Ichnofabric analysis of the Tithonian shallow marine sediments (Bhadasar Formation) Jaisalmer Basin, India

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The shallow marine sedimentary sequence of the Jaisalmer Basin exhibits one of the important and well-developed Tithonian sedimentary outcrops for western India. The ichnology and ichnofabric of the lower part of Bhadasar Formation (i.e., Kolar Dongar Member) belonging to Tithonian age are presented and discussed. The Kolar Dongar Member represents a shallow marine succession that contains 16 ichnotaxa: *Ancorichnus ancorichnus*, *Conichnus conicus*, *Gyrochorte comosa*, cf. *Jamesonichnites heinbergi*, *Imponoglyphus kevadiensis*, *Laevicyclus mongraensis*, *Monocraterion tentaculatum*, *Ophiomorpha nodosa*, *Palaeophycus tubularis*, *P. bolbitermius*, *Phycodes palmatus*, *Planolites beverleyensis*, *Rhizoco-rallium* isp., *Rosselia rotatus*, *R. socialis*, and *Teichichnus rectus*. The ichnofabric analysis divulges five distinct ichnofabrics, each typifying distinct depositional environment within shallow marine conditions. The ichnofabric *Ophiomorpha* 1 with syn-sedimentary faulting exemplifies high energy conditions typical of lower shoreface environment, whereas the *Ophiomorpha* 2 ichnofabric typifies upper shoreface environment. The *Ancorichnus* ichnofabric reflects lower offshore condition of deposition. The high ichnodiversity *Ancorichnus*–*Rosselia* ichnofabric is indicative of inner shelf conditions, while low ichno-diversity *Teichichnus* ichnofabric indicates prevalence of low energy brackish bay environment. Thus, Tithonian Kolar Dongar Member indicates depositional environment ranging from shoreface to offshore to inner shelf and finally to brackish bay environment.

1. Introduction

The term ‘ichnofabric’ refers to all aspects of the texture and internal structure of sediment that result from bioturbation and bioerosion at all scales; includes both bioturbation fabric and bioerosion fabric (Ekdale *et al.* 1984). Ichnofabric analysis provides an integrated insight into the processes and responses involved in a bed or a sedimentary unit, classifying the unit based on sedimentation processes, responses of organisms, and ecological succession. Thus by applying the concept, the entire spectrum of the processes

responsible for the preservation of the trace fossils can be delineated. The shallow marine Mesozoic sediments of Jaisalmer Basin provide an excellent opportunity of analysing the ichnofabric because of the basin’s low dipping profiles and extensive outcrop exposures. The Jaisalmer Basin is considered to be part of the extended Indus shelf (Zaigham and Malick 2000). The shallow marine Jurassic sequence of Jaisalmer was extensively studied in the past for its stratigraphy (Dasgupta 1975 and references therein; Pareekh 1981; Pandey *et al.* 2006a, b, 2009, 2012). Recently, Singh (2006) reviewed and re-described the Mesozoic and

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pre-Mesozoic stratigraphy of the Rajasthan shelf, providing a correlation between subsurface and surface outcrops. The biostratigraphy scheme for the Rajasthan shelf was extensively dealt with by various researchers (Krishna 1987; Dave and Chatterjee 1996 and references therein). In comparison to the extensive studies on the stratigraphy and biostratigraphy, ichnological studies are very sporadic and scattered (Kumar 1979; Chiplonkar *et al.* 1981; Sudan *et al.* 2000; Borkar and Kulkarni 2001, 2006; Fürsich *et al.* 2006; Kulkarni *et al.* 2008). The present paper aims at investigating rich and diverse trace fossils of the clastic succession of the lower part of the Bhadasar Formation that is classified as Kolar Dongar Member. It is exposed in continuous low dipping outcrops from the top of the Bhadasar Scarp onwards until 2 km northwest. The stratigraphic convention of Prasad (2006) is followed for the present paper.

2. Geology, lithostratigraphy and age

The Peri-cratonic Jaisalmer Basin (figure 1) forms the eastern flank of the Indus Basin with low dipping (3° – 5° dip) Mesozoic sediments that are exposed as arcuate outcrop. The entire Mesozoic is divisible into six mapable formations (table 1), viz., Lathi, Jaisalmer, Baisakhi, Bhadasar, Pariwar, and Habur ranging in age from Lias (Singh 2006) to Albian (Rai *et al.* 2013). The basement of the Jaisalmer Basin is composite in nature and comprises of Malani igneous rocks and metasedimentaries of Randha–Birmanian formations. The Mesozoic sedimentation in the basin commenced with sandstone dominated sequence of Pre-Lathi (?) and Lathi formations that is overlain by a thick sequence of Bajocian to Oxfordian carbonates (Jaisalmer Formation). The carbonate succession is capped by a thick Kimmeridgian sandstone/shale sequence (Baisakhi Formation) followed by Tithonian sandstone sequence (Bhadasar Formation). In subsurface, these Kimmeridgian–Tithonian clastic sequences that overlie the Callovian–Oxfordian carbonates are undifferentiated (Singh 2006). In outcrop, the Tithonian Bhadasar Formation is overlain by Early to Middle Albian (Rai *et al.* 2013) cross bedded feldspathic sandstone sequence of Pariwar Formation. A highly fossiliferous Albian sedimentary unit of alternating calcareous sandstones and fossiliferous limestone (Habur Formation) overlies the feldspathic sandstone sequence.

The composite Baisakhi–Bhadasar Formation *sensu* Singh (2006), (figure 2a) is considered to be one of the most important and extensive source rock shale sequence in Jaisalmer and surrounding hydrocarbon producing basins (Bhowmick and Mishra 2008). In outcrops, maximum thickness

measured for Bhadasar Formation is up to 70 m thick. The formation is divided into two members, viz., (1) Kolar Dongar Member and (2) Mokai Member. The Kolar Dongar member is the oldest member of the two and is characterized by ferruginous and calcareous sandstone alternating with clay stones and shales. The younger Mokai Member is represented by hard jointed, fine grained argillaceous, ferruginous sandstones.

The present studied section (figure 2 and table 2) can be correlated with ‘Beds 6(a–d) to 11(a–c)’ of Pandey and Krishna (2002). Based on the fossil content, Dave and Chatterjee (1996); Pandey and Krishna (2002) and Singh (2006) have considered Bhadasar Formation, especially Kolar Dongar Member to be of Tithonian age. Pandey and Krishna (2002) based on ammonites gave a biostratigraphic age ranging from *Communis* zone to *Densiplicatus* zone of Indo-East African standard scheme for Kachchh. For easy reference, the present section is numbered (table 2).

The lower contact between Baisakhi Fm (Lanala Member) and Bhadasar Fm (Kolar Dongar Member) is well exposed in the Bhadasar escarpment (figure 2a); the study section is exposed few meters away from the escarpment towards northwestern side. The section (figure 2b) starts with thick, white, off-white to pinkish shales (bed no. 1) overlain by 10 cm thick hard ferruginous fine grained calcareous sandstones (bed no. 2, figure 2c), the sandstone comprises of synsedimentary small scale faulting and deformation (figure 2d) with plane bed laminations (figure 2e). Sometimes ferruginous nodules and concretions are also seen. The thickness of this bed is not uniform throughout and varies from 8 to 14 cm. This bed is overlain by thick sequence (bed nos. 3–9) of shale and clay stones with thin to very thin siltstone partings. The shales are variegated and gypseous in nature and occasionally intercalates with numerous maroon to yellowish orange fine grained siltstones, occasionally containing concretionary nodules. The shale sequence is overlain by a prominent bed no. 10 (figure 2f), which is of varying thickness (8–15 cm), hard, with maroon, fine-grained calcareous sandstone comprising of plane bed laminations. Bed nos. 12, 13 and 14 are alternate sequences of lime, mudstone, and shale that is highly bioturbated in nature.

3. Methodology

The studied section from which the ichnofabric analysis carried out was correlated with the published literature considering field mapping, fossil content especially by presence of ammonites and belemnites, etc. The trace fossils were

Figure 1. (a) Generalized outcrop geological map showing location of the study area (star indicates studied location). (b) Simplified surface Jurassic litho-stratigraphic column of the Jaisalmer Basin, studied section indicated by colour code (modified after Singh 2006).

Table 1. Detailed lithostratigraphic classification of the Mesozoic sediments of Jaisalmer Basin.

Age	Formation	Member	Dominant lithology
Albian	Habur	–	Shales, calcareous sandstones and fossiliferous limestones (Coquina limestone)
Albian ¹	Pariwar	Upper	Coarse grained, cross bedded, thick bedded, feldspathic sandstones. Sometimes contains wood fossils
		Lower	Sandy siltstone and calcareous sandstones
?Early Cretaceous Tithonian	Bhadasar	{ Mokai Dongar Kolar Dongar	Coarsening upward sandstones with shales Shale and siltstone alteration with sandstones
Late Kimmeridgian } Kimmeridgian } Early Kimmeridgian }	Baisakhi	{ Lanala Ludarwa Rupshi	Shale siltstone alteration Shales with thick sandstones Shales with minor siltstones
Oxfordian }	Jaisalmer	Jajiya	Highly bioturbated (<i>Zoophycos</i> and <i>Rhizocorallium</i>) limestone
Callovian }		Kuldhar	Bioturbated limestone with three hardgrounds levels, shales
Bathonian }		Badabag	Cross bedded calcareous sandstones, intraformational bored conglomerates
		Fort	Cyclic alteration of limestone, calcareous sandstones and shales
Bajocian }		Joyan	Bioturbated limestones and fine grained sandstones
		Hamira	Calcareous sandstones
Early Jurassic to Bajocian	Lathi	{ Thaiyat Odonia	Fine grained sandstones and siltstones Pebbly, cross bedded poorly sorted sandstones

Note: ¹Age after Rai *et al.* (2013).

systematically studied in the field and representative samples were also collected from individual beds. The position of the trace fossil with respect to the top/bottom of the bedding surface was also noted. Ichnometry and ichnofabric were also performed in field, as well in the laboratory. Bioturbation index of Taylor and Goldring (1993) is followed for cross section of the beds, while methodology suggested by Miller and Smail (1997) is followed for bedding plane bioturbation index. Häntzschel (1975) was followed for identification of the trace fossils. Representative samples of trace fossils were also studied by serial sectioning. Representative samples are collected and preserved in the repository of Ichnology laboratory of Pandit Deendayal Petroleum University.

4. Ichnological description

Ancorichnus ancorichnus (Heinberg 1974)

Figure 3 (a and b)

Material: PDP/IL/BGD/Jaisal/41, 42, 43 and several field photographs

Description: Epichnial preserved, bedding parallel to subparallel, unbranched, straight to slightly

curved, cylindrical in cross section, meniscus filled burrow with tube-shaped mantle. Mantle separated from the host rock and central tunnel by a thick lining; burrow fill sediments are similar to the host and mantle sediment and consist of fine-to-medium silt size particles. Width of burrow varies between 10 and 15 mm while thickness of the mantle varies between 2 and 3 mm ($n = 17$).

Remarks: The characteristics of the present specimen matches with those described by Heinberg (1974). The burrow is regarded as activity of deposit feeding organism. *Ancorichnus* is considered to be monospecific after its revision by Keighley and Pickerill (1994). The specimen was described in detail from Jurassic sediment of Greenland by Heinberg (1974) and Dam (1990). In the Jurassic sediment of western India it is reported from Middle Jurassic Kaladongar Formation of Kachchh (Fürsich 1998), and Callovian sediment of Habo dome (Patel *et al.* 2008), and Oligocene Bokabil Formation of Manipur (Singh *et al.* 2010). *Ancorichnus* represents inner shelf depositional environment (Keighley and Pickerill 1994, figure 4).

Figure 2. Stratigraphic context of the studied section. (a) Bhadasar escarpment showing contact between shale dominated Lanala Member of Baisakhi Formation and Bhadasar Formation. The lowest bed (pointing arrow) is rich with diverse fossils including ammonites, belemnites, bivalve and wood fossils. (b) Detailed measured lithosection of the studied section. Numbers in bracket indicates bed number. (c) Stream section west of Bhadasar Escarpment showing exposure of bed no. 2; note the variation in bed thickness due to compaction (man in photograph is 5 feet and 7 inches). (d) Syn-sedimentary faulting in the bed no. 2, note the formation of minor-horst and graben structures. (e) Plane bed laminations in bed no. 2. (f) Exposure of bed nos. 10 and 11 along the stream section.

Table 2. Correlation of the present work with established biostratigraphy and lithostratigraphy.

Pandey and Krishna (2002)				Singh (2006)		Present Work
		Zone	Subzone			Bed No.
B No. 11 (a–c)	4.40 m thick yellow to whitish ferruginous, coarse grained bioturbated sandstone	DENSIPlicatus	Opelli	<div>↑ A: Kolar Dongar Mb ↓</div>	Consisting of four ferruginous gritty sandstone alternating with loosely cemented red sandstone with clayey and calcareous intercalations containing ammonite shells. The grit beds are cherry red hard and compact with ammonites and oolitic and coquina layer in basal grit unit sandstone is medium to coarse grained loosely cemented with intercalation of claystone.	12, 13, 14
B No. 10 (a–g)	4.20 m thick gypseous shale/ siltstone					10, 11
B No. 9 (a–d)	4.0 m thick marker bands, maroon to yellowish maroon ferruginous, coarse hard compact bioturbated sandstone		Densiplicatus			5, 6, 7, 8, 9
B No. 8	12.20 m variegated gypseous shale/ siltstone					3–4
B No. 7	0.80 m Marker Bed	COMMUNIS	Subfrequens			2
B No. 6 (a–g)	2.4 m thick variegated, highly gypseous shale/siltstone					1
B No. 5	Unexposed					Not studied

Conichnus conicus (Männil 1966) Figure 3(d–i)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh 16

Description: Small, conical, escape structure. This specimen shows chevron-shaped margins, and the base is similar to ‘broad U’ with an angle of 105 degrees. The length and width measurement for single specimen is 12 mm × 12 mm width.

Remarks: Buck and Goldring (2003) have revised all conical structures and according to the criteria suggested by them, the present conical structures can be classified as burrow exhibiting escape behaviour. Based on the size it can be said that the escape structure produced might be created by some polychaetes/bivalve. Similar *Conichnus* are widely reported from shoreface deposits (MacEachern and Pemberton 1992) and from limestones deposited in a lagoonal setting (Shinn 1968; Curran 1994). It is considered to be an important element of the *Skolithos* ichnofacies.

Gyrochorte comosa (Heer 1865) (Figure 3c-ii and e)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh 17

Description: Epichnial preservation, simple, slightly curved to straight, bilobed burrow comprising of two convex lobes with a sharp V-shaped median furrow. Sometimes, the specimens also exhibit negative epirelief comprising of two grooves with a median ridge. The width varies from 5 to 12 mm.

Remarks: The present specimens show two classes of burrow width (1) between 5 and 7 mm wide with sharp ‘V’ shaped median groove and (2) 10–12 mm wide with broad ‘U’ shaped median groove. The trace fossil with broad ‘U’ shaped groove can be compared with *Gyrochorte robusta*; however, this ichnospecies was merged with *Gyrochorte comosa* by De Gibert and Benner (2002). The trace commonly occurs in the Jurassic sediment of Kachchh especially from Jumara Formation of

Figure 3. Trace fossils from the Kolar Dongar Member, scale bar equals to 2 cm (a) bedding parallel *Ancorichnus ancorichnus* in the fine grained siltstone of bed no. 9 showing meniscus filled burrow with tube-shaped mantle. White arrows indicate thick mantle. (b) Unbranched but overlapping nature of *Ancorichnus ancorichnus* from bed no. 9, showing distinct cross cutting of the previously formed burrow. White arrows indicate thick mantle. (c) Bedding surface view of bed no. 2 showing thin siltstone with veneer of mud containing *Gyrochorte* burrow. (d) Cross section of plane laminated bed showing small 'V' shaped escape structure *Conichnus conicus*, (i) and cross sectional view of inclined *Rosselia socialis* from bed no. 11. (e) Bedding view of criss cross *Gyrochorte* burrows. (f) Subhorizontal cf. *Jamesonichnites heinbergi* with chevron shaped meniscus filled tunnels preserved in siltstone of bed no. 9. (g) *Imponoglyphus kevadiensis* a backfilled burrow showing invaginated cone in cone arrangement of meniscus fills preserved in thinly bedded siltstone of bed no. 9.

Habo dome (Patel *et al.* 2008), Jhuran Formation of Jara Dome (Desai *et al.* 2008). It is also reported from cretaceous sediment of Bagh beds (Kundal and Sanganwar 2000) and Oligocene sediment of Manipur (Singh *et al.* 2010). Kumar (1979) has reported this trace fossil from Jaisalmer Formation. *Gyrochorte* is facies transgressive trace fossil, produced by opportunistic animals (Powell 1992). It is considered to be a post-event burrow, with its producer colonizing substrate during quiet period (De Gibert and Benner 2002). The trace fossil indicates shallow marine depositional environment.

Cf. *Jamesonichnites heinbergi* (Dam 1990)
(Figure 3f)

Material: SPT/IL/BGD/12

Description: Epichinally preserved cylindrical meniscus filled tunnels. Tunnels are chevron shaped and subhorizontal and at an angle to the bedding. The tunnels have structureless mantle which separates the central meniscus filled tunnel with the host sediment. The tunnel divides alternately from each side, with mantle forming chevron shape or broad 'U' shaped pattern. The tunnel width is 27–30 mm with mantle width about 7–9 mm, and 70–90 mm in length ($n = 5$).

Remarks: The present specimen differs slightly from that described in Greenland specimens by Dam (1990), the nature of the chevron shape is very angular and diverges widely from the midline, while the present specimen is more 'U' shaped in nature and does not diverge much from the midline. The specimen is also different from *Ichnogenus Hillichnus* which has lateral spreiten structures with vertical rising tubes (Bromley *et al.* 2003). However, this difference might be due to differential weathering. The trace fossils are closely associated with *Ancorichnus ancorichnus* bearing sediments and might represent preservation variant of the *Ancorichnus*. The *Ancorichnus*–*Jamesonichnites* association is also found in Jurassic sediment of Greenland (Dam 1990). It is interpreted to be deposit feeding activity.

Imponoglyphus kevadiensis (Badve and Ghare 1980) (Figure 3g)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh 11

Description: Endichnially preserved, simple, non-winding, horizontal, cylindrical, backfilled burrow. Individual meniscus forms invaginated cone in cone arrangement. Burrow is 11 mm wide with length of individual meniscus about 4 mm.

Remarks: The trace fossils are described from Cretaceous sediment of Bagh beds (Badve and Ghare 1980). It differs from *Imponoglyphus troquendus* as described by Vyalov (1971) from Upper Triassic of Asia (Pamir) in having larger dimensions of the meniscus, while Vyalov's specimens are slender. It is considered to be deposit feeding trace. It appears together with *Ancorichnus ancorichnus*. The trace fossil *Imponoglyphus kevadiensis* described by Badve and Ghare (1980) is a comparatively small specimen. It might be possible that the present specimen represents the core of the *Ancorichnus*. However, more samples are needed to confirm the interpretation.

Laevicyclus mongraensis (Verma 1969) (Figure 4a)

Material: Field photograph

Description: Endichnia preservation of burrow. Cylindrical, vertical, unbranched, burrow that is circular to elliptical in cross section. The full burrow consists of circular bodies with hollow central tubes filled with sediment. In cross-section, the burrow consists of 3–4 concentric rings. Outer diameter of the ring is 20 mm with diameter of the central knob about 9 mm. Traces are perpendicular to the bedding plane.

Remarks: The specimens are comparable with the specimens described by Verma (1969) and Chiplonkar and Badve (1970) from the Cretaceous Bagh beds of India. The Bhadasar specimen differs from the specimen described by Chiplonkar and Badve (1970) in the dimensional ratio of the outer and inner diameters; however, they are comparable with the Kachchh specimen described from Habo dome (Patel *et al.* 2008). It is also reported from Kachchh, especially from cross-bedded sandstones of Jumara Formation of Habo dome (Patel *et al.* 2008) and from flaggy siltstones of Jhuran Formation of Jara dome (Desai *et al.* 2008). However, the present specimens are slightly robust as compared to those described by Chiplonkar and Badve (1970). It is considered to be feeding traces of annelids (Chiplonkar and Badve 1970). The trace fossil was earlier reported from wide ranging environments, from deep water flysch deposits to shallow marine to even continental environment (for detail reference, Uchman 1995).

Monocraterion tentaculatum (Torell 1870)
(Figure 4b)

Material: Field photograph

Description: Endichnial full burrow preservation; simple, unlined tube with funnel at the top. Burrow

Figure 4. Trace fossils from Kolar Dongar Member, scale bar equals to 2 cm. (a) Bedding plan view of *Laevicyclus mon-graensis* showing concentric rings developed in very fine grained sandstone. (b) Cross sectional view of *Monocraterion tentaculatum* showing unlined tube with funnel at the top. (c and d) *Ophiomorpha nodosa* in different preservation style. (e) *Palaeophycus tubularis* showing outer wall ornamentation similar to *Palaeophycus annulatus*. (f) Transitional forms of *Palaeophycus tubularis* and *P. annulatus*. (g) *Palaeophycus bolbiterminus* with bulb like feature at one end of the burrow. (h) Unlined smooth burrow of *Planolites beverleyensis*.

perpendicular to the bedding plane. Burrow circular in cross section with burrow sides almost parallel to slightly converging forming weak cone.

Funnel diameter 25–28 mm with tube diameter ranging from 6–12 mm. Length of the tubes 25–34 mm.

Remarks: The nature of the funnel and its association with the tubes suggest that the trace can be considered as Ichnogenus *Monocraterion*. Several authors have suggested that tubes without funnels are considered as *Skolithos*. Such a type of preservation is commonly produced by erosion of funnels and preservation of only tubes and hence *Monocraterion* can be considered similar to *Skolithos* (Goodwin and Anderson 1974; Schlirf 2000). Similar funnel-shaped burrows were also reported from recent intertidal sediment of Mandvi (Kachchh); however, the recent Kachchh specimens occur as grouped funnels interconnected with branched tunnels (Patel and Desai 2009), while the Bhadasar specimen occurs as simple unbranched tubes below funnel. Functionally, the funnel helps in suspension feeding and irrigating the burrow. Hence the burrow is considered as temporary dwelling burrow of suspension feeding activities and irrigation of the burrow.

Ophiomorpha nodosa (Lundgren 1891) (Figure 4c, d)

Material: PDP/PU/SPT/IL/BGD/Jaisal/95

Description: Endichnial full burrow preservation, horizontal to inclined, branched, three-dimensional burrow systems. Burrow wall distinctly lined; outer wall with nodular structure with a rim of iron oxide surrounding the burrow wall. Burrow fill similar to the host sediment. Burrow diameter varies from 24 to 35 mm, with outer wall 5–6 mm thick.

Remarks: The trace fossils have been identified based on thick lined wall with nodular structures. The trace fossil is commonly reported from Middle Jurassic of Habo dome (Patel *et al.* 2008), Upper Jurassic Jhuran Formation (Desai *et al.* 2008), Cretaceous Bagh beds (Kundal and Sanganwar 2000) and from Miocene sediment of Manipur (Singh *et al.* 2010). Ichnogenus *Ophiomorpha* is also reported from intertidal sediments of Mandvi, Kachchh (Desai and Patel 2008), where they belong to pre-omission suites. The *Ophiomorpha* is a characteristic trace fossil for the high energy, mobile substrate belonging to shallow marine environment, especially subtidal to lower intertidal zone (Patel and Desai 2009). The trace maker of these burrows is stomatopodeans (Patel and Desai 2001) or *Callianassa* shrimp.

Palaeophycus tubularis (Hall 1847) (Figure 4e, f)

Material: PDP/PU/SPT/IL/BGD/Jaisal/88, 89

Description: Endichnially preserved full relief burrow. Burrow thinly lined, straight to slightly

curved. Burrow wall consisting of distinct thick annulations 2–3 mm thick. Annulations consist of thick wavy ridges and grooves that are spaced regularly. Burrow cylindrical in cross section with diameter ranging from 13–18 mm and in some cases it is up to 25 mm. Fill identical to the host rock.

Remarks: The type of characteristic annulations occurring on the burrow wall matches with the *Palaeophycus annulatus* described by Badve (1987). In some cases transitional forms for the outer wall ornamentation between *Palaeophycus tubularis* and *Palaeophycus annulatus* are also noticed. However, Buckman (1995) doubted the validity of the *Palaeophycus annulatus*. We also, based on our study of the type specimen, agree to the views of Buckman (1995) and hence consider present material to be *P. tubularis*. The species is earlier reported from Jurassic of Jara dome (Desai *et al.* 2008) and from Oxfordian sediment of Dhosa Oolite member (Patel *et al.* 2009).

Palaeophycus bolbiterminus (Kim *et al.* 2000)
(Figure 4g)

Material: PDP/PU/SPT/IL/BGD/Jaisal/33, 35

Description: Endichnial preservation of tubular burrow, oriented horizontal or oblique to bedding plane. Burrow thinly lined, unbranched circular in cross section. Burrow terminates with a hemispherical, terminal bulb. Bulb lengths about 18–19 mm with diameter of 35 mm, tube length more than 40 mm while tube diameter is about 22 mm. Burrow fill similar to the host rock.

Remarks: *P. bolbiterminus* is characterized by terminal bulbs that are hemispherical to hemieliptical, resembling the cap of a button mushroom (Kim *et al.* 2000). From the Indian subcontinent, it is earlier reported from Early Cambrian of Tal Formation (Desai *et al.* 2010). It is interpreted to be passively filled dwelling structure (Kim *et al.* 2000).

Phycodes palmatus (Hall 1852) (Figure 5d)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh 111, 131, 132, 135

Description: Endichnial, full relief preservation of burrows that are horizontal to inclined to bedding plane. Burrows are branched, straight, or slightly curved; occasionally tube may contain lamina forming spreite structures. Tubes are convexo-convex to oval in cross section with width greater than height, diameter of the tube ranges from 22–28 mm while height of the tube ranges from 11–16 mm. Burrow fill identical to matrix.

Remarks: *P. palmatus* is characterized. These trace fossils are considered as deposit feeding, back-filled tunnels made by arthropods (Chamberlain 1977). They have been earlier reported from Early Cambrian shallow marine quartzite from Sankholi Formation exposed at Nigalidhar syncline of the Himalayas (Desai *et al.* 2010).

Planolites beverleyensis (Billings 1862) (Figure 4h)

Material: PDP/PU/SPT/IL/BGD/Jaisal/142, 108

Description: Endichnial tubular burrow, simple, straight to curved, unlined, unbranched, smooth walled, oriented horizontal to the bedding plane. Tubes are cylindrical in cross section. Burrow fill similar to host rock.

Remarks: *Planolites beverleyensis* differs from other species of *Planolites* in that tube diameter is larger and the tube is more gently curved. It reflects active back filling by deposit feeding activity of the trace maker.

Rhizocorallium isp. (Figure 5a)

Material: PDP/PU/SPT/IL/BGD/Jaisal/28 and field photograph

Description: Epichinally preserved, full relief, horizontal to slightly inclined, small 'U' shaped trace with well-developed spreite and poorly developed marginal tube. Width of spreite varying from 3–6 mm, with spreite thickest in the middle. Width of the U is 2.3 cm.

Remarks: The specimen is moderately preserved, with poorly developed marginal tubes. This is interpreted to be deposit feeding burrow.

Rosselia rotatus (McCarthy 1979) (Figure 5b)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh 140

Description: Endichnial, vertical to inclined, lined, straight to curved, funnel shaped burrows with crescentic to near circular backfill structures on the funnel wall. In vertical section the burrow appears as wide 'V'. The bedding plan view of the burrow is elliptical to elongate in shape with minimum diameter of about 25 to 30 mm. The centre of the circular structures shows pattern of rotational movement of the burrow. Diameter of the central tube ranges from 10 to 13 mm.

Remarks: In horizontal plane, *R. rotatus* is characterized by concentric rings with eccentricity

placed central tube indicating rotational movement of the burrow along the central axis. In contrast the concentric rings of the *R. socialis* shows systematic concentric layering with centrally placed tube. The rotational movement of the burrow along the central axis is absent in case of *R. socialis*. The actual morphology of the *Rosselia* is spindle-shaped and only the funnel-shaped preservation of the trace suggests that upper part of the trace might be eroded away (Nara 1997; Frieling 2007). The trace fossils were earlier described from Permian shoreface environment (McCarthy 1979). Trace fossils are interpreted as formed by activity of suspension feeding organism.

Rosselia socialis (Dahmer 1937)
(Figures 5c and 3d–ii)

Material: PDP/PU/SPT/IL/BGD/Jaisal/Bh16, 150, 151, 154

Description: Endichnial burrow, oriented vertical to slightly inclined, lined, straight, conical to bulbous in shape with crescentic to near circular backfill structures in cross section. In vertical section the burrow appears as wide 'V'. The bedding plan view of the burrow is circular to elliptical with diameter ranging from 25 to 40 mm. The centre of the circular structures shows pattern of rotational movement of the burrow. Diameter of the central tube ranges from 12 to 15 mm.

Remarks: The Ichnogenus, in Jaisalmer Basin is represented by two species *R. rotatus* and *R. socialis*. Former is characterized by distinct pattern of rotational movement of the funnel burrow, while *R. socialis* is characterized by systematically concentric nature of central areas. The trace fossil is interpreted to be the work of suspension feeding organisms and the preservation of only funnel shaped forms indicates that the upper part of the fossil might be eroded away (Nara 1997; Frieling 2007).

Teichichnus rectus (Seilacher 1955) (Figure 5e, h)

Material: PDP/PU/SPT/IL/BGD/Jaisal/106, 128, 129

Description: Endichnial, full relief burrows, horizontally oriented, unbranched with convex lamina and tube, forming retrusive spreite. The burrow diameter ranges from 14–18 mm. Lamina are thick, simple convex up and gutter shaped.

Remarks: Based on the retrusive nature and simple gutter shaped morphology of lamina, the present specimens can be safely placed under *T. rectus*. These traces are interpreted to be feeding

Figure 5. Trace fossils from the Kolar Dongar Member (scale bar equals 2 cm). (a) Small *Rhizocorallium* with well-developed spreite. (b) Bedding plan view of *Rosselia rotates* showing elliptical to elongate nature of backfill structures. (c) Dense *Rosselia socialis* showing in circular outline of the burrow with circular and concentric outline of the burrow. (d) *Phycodes palmatus* showing branching nature of the tubes. (e) Horizontal and unbranched *Teichichnus rectus* showing retrusive nature of spreite in cross section. (f) Full relief *Teichichnus rectus* burrow. (g) Cross section of *Teichichnus rectus* showing thick vertical shifting of the spreite. (h) *Teichichnus rectus* with characteristic simple gutter shaped lamina.

structures. It is earlier reported from Jara dome (Desai *et al.* 2008). *T. rectus* is also reported from Bhuan Formation of Surma Group by Tiwari *et al.* (2011).

5. Ichnofabric analysis

Ichnofabric analysis of the Kolar Dongar Member was done following recommendations of

Taylor *et al.* (2003). Five distinct ichnofabrics are recognized from the study area and are summarized in table 3.

5.1 Ichnofabric 1: *Ophiomorpha* 1 ichnofabric with syn-sedimentary faulting

The ichnofabric (figure 6) occurs in calcareous siltstones and shales containing basal part of the section (i.e., Bed No. 1–3). Sediment characteristics vary from fine to very fine grained silt size particles with dominantly plane bed laminations. Some of the cross sections across the plane bed laminated siltstone show small scale synsedimentary normal faulting and micrograben. The top surface of the beddings has occasional ferruginous nodules and layers. Based on the ichnofabric characteristic listed in table 3, the type of colonization represented by shallow to deep tier mixed deposit and suspension feeding community may represent multiple colonization events. The tier seems to represent replacement of the suspension feeding community by deposit feeding community. The presence of plane bed laminations indicates deposition of sediment under upper flow regime conditions (Reineck and Singh 1980). Such upper flow regime conditions are primary causes for high rate of sediment transport and high suspended load conditions. The traces of suspension feeding organisms like *Ophiomorpha*, *Palaeophycus* and *Laevicyclus* are also made in similar type of conditions with high rate of sedimentation and high suspended load (Patel and Desai 2001). These traces signify the work of motile, burrowing, suspension feeding epifauna burrowing in soft ground. The presence of syn-sedimentary faulting indicates that such a deformation develops as a result of cohesive nature of the sediments especially when the grain to grain packing is established soon after the liquefaction processes. Soft sedimentary deformation structures are also possible in the shallow marine conditions on account of wave pounding; however such wave pounding may not be able to produce faulting. Similar syn-sedimentary fault associated with liquefaction due to earthquake was studied from the recent sediments of the Mandvi intertidal zone in the Gulf of Kachchh (Desai and Patel 2004). Therefore the possibility of paleoseismic events influencing the changes in the substrate conditions (Desai and Patel 2004) are higher. Thus changes in substrate conditions along with flow conditions may be responsible for replacement of the suspension feeding community by a deposit feeding one. One of the major factors governing the change in feeding community is substrate as well as flow conditions. High energy of the flows will keep the organic matter food

particles in suspension enabling the settlement of suspension feeders. For example, the middle tier *Gyrochorte*; *Rhizocorallium* (passichnia and fodichnia) and deep tier *Ophiomorpha* (domichnia) are known as traces made by opportunistic organism capable of living in high energy conditions. Changes in the substrate type and lower energy flow conditions (in comparison to above-discussed conditions) will lead to settlement of the food particle aiding mobile deposit feeders, like trace makers of *Planolites*, to settle in soft ground. Such a type of mixed colonisation and dominance of trace fossils indicates deposition of the sediment in lower shoreface marine conditions, where the disturbance caused by the fair-weather wave base may be responsible for environment suitable to both suspension and deposit feeding organisms.

5.2 Ichnofabric 2: *Ophiomorpha* 2

This ichnofabric occurs in calcareous siltstones and shales of bed nos. 4–8 (figure 6). The primary sedimentary structures are upper flow regime plane laminations. The ichnofabric is similar to the earlier ichnofabric (Ichnofabric-1) but lacks ferruginous layers and synsedimentary faulting. Reduction in the diversity of trace fossils is also seen, while tiering style is represented by simple tier with multiple colonisations by organisms. The *Ophiomorpha* and *Palaeophycus* occupy the deep tier, whereas, *Planolites* and *Gyrochorte* occupy mid and shallow tiers, respectively. The continuance of certain trace fossils common to previous ichnofabric indicates that, the previous opportunistic, suspension feeding community continued to bioturbate the substrate. Changes in either substrate conditions or depositional environment might have led to elimination of specific substrate or depositional environment preferring organisms and as a result only opportunistic and pioneering species might have survived. Reduction in the ichnological diversity and bioturbation indices was also documented from tidally modulated shorefaces, especially during the transition from lower shoreface to upper shoreface conditions (Dashtgard *et al.* 2009). The dominance of plane bed laminations also indicates high energy conditions. Based on the tiering, nature of the opportunistic trace fossils and primary sedimentary data, the ichnofabric represents soft ground substrate condition of upper shoreface depositional environment (figure 6).

5.3 Ichnofabric 3: *Ancorichnus* ichnofabric

This ichnofabric occurs dominantly in shale with thin siltstones of bed nos. 9 and 10 (figure 6).

Table 3. Summary table of the different ichnofabric found in Tithonian sediments of Jaisalmer Basin (BI = Bioturbation index, BPBI=Bedding plane bioturbation index, D = diversity).

Sl. no.	Ichnofabric	Definition	Trace fossils	BI	BPBI	D	Colonisation style
1	<i>Ophiomorpha</i> 1 with syn-sedimentary faulting	Moderately bioturbated siltstones with <i>Ophiomorpha</i> along with syndimentary faulting	<i>Ophiomorpha</i> , <i>Paleophycos</i> , <i>Laevicyclus</i> , <i>Gyrochorte</i> , <i>Rhizocorallium</i>	3	3 (25–40%)	6	Multiple colonization, complex tier with shallow to deep tier mixed suspension feeding community replaced by deposit feeding community. Substrate represented by soft ground and firm ground?
2	<i>Ophiomorpha</i> 2	Sparsely bioturbated siltstone with <i>Ophiomorpha</i>	<i>Ophiomorpha</i> , <i>Planolites</i> , <i>Paleophycus</i> , <i>Gyrochorte</i>	2	2 (10–25%)	4	Single colonization, simple mixed tier, dominated by suspension feeding community, soft ground substrate.
3	<i>Ancorichnus</i>	Moderately bioturbated siltstones with <i>Ancorichnus</i>	<i>Ancorichnus ancorichnus</i> , <i>Jamesonichnites</i> ; <i>Imponoglyphus</i>	3	3 (25–40%)	3	Single colonization, shallow to middle tier, active, mobile deposit feeder community, soft ground substrate.
4	<i>Ancorichnus</i> – <i>Rosselia</i>	Highly bioturbated siltstones dominated with <i>Rosselia</i>	<i>Ancorichnus ancorichnus</i> , <i>Gyrochorte comosa</i> , cf. <i>Jamesonichnites heinbergi</i> , <i>Imponoglyphus kevadiensis</i> , <i>Laevicyclus mongraensis</i> , <i>Monocraterion tentaculatum</i> , <i>Planolites beverleyensis</i> , <i>Rosselia rotates</i> , <i>Rosselia socialis</i> , <i>Conichnus conicus</i>	4	3 (25–40%)	10	Multiple colonization, complex tier, mixed feeding strategies, soft ground substrate.
5	<i>Teichichnus</i>	<i>Teichichnus</i> dominated bioturbated siltstones	<i>Phycodes palmatus</i> , <i>T. rectus</i>	5	4 (40–60%)	2	Single colonization, continuous aggradation, opportunistic deposit feeding community, soft ground substrate.

Thus the ichnofabric indicates its development in lower offshore depositional environment.

The ichnofabric is characteristically developed in highly bioturbated siltstones with intercalated shales in bed nos. 11 and 12 (figure 6). This ichnofabric shows marked increase in degree of bioturbation and diversity of trace fossils. The trace fossils show mixed feeding and dwelling strategies. The meniscated burrows like *Ancorichnus*, *Jamesonichnites* and *Imponoglyphus* continue to be abundant. *Rosselia*, in contrast, represents the work

of shallow-passive suspension feeder organism. Together, these traces occupy shallow tier traces; deep tier traces are represented by *Laevicyclus* and *Monocraterion* all representing the work of motile suspension feeder, while *Planolites* represents active backfilling by deposit feeding organisms. The presence of *Conichnus conicus* indicates escape structures. The ichnofabric is interpreted to have been formed in intermediate to low energy conditions with mixed population of deposit and suspension feeding. Based on the nature of the ichnofabric, and associated trace fossils, the depositional conditions of beds 11 and 12 represent near shelf environment.

5.4.1 Ichnofabric 5: *Teichichnus* ichnofabric

The *Teichichnus* ichnofabric occurs in the siltstones and sandstone and in bed nos. 13 and 14 (figure 6). The sandstones are fine-grained with calcareous matrix, while siltstones are very fine grained in nature. Trace fossil assemblage consists of dominance of morphologically similar traces. These are common *Phycodes palmatus*, and abundant *T. rectus*. The sediments are almost completely churned out and no tiering levels are visible. *Teichichnus* are made by opportunistic deposit feeders and hence their low diversity and low ichnogenic abundance indicates a shallow depositional environment which is usually rich in organic matter, probably brackish bay environment (Gerard and Bromley 2008). Similar low diversity *Teichichnus* ichnofabrics that are indicators of brackish bay environment have earlier been reported by many researchers, including (Benyon and Pemberton 1992; De Gibert and Martinell 1998, Bromley and Uchman 2003). Thus the beds associated with *Teichichnus* ichnofabric indicate brackish bay environment.

6. Discussion and conclusion

The Tithonian sediments of the Jaisalmer Basin were studied for the basin's ichnological and ichnofabric analysis. Based on the earlier published ammonite data and lithological correlation, the present studied section can be correlated with Communis biozone to *Desniplicatus* ammonite biozone of Tithonian age (Pandey and Krishna 2002). These Tithonian sediments belonging to Kolar Dongar Member are continuously exposed in surface as well as subsurface. Based on the analysis of surface and subsurface combined data, a high energy stacked shoreface aggradational depositional environment is interpreted (Singh 2006). In the outcrop, the entire formation (Baisakhi-Bhadasar), particularly the

younger part of Bhadasar Formation indicates coarsening and thickening upward trend in sandstones topped by thick massive sandstones belonging to Mokai Member, while the studied lower part indicates rapid sea level changes. Recently, a Late Tithonian age was suggested for the Kolar Dongar Member based on the discovery of Late Tithonian index ammonite of genus *Himalayites* (Jain and Garg 2012). According to Jain and Garg (2012), the recent findings of *Himalayites* ammonites from Jaisalmer and its other published occurrences in coeval late Tithonian sediments of rest of the Indian subcontinent (Kachchh, Jaisalmer and Himalaya) suggested a time of rapid sea level rise, facilitating opening of new sea way connections during latest Tithonian. The published data on ammonites also supplement our findings of rapid/high frequency sea level changes in basal part of Kolar Dongar Member. Studies from adjacent Kachchh basin from the coeval sediments of 'Umia Ammonite bed' (Pandey *et al.* 2012) or Upper Member of Jhuran Formation (Desai *et al.* 2008) also point towards similar rapid changes in sea level during the Tithonian. Ichnological analysis of Tithonian sediments of Kachchh from Upper Member of Jhuran Formation indicates high frequency of the sea level changes along with fluctuation of bottom water oxygenation (Desai *et al.* 2008).

Ichnologically, rapid sea level changes will leave overprinting of the traces formed by one community over traces of another community. Desai and Patel (2008) provided a model to understand the effect of sudden or gradual change in environment either due to tectonic or eustatic changes on trace fossil community. According to Desai and Patel (2008) model, the sudden shift of the environment, i.e., sudden regression or uplift in the subtidal environment will lead to retention of certain stress tolerant communities only, leading to the decrease in bioturbation and dominance of r-selected traces. On the contrary, sudden subsidence/transgression will cause sudden increase in bioturbation and overprinting of K-selected traces over the r-selected traces. In the present case, the transition from Ichnofabric-1 to Ichnofabric-2 shows (a) retention of stress tolerant community of r-selected trace fossils (*Ophiomorpha*) and (b) decrease in bioturbation and diversity of trace fossils (table 3) indicating regression of the sea level. On contrary, the transformation from Ichnofabric-2 to Ichnofabric-3 (IF-3) shows change from multiple colonization to single colonization and along with replacement of suspension feeder traces by mobile deposit feeder traces indicates transgression of sea level. Ichnofabric-4 indicates diversification of trace fossils from the previous ichnofabric (IF-3) along with changes in colonization style

and increase in bioturbation index and diversity. The transition of IF-4 to IF-5 shows a sharp change in trace fossils with dominance of opportunistic trace fossils showing high bioturbation and low diversity indicating return to near-shore brackish water depositional environment. Such frequent changes in deposition environment without any significant break in sedimentation are interpreted as high frequency sea level changes. In Kachchh basin, high frequency sea level changes are envisaged based on several published records including two factors namely (1) systematic ichnological data and (2) systematic shell bed analysis. Ichnological data indicates that the sequence commenced with moderate diversity *Planolites*–*Palaeophycus* ichnoguild followed by diverse ichnoguild of representing shelf assemblage, e.g., *Taenidium*, *Nereites*, *Helminthopsis*, *Chondrites*, and *Phycosiphon*, etc., followed by a low diversity, high individual density, shallow tier ichnotaxa of *Palaeophycus* and *Planolites* (Desai *et al.* 2008). The shell bed analysis data published by Fürsich and Pandey (2003) revealed that these coeval Tithonian sediments of Kachchh were deposited in a Transgressive System Tract with a maximum flooding surface at the top of the member (Umia Ammonite Bed). Sedimentologically, Bose *et al.* (1988) also interpreted transgressive–regressive couplet for the sediment deposited during Tithonian time.

The Jaisalmer Basin had also experienced several episodes of high frequency/rapid sea level changes during the Middle Jurassic. The deposition of the Jajiya member (Oxfordian) also witnessed similar rapid sea level changes. All together four transgressive system tracts (TST) and five high stand system tracts (HST) were recorded from 10 m section by Pandey *et al.* (2010). The detailed ichnofabric analysis from the Tithonian sediments of Jaisalmer Basin also reveal similar events of sea level changes. These trace fossils and resulting ichnofabric analysis from the present study, are grouped into five characteristic ichnofabric namely Ichnofabric 1: *Ophiomorpha* 1 ichnofabric with syn-sedimentary faulting; Ichnofabric 2: *Ophiomorpha* 2; Ichnofabric 3: *Ancorichnus*; Ichnofabric 4: *Ancorichnus*–*Rosselia*; Ichnofabric 5 *Teichichnus*. The Ichnofabric 1 and 2 indicate a high energy shore face depositional environments. This view is again supported by dominance of *Ophiomorpha nodosa* trace fossils which indicate that these three-dimensional networks were built in high energy shifting sands (Patel and Desai 2009). The overlying Ichnofabric 3 comprises dominantly of *Ancorichnus ancorichnus*. During the Jurassic periods, *Ancorichnus ancorichnus* is considered to be a robust indicator of shelf environment ranging from inner shelf to outer shelf (Keighley

and Pickerill 1994). The mixing of *Rosselia* and *Laevicyclus* in overlying IF-4 suggests that it was a mixed colonisation involving deposit and suspension feeding organisms. Such conditions are indicators of shelf environment near the storm wave base, where storm conditions lift the sediment in suspension favouring the colonisation of suspension feeding organism (Frey 1990). The youngest IF-5 is typically an impoverished marine assemblage with dominant low diversity deposit feeding traces dominated by *Teichichnus*. This indicates a brackish water depositional environment. Thus, the detailed analysis of the five ichnofabric (figure 6) indicates short term, rapid fluctuation in sea level changes during the latest Tithonian. Thus, the interpretation of high frequency sea level changes in Jaisalmer Basin, based on ichnofabric data indicates that the sea level changes were consistent among the regional basins including Kachchh basin.

Based on the stratigraphic mapping and biostratigraphic correlation based on collected fossil contents, the studied section was correlated with the published literature of Pandey and Krishna (2002) for Tithonian biostratigraphy for Kolar Dongar Member (= Bhadasar Member). The Ichnofabric 1 (*Ophiomorpha* 1 ichnofabric with syn-sedimentary faulting) co-relatable subfrequent subzone (Communis Zone) indicates its deposition in high energy conditions typically of lower shoreface marine conditions. The overlying IF-2 corresponding to lower and middle part of *Densiplicatus* subzone, indicates high energy conditions of upper shore face depositional environment. The overlying two ichnofabrics (*Ancorichnus* and *Ancorichnus*–*Rosselia* Ichnofabric) with upward increase in diversity of trace fossils indicates deposition of sediment in lower offshore to inner-shelf environment, corresponding to upper part of *Densiplicatus* subzone. The overlying sediments with Ichnofabric-5 corresponding to *Oppeli* subzone indicate brackish bay environment for the deposition of sediment. Thus, Kolar Dongar Member belonging to Tithonian age indicates fluctuating depositional environment ranging from lower shoreface to upper shore face to shelf and finally to brackish bay environment.

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