorted silts to interbedded muddy and clean sands. The presence of *Ophiomorpha* in SS facies in member I indicates moderate to high energy conditions in the shoreface zone where there were abrupt changes in substrate levels.

RHIZOCORALLIUM ICHNOCOENOSIS

The ichnocoenosis constitutes primarily of *Rhizocorallium jenense*, *Rhizocorallium irregulare* and *Rhizocorallium* isp. and found to be developed in members I (Pl. 3:2), III and IV, and also represents varying ichnocoenose. In the member I, the trace fossils present in the ichnocoenosis are *Rhizocorallium*, *Laevicyclus*, *Palaeophycus*, *Phycodes*, *Planolites*, *Ophiomorpha*; in member III, it occurs in LSS facies and is associated with *Planolites*, *Palaeophycus* and *Chondrites*; in member IV it is observed with bilobate trails in LSS facies.

Most elements of this ichnocoenosis are shallow, burrowing deposit feeders, found in fine to medium grained sandstone-siltstone alternations of the Jumara Formation. Sediments in this formation, wherever the *Rhizocorallium* ichnocoenosis is located, do not exhibit any sedimentary structures except ripplemarks. *R. jenense* may indicate marginal marine conditions and also possibly a sediment-feeding mode of life in some cases (Buckman, 1992). Compared with these observations, the *Rhizocorallium* ichnocoenosis in Kachchh seems to be indicative of low energy lower foreshore - shoreface areas, less protected with intermittent currents sweeping the sea floor. The Kachchh assemblages occur variedly from the lower foreshore to shoreface zone where wave and current energy and rate of sedimentation dropped. *Rhizocorallium* is interpreted as a structure produced by suspension feeding (only short oblique, retrusive forms) or by deposit feeding organisms, mostly crustaceans (Fürsich, 1974a; Schlirf, 2000; Rodríguez-Tovar, Pérez-Valera, 2008). According to previous authors, the *Rhizocorallium* producer was probably a crustacean (*e.g.*, Fürsich, 1974a, c, 1975; Fürsich *et al.*, 1980; Pemberton, Frey, 1984; Geister, 1998; Patel *et al.*, 2009, 2012). Thus, a recent detailed review of the ichnogenus by Knaust (2013) assigning the producer to a worm-like animal is very unlikely.

It occurs mostly in shallow marine deposits to marginal marine settings (*e.g.*, Farrow, 1966; Hakes, 1976). All the trace fossil assemblages (*Ophiomorpha nodosa*, *Rhizocorallium jenense*, *Skolithos*, *Taenidium*) point to shallow marine environments (Uchman, Gaździcki, 2006). The record of *Thalassinoides* and *Rhizocorallium* indicates bottom conditions ranging from soft to firm. The low sedimentation rate and sediment by-passing probably favoured early lithification (Reolid *et al.*, 2014).

SKOLITHOS ICHNOCOENOSIS

The *Skolithos* ichnocoenosis consists primarily of *Skolithos linearis* (Pl. 3:3) and *Skolithos* isp. with other characteristic elements including mainly dwelling burrows. This ichnocoenosis is developed in members II and III. In member II, the ichnocoenosis occurs in SS and HS facies in association with *Arenicolites*, *Diplocraterion*, and *Monocraterion*; in member III, it is found in LSS in association with *Diplocraterion*, *Ophiomorpha*, *Tisoa*, *Palaeophycus* and *Planolites*.

In the majority of the cases, the traces are thinly populated and generally show a low to moderate degree of bioturbation. The *Skolithos* ichnocoenosis as claimed by Bromley (1990) chiefly represents suspension feeding organisms living in a high energy hydrodynamic setting and shifting substrate subject to abrupt erosion and deposition. The animal seeks security through burrowing deeply and remaining stationary for longer periods. According to Vosslar and Pemberton (1988a), opportunistic ichnocoenose are commonly heavily dominated by *Skolithos linearis*. This ichnocoenosis generally corresponds to the beach, foreshore, and shore face settings where the energy level is comparatively high (Frey *et al.*, 1990). *Skolithos* is most typical of the *Skolithos* ichnofacies (Frey, Seilacher, 1980; Pemberton *et al.*, 2001), which typifies foreshore–middle shoreface environments with sandy substrate (Uchman, Gaździcki, 2006).

The *Skolithos* ichnocoenosis of the study area shows low ichno-diversity, low to moderate density, vertical orientation and deep burrowing of suspension feeders, and is dominated by *Skolithos*, *Arenicolites* and *Diplocraterion*. The development of the *Skolithos* ichnocoenosis indicates an unconsolidated shifting substrate and relatively high energy conditions in lower foreshore to upper shoreface environments.

TAENIDIUM ICHNOCOENOSIS

The *Taenidium* ichnocoenosis (Pl. 2:6, Pl. 2:7) is found to develop in SS facies of member I and consists of active/passive filled feeding trails. It is mainly associated with *Planolites*, *Helminthopsis*, *Protopalaeodictyon*, and *Bolonia*. The ichnocoenosis occurs in fine-grained sandstones and shales indicating dominance of deposit feeders that lived in a low energy environment, an interpretation supported by the fine-grained nature of the enclosing sediments. The trace fossil determined as *Helminthopsis* Heer by Wiedman and Feldmann (1988) displays a meniscate filling, a typical feature of *Taenidium* Heer (D'Alessandro, Bromley, 1987). *Rhizocorallium jenense*, *Taenidium*, *Teichichnus*, *Protovirgularia* and *Lockeia* are common in the *Cruziana* ichnofacies, which typifies lower shoreface–offshore settings (Uchman, Gaździcki, 2006). Keighley and Pickerill (1994) distinguish *Taenidium* as a "simple, unwalled, meniscate, backfilled structure". According to Frey *et al.* (1990), the assemblage occurs in more distal regions and records continuous slow deposition and bioturbation yielding complex bioturbate textures. It also indicates quiet but oxygenated waters, and stable and slowly accreting substrates, as further postulated by Frey *et al.* (1990).

In the Kachchh specimens, *Taenidium* contains a typical meniscate filling. It is associated with *Rhizocorallium* and *Lockeia* which is typical of lower shoreface to offshore conditions (Uchman, Gaździcki, 2006) in fine grained sandstone.

THALASSINOIDES ICHNOCOENOSIS

The *Thalassinoides* ichnocoenosis is widely distributed stratigraphically and is frequently observed in interbedded sandstone-shale sequences of members I, II (Pl. 3:4) and III (Pl. 3:5). In member I, it is observed in LSS and SS facies in association with *Phycodes*, *Rhizocorallium* and *Ophiomorpha;* in member II, it occurs in SS facies, which shows a low degree of bioturbation and is almost monodominant, while in member III, it is found in LSS facies with *Rhizocorallium* and *Planolites.* The large, semipermanent, mainly horizontal tunnel system, exhibiting exclusively deposit feeding traces, probably occupied the lowest energy levels (Fürsich, Heinburg, 1983) with substrate consistencies varying from soft- to firmground (*e.g.*, Ekdale *et al.*, 1984; Fürsich *et al.*, 1992; Pemberton *et al.*, 1992; McEachern *et al.*, 2007; Gerard, Bromley, 2008). Bromley (1990) considered it as semivagile and vagile, middle level deposit feeder structures, present in oxygenated situations, formed by intermediate to equilibrium or climax, trace fossils. *Thalassinoides* is produced by decapods crustaceans (Frey *et al.*, 1984).

This ichnocoenosis mostly occurs in well sorted siltstone-sandstone beds which are moderately to intensely bioturbated. Because of the lower energy level, less abrupt shifting of sediments and also less abrupt change in temperature and salinity - the bioturbation structures are mainly characterised by feeding and grazing traces, marking the presence of the characteristic originators. The ichnocoenosis indicates the low energy conditions in the shoreface zone where sediments were deposited normally below daily wave base but not storm wave base.

ZOOPHYCOS ICHNOCOENOSIS

This ichnocoenosis is observed only in OL facies of member IV of the Jumara Formation in association with *Chondrites*. *Zoophycos* (Pl. 3:6) mainly consist of `U' and `J' shape nets, the former related to oxygen deficiencies and the latter may indicate a respiratory connection with oxygenated bottom waters. The structures are efficiently executed feeding traces, with spreiten typically planar to gently inclined, distributed in delicate sheets, ribbons or spirals. They normally show low diversity, and given structures may be abundant. Bromley (1990) considers *Zoophycos* an opportunistic, which can appear together with *Chondrites* in opportunistic situations in low-resource, inhospitable oxygen-depleted environments. *Zoophycos* is indicative of a lower dysaerobic to nearly anaerobic environment, reflecting a decrease in oxygenation of the substrate (Ekdale, 1988; Wetzel, 1991; Savrda, 1992; Bromley, 1996; Wetzel, Uchman, 1998). Bromley (1990) further considered the ichnocoenosis as non-vagile, deep deposit feeder, which comprises the deepest tier structure. *Zoophycos* ichnocoenosis is thus characterised by low ichnodiversity, and *Chondrites* is labelled as a facies breaking form (Seilacher, 1978). *Zoophycos* remains an enigmatic ichnofossil. *Zoophycos* is used in environmental reconstruction, mostly for the interpretation of the palaeobathymetry and the paleo-oxygenation in bottom waters (Barbu, 2005). Traditionally, *Zoophycos* has been interpreted as a deposit feeder (Seilacher, 1967a), but there has been extensive discussion about the affinities of the producing organisms over the years (*e.g.*, Lewis, 1970; Wetzel, Werner, 1981; Ekdale, Lewis, 1991; Kotake, 1992). However, in the last three decades, several alternative ethological hypotheses have been put forward such as inverse conveyor activity (Kotake, 1989), cache (Jumars *et al.*, 1990; Bromley, 1991; Miller, D'Alberto, 2001), refuse dump (Bromley, 1991), gardening of symbiotic microorganisms (Bromley, 1991; Fu, Werner, 1995; Bromley, Hanken, 2003), and a combination of surface detritus feeding and cache-behaviour (Löwemark, Schäfer, 2003).

The ichnocoenose of *Chondrites* and *Zoophycos* compare favorably with the *Zoophycos* ichnofacies, which is typical, although not exclusive, of outer shelf to slope settings (Frey, Pemberton, 1984).

The presence of the *Zoophycos* ichnocoenosis in OL facies of member IV indicates quiet water conditions, or protected intracoastal to epeiric sites with poor water circulation. It is also typified by nearly thixotropic muds or muddy sands rich in organic matter but somewhat deficient in oxygen.

DISCUSSION AND CONCLUSIONS

Each member (except member IV) of the Jumara Formation displays bioturbated layers occupied by bottom dwelling organisms, which slowly migrate or re-colonise in an upward direction with the advancement of deposition. Recolonization of benthic communities in the shoreface environment are generally more highly variable than deep water and are subjected to more rapid and more regular changes. Consequently, animals which inhabit these shallow water zones are tolerant to a wider range of conditions than their deeper water counterparts and are able to relocate readily following the onset of unfavourable conditions. Environmental zonation based on trace fossil distributions in various aspects, as suggested by Rhoads (1975) and Pemberton *et al.* (1992), has been applied to the sedimentary succession of the Jumara Formation which shows complex shallow water environmental patterns. The trace fossils of the Jumara Formation of the Gangeshwar Dome belong to the *Skolithos* and the *Cruziana* ichnofacies of Seilacher's (1967b) archetypic classification. The *Skolithos* and the *Cruziana* ichnofacies type conditions are found to develop in members I and III, the *Skolithos* ichnofacies in member II, and the *Cruziana* ichnofacies in member IV. The ethological grouping and their associated common trace fossils are depicted in Tab. 4.

The biogenic sedimentary structures of member I show a wide range of benthic communities (Tab. 2) and behavioural habits (Tab. 4). The entire sequence appears as coarsening upward, with intermingling of shale-dominated beds and associated sandstones demonstrating the development of physical structures (low angle cross-stratification, interference ripplemarks, parting lineations *etc*). The presence of the *Gyrochorte* and the *Rhizocorallium* ichnocoenose in laminated shales-siltstones in the lower part are indicative of very low energy conditions in foreshore to transitional environment. The intermingled sandstones mainly show a low density of the structures of both the *Thalassinoides*, and/or the *Ophiomorpha* ichnocoenose and the *Gyrochorte* ichnocoenosis, which normally indicate moderate to low energy conditions below daily wave base or quieter near shore conditions respectively. The shale-sandstone intervening sequence and sandstones of the upper part with physical structures and the *Taenidium*, *Thalassinoides*, *Rhizocorallium*, *Ophiomorpha* and *Diplocraterion* ichnocoenose suggest low to moderate energy conditions in a quieter upper shoreface region. The presence of the ichnocoenose of member-I suggests moderate to lower energy conditions, less abrupt changes in temperature, salinity, and less abrupt shifting sediments resulting in densely populated deposit feeders, grazers or mud ingesters, predators and suspension feeders. The *Ophiomorpha* and *Diplocraterion* ichnocoenose suggest that fluctuating or changing energy conditions and allied parameters represent a temporary excursion of one type

Table 4

Relative abundance of the various ethological categories in the different Members of Jumara Formation

Members	Domichnia	Fodinichnia	Pascichnia	Repichnia
Member I	17.39%	47.83%	17.39%	17.39%
	Diplocraterion parallelum, *Ophiomorpha nodosa*, *Palaeophycus sulcatus*, *Tisoa siphonalis*	*Bifungites isp.*, *Ophiomorpha annulata*, *Laevicyclus isp.*, *Phycodes isp.*, *Phycodes palmatum*, *Phycodes circinnatum*, *Treptichnus pedum*, *Rhizocorallium jenense*, *Rhizocorallium irregulare*, *Thalassinoides isp.*, *Thalassinoides paradoxicus*	*Helminthopsis hieroglyphica*, *Taenidium isp.*, *Planolites annularis*, *Protopaleodictyon incompositum*	*Bolonia lata*, *Didymaulichnus lyelli*, *Gyrochorte comosa*, *Cruziana problematica*
Member II	71.43%	14.29%	–	14.29%
	Arenicolites carbonarius, *Diplocraterion parallelum*, *Monocraterion tentaculatum*, *Skolithos isp.*, *Skolithos linearis*	*Thalassinoides paradoxicus*	–	*Cruziana problematica*
Member III	46.15%	30.76%	7.69%	15.38%
	Diplocraterion parallelum, *Monocraterion tentaculatum*, *Ophiomorpha nodosa*, *Palaeophycus sulcatus*, *Skolithos linearis*, *Tisoa siphonalis*	*Chondrites isp.* *Rhizocorallium jenense*, *Rhizocorallium irregulare*, *Thalassinoides paradoxicus*	*Planolites annularis*	*Bolonia lata*, *Gyrochorte comosa.*
Member IV	33.33%	50%	16.67%	
	Arenicolites carbonarius, *Palaeophycus sulcatus*	*Chondrites isp.* *Rhizocorallium irregulare*, *Zoophycos brianteus*	*Planolites annularis*	–

of association into another type of setting and thus overlapping two or three types of assemblages. The *Taenidium* assemblage suggests the development in deeper level of oxygenated sediments in somewhat distal parts of shoreface conditions and slow sedimentation.

The depositional conditions of the member-II appear to be quite different than those of member-I and the changes are well documented in lithology, and physical and biogenic structures. The lower massive to horizontally stratified beds (SS facies), represented by the *Skolithos* and *Diplocraterion* ichnocoenose, indicate a high energy hydrodynamic setting and shifting substrate further subjected to abrupt erosion and deposition where opportunistic suspension feeding organisms colonized and lived in permanent shelters (Seilacher, 1967b; Pemberton, 1992). Due to shifting of environmental conditions in the upward direction, the *Thalassinoides* and *Gyrochorte* ichnocoenose are superimposed on the *Skolithos* and *Diplocraterion* ichnocoenose. These deposit feeding and crawling traces are indicative of relatively low or quieter water conditions with little reworking where organic matter was being deposited. The reappearance of the *Skolithos* and *Diplocraterion* ichnocoenose in the upper part of member-II (cross-stratified HS facies) most probably demonstrates conditions which are identical to those in the lower part. The occurrence of wave-ripple and large cross-stratification in the upper part along with the ichnoassemblage depicts the onset of lower foreshore to upper shoreface environmental conditions and temporary colonization by a stress pioneer community (Bromley, 1990).

Member III contains a considerably high frequency of traces and represents development of the *Skolithos*, *Diplocraterion*, *Ophiomorpha*, *Gyrochorte*, *Thalassinoides*, *Chondrites* and *Rhizocorallium* ichnocoenose. It contains the *Skolithos* and *Diplocraterion* ichnocoenose at its base in BS facies followed by the *Rhizocorallium*, *Ophiomorpha*, *Thalassinoides* ichnocoenose in LSS facies; the *Chondrites* assemblages in SS facies; the *Thalassinoides* ichnocoenosis in BS facies; the *Chondrites*, *Thalassinoides*, *Rhizocorallium*, *Ophiomorpha* ichnocoenose in LSS and at the top by the *Skolithos*, *Diplocraterion*, *Ophiomorpha*, *Rhizocorallium* ichnocoenose in LSS facies. The changes are appearing to be very significant, and demonstrate the broad range of forms and several behavioural activities of worms, crustaceans, polychaete, gastropod *etc*.

The lowermost BS facies is represented by the *Skolithos* and *Diplocraterion* ichnocoenose in which the presence of a low frequency of structures indicates moderate to high energy conditions and an unconsolidated shifting substrate of the upper shoreface zone colonized by low diversity opportunistic animals having a suspension mode of feeding habit. The ichnocoenose *Rhizocorallium*, *Ophiomorpha* and *Thalassinoides* occur in partings of siltstones of LSS facies and consisting of *Palaeophycus*, *Planolites*, *Tisoa*, *Rhizocorallium*, *Ophiomorpha* and *Thalassinoides* traces. The fine-grained nature of the clastic sediments and the mainly horizontal structures indicate relatively low energy and a slow rate of sedimentation in the middle to lower shoreface zone. The dwelling, feeding, grazing and crawling traces indicate an oxygenated substrate colonized by the deposit feeding animals.

The *Chondrites* ichnocoenosis developed in the calcareous siltstone-fine sandstone of SS facies and is characterized by deposit feeding activity of worm like organisms. Its moderate density and low diversity to monodominant structure indicates quiet water oxygen depleted conditions at the sediment interface. It also indicates minor fluctuations in the general environment or local environment affecting the availability of such a niche to the community in the shoreface zone, in distal part of bars and barriers. The *Chondrites* ichnocoenosis in turn is followed by the *Thalassinoides* ichnocoenosis (BS facies) which contains *Thalassinoides*, bilobe bivalve trails and *Monocraterion*. The assemblage indicates low density and diversity and is considered to demonstrate post-depositional activity of trace fossils which were opportunistic, or were intermediate between opportunistic and climax trace fossils, produced by crustaceans, bivalves, annelid, polychaete, and worm like organisms. This ichnoassemblage indicates quiet water conditions with little reworking where organic matter was being deposited in the low energy shoreface zone.

The *Chondrites*, *Thalassinoides*, *Rhizocorallium* and *Ophiomorpha* ichnocoenose of LSS facies indicate shoreface (near shore) marine conditions with relatively low energy and a slow rate of sedimentation. The occurrence of *Chondrites* in some of the partings and nodules depicts deep level oxygen depleting conditions in fine grained unconsolidated sediments. The topmost part of the LSS facies represented by the *Skolithos*, *Diplocraterion*, *Ophiomorpha*, *Rhizocorallium* ichnocoenose suggest higher energy conditions and an increase in suspended organic rich material. The assemblage of dwelling, suspension feeding and deposit feeding organisms depicts shallowing of the basin and the development of upper shoreface conditions above normal wave base, which are reflected by the occurrence of oscillation ripplemarks.

The dominance of dwelling structures over feeding and crawling structures indicates moderate to high energy conditions with shifting substrate and the presence of ample food in suspension modes in upper shoreface environments. The presence of *Thalassinoides* in the thick sandstone facies probably represents the lowest energy levels (Fürsich, Heinberg, 1983) and the middle level deposit feeder structures of semivagile and vagile organisms in the oxygenated substrate marks the intermediate to equilibrium or climax trace fossil (Bromley, 1990) ichnocoenosis.

Member IV shows significant changes in trace fossil content as compare to other members of the Jumara Formation. The silty shales of LSS facies, in the lower part, contain fewer trace fossils, but include *Rhizocorallium* and bilobe trails. The above assemblage indicates slow sedimentation and little physical reworking in the shoreface to transitional zone where the substrate is less protected, with intermittent current sweeping the sea floor (Fürsich, 1974c) and also have a sediment feeding mode of life (Buckman, 1992). At the higher level, the oolitic limestone facies contains *Zoophycos* and the *Chondrites* ichnocoenose along with *Planolites*. These forms indicate quiet low energy and probably deeper water shelf conditions where the rate of sedimentation is rather slow, and is typified by calcareous mud and muddy sands, rich in organic matter but somewhat deficient in oxygen. The ichnocoenose indicate deposit feeding and grazing behaviour of vagile mud ingesters like polychaetes, annelids, worms *etc*.

In general, the trophic and behavioral characteristics of the ichnocoenose indicate a gradient in bottom water agitation. The suspension feeding *Skolithos*, *Diplocraterion* and *Ophiomorpha* ichnocoenose represent the highest energy levels. The deposit feeding *Rhizocorallium* and *Thalassinoides* ichnocoenose reflect progressively lower energy conditions. On the other hand the *Chondrites*, *Gyrochorte*, *Taenidium* and *Zoophycos* ichnocoenose are characterised by extremely low energy conditions, where slow deposition and less erosion prevailed. Finally, the trophic diversity of the trace fossil data reflects different types of substrate conditions, varying rates of sedimentation, salinity differences and different degrees of wave agitation. Many of these factors, individually or collectively, may have been responsible for the overall distribution of the animal communities in sedimentary units of the Jumara Formation.

The Jumara Formation is well exposed in the Gangeshwar Dome and attained a 247 m - thick bioturbated succession and comprises various types of sandstones, grey and khakhi shales, limestones and conglomerates. The following conclusions are drawn from the present study.

The presence of trace fossils in the entire succession suggests oxygenated substrate conditions.

The low to moderate energy environments in the basin was favoured by deposit feeding, grazing, crawling and resting organisms.

Changing environment conditions had allowed the various suspension and deposit feeding animals to explore niches at different times.

The onset of various environmental conditions and different ichnocoenose together show the quick successional changes preserved in them.

The ichnological data of the Jumara Formation of the Gangeshwr dome suggests fluctuation of energy conditions, mode of food supply, change in rate of sedimentation and exploitation of niches by opportunistic animals in the shoreface, transitional to shelf, region during deposition of the sediments.

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PLATE 1

Field photographs

Fig. 1. Shale-siltstone-sandstone intercalated sequence of the top part of the member I near Gangashwar Mahadev; highly bioturbated top part of the rippled sandstone consisting of *Gyrochorte*

Fig. 2. *Gyrochorte* (member I)

Fig. 3. *Taenidium* (member I)

Fig. 4. Cross-bedded sandstone of the member II

Fig. 5. Coarse grained cross bedded sandstone of member III

Fig. 6. Highly fossiliferous limestone with common bivalves (member III)

Fig. 7. Oolitic limestone–shale sequence of the member IV

Fig. 8. Top part of the member IV consisting of intrabasinal conglomerates representing the storm-lag deposit

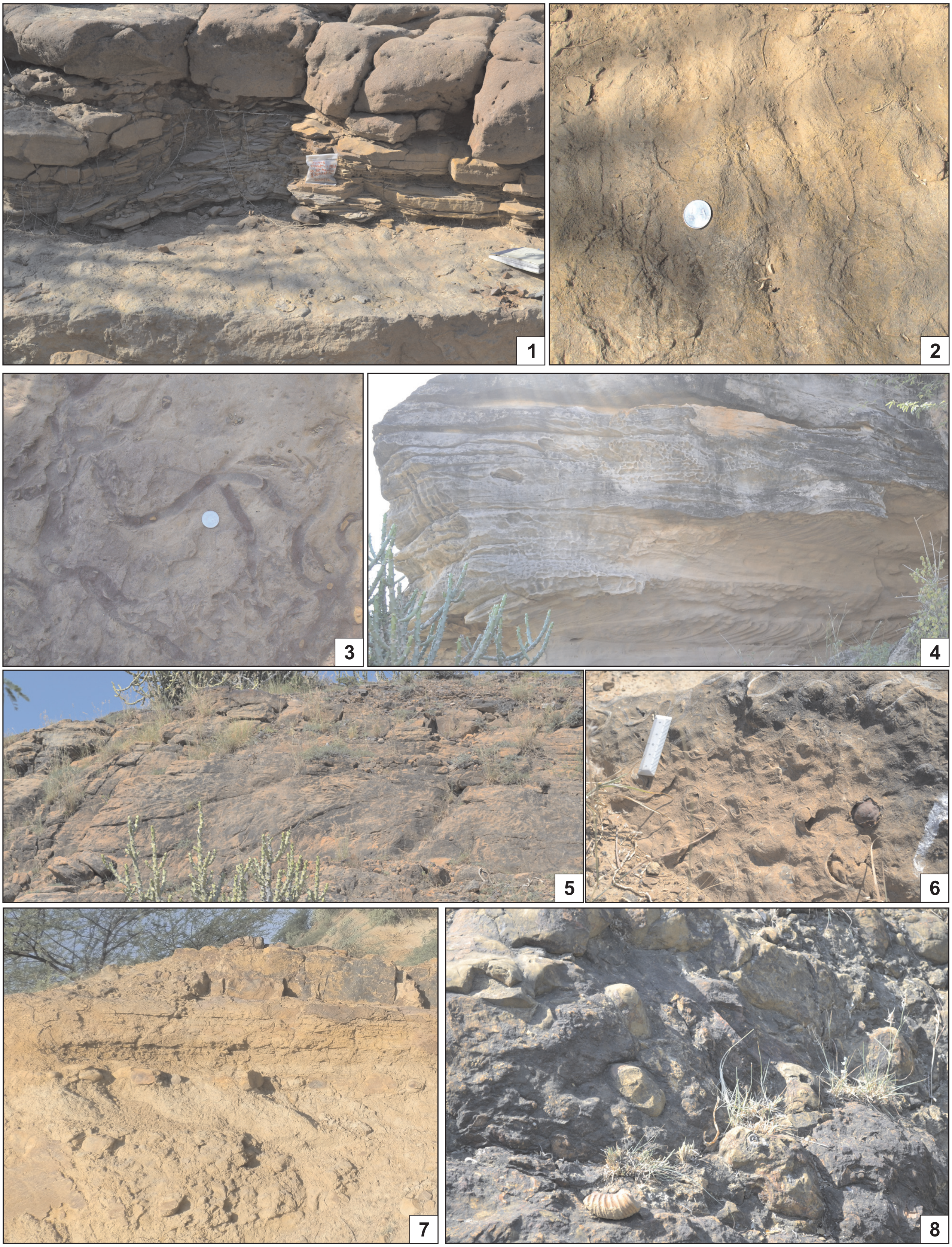

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PLATE 2

Fig. 1. *Chondrites* isp., OL in Member IV near Gangeshwar (scale bar = 1 cm)

Fig. 2. *Diplocraterion parallelum* Torell, SS in Member II near Gangeshwar Mahadev (scale, coin = 2.5 cm)

Fig. 3. *Laevicyclus* isp., LSS, Member I of Jumara Formation in quarries near Jamaywadi (scale bar = 1 cm)

Fig. 4. *Bifungites* isp., SS in Member I in quarries near Gangeshwar Mahadev (scale bar = 1 cm)

Fig. 5. *Gyrochorte comosa* Heer, LSS and SS in Member I near Gangeshwar Mahadev (scale, coin = 2.5 cm)

Fig. 6. *Taenidium* isp., SS in Member I near Gangashwar Mahadev (scale bar = 8 cm)

Fig. 7. *Taenidium* isp., SS in Member I near Jamaywadi (scale, pen = 15 cm)

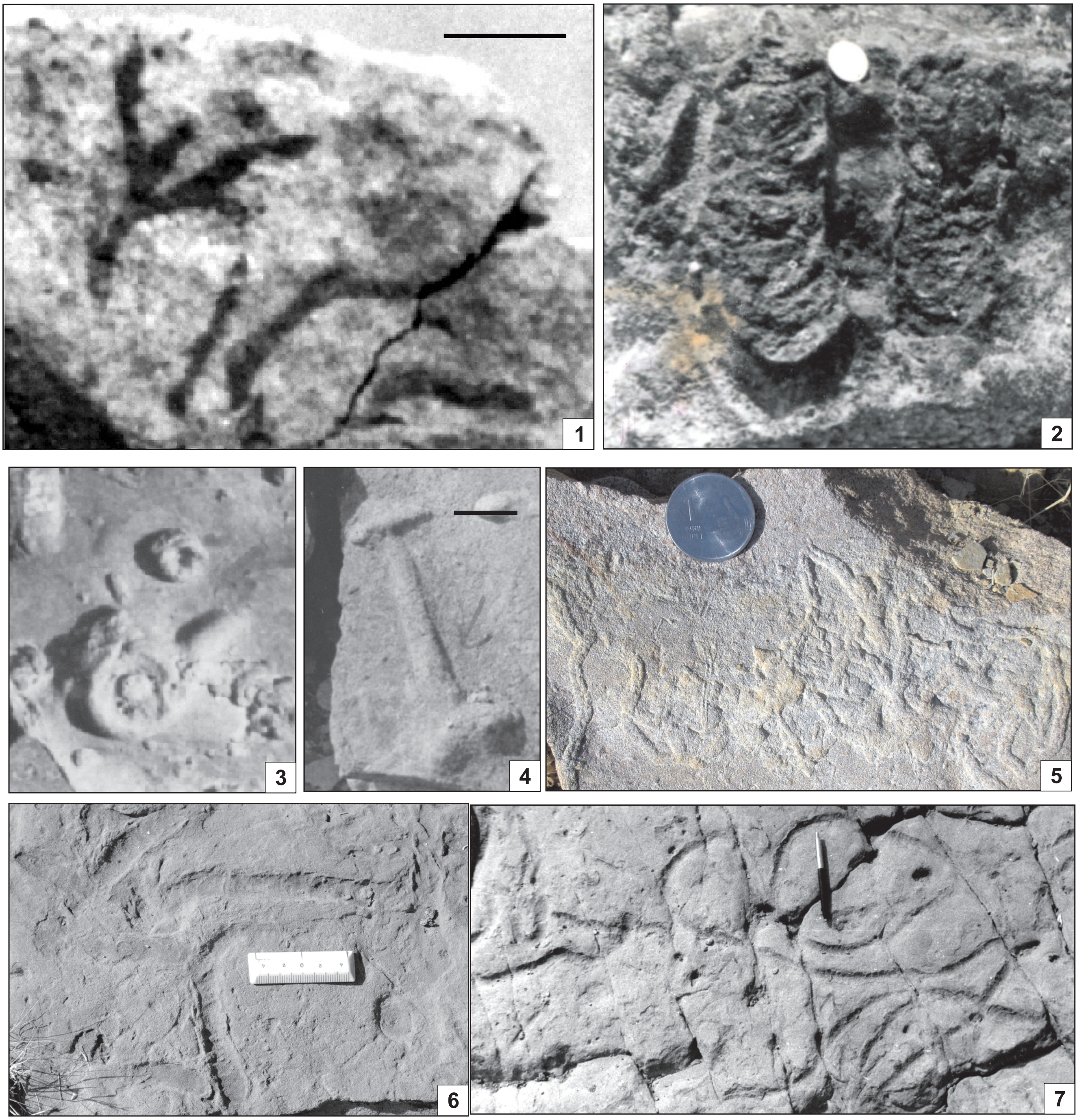

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PLATE 3

Fig. 1. *Ophiomorpha nodosa* Lundgren, LSS in Member I near Jamaywadi (scale bar = 1 cm)

Fig. 2. *Rhizocorallium irregularre* Mayer, LSS in Member I near Gangeshwar Mahadev (scale bar = 10 cm)

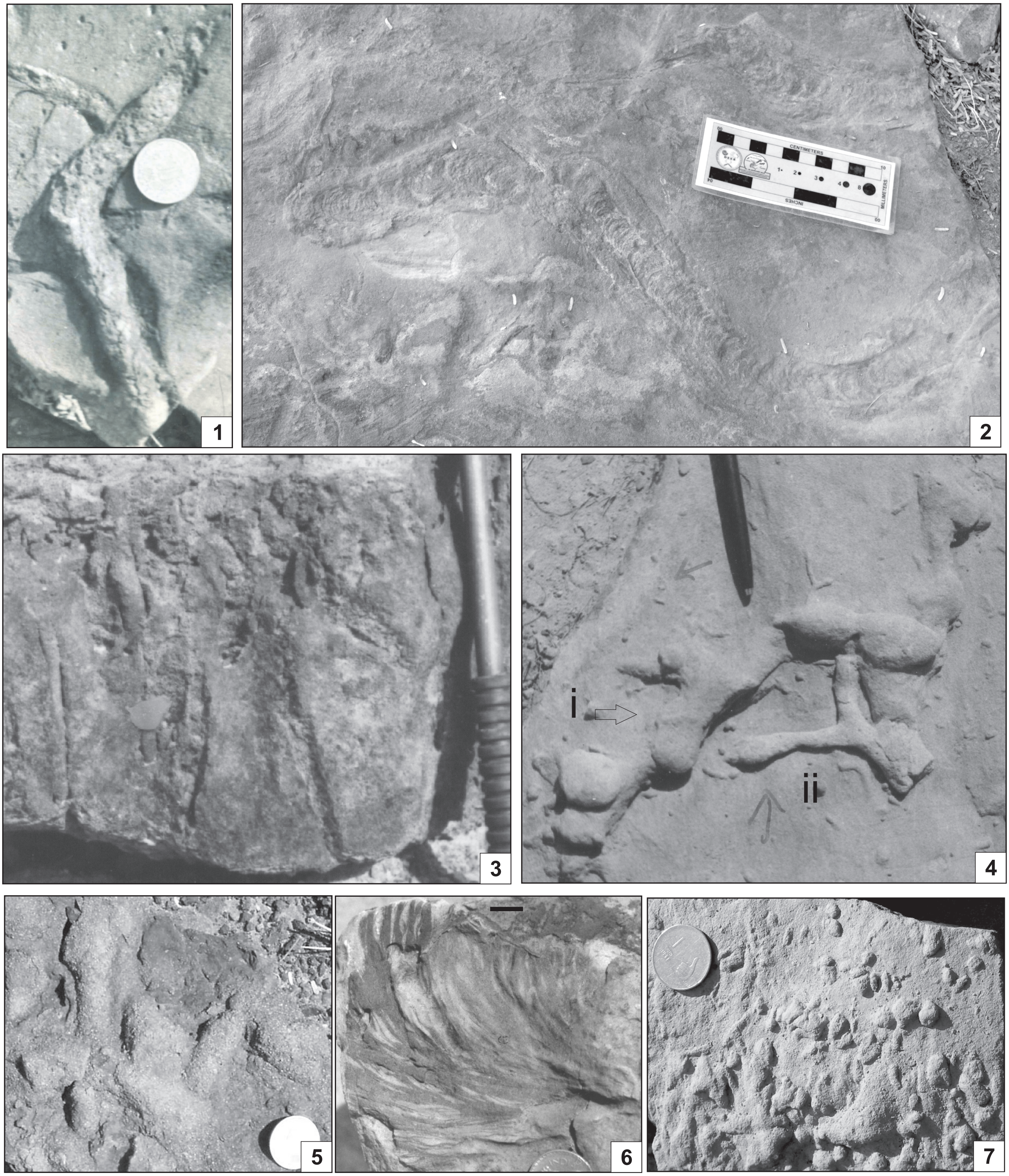
Fig. 3. *Skolithos linearis* Haldeman, SS, Member II, Gangeshwar Mahadev (scale, hammer = 31 cm)

Fig. 4. *Thalassinoides paradoxicus* (Woodward) (scale, part of pen = 8 cm), LSS in Member I in quarries near Gangeshwar

Fig. 5. *Thalassinoides* isp. (i) and *Thalassinoides paradoxicus* (Woodward) (ii) in bivalve sandstone facies of member III (scale, coin = 2.5 cm)

Fig. 6. *Zoophycos brianteus* Massalongo, OL in Member I near Gangeshwar Mahadev (scale bar = 1 cm)

Fig. 7. *Lockeia amygdaloides* (Seilacher) LSS and SS in Member I (scale, coin = 2.5 cm)



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