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Trace Fossils and Sedimentary Depositional Environment: A Case Study from Early Permian Barakar Formation, Raniganj Basin, India

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Abstract

Behavioral responses of organisms with respect to changing environment have a wide area of research possibility. For a palaeontologistit is a challenge to interpret the organism-sediment interaction from the study of the trace fossils preserved in the ancient rock record. Theethological significance which is derived out of different intentional or accidental activities of the organisms may be preserved within the rock and is largely controlled by the substrate stability, grain size of the sediments, energy and rate of sedimentation of the driving process, typesof nutrients and its supply, salinity, temperature and oxic/sub-oxic/an-oxic conditions etc.So, the viability of this study insensustricto depends on the preservation potential of the organism as a whole or in parts or its activities (indirect evidences) on or within the substrate upon which they have survived thousands and millions of years ago. The indirect evidences of the organism's activities may beits locomotory/respiration/feeding/resting/dwelling/predating traces etc. which have different nomenclature based on their morphological classification.The study area encompassing the major river section of the Barakar, Khudia, Ajoy holds partly enriched and partly impoverished trace fossils within the sedimentary rocks hosting huge reserves of coal. There are several concepts regarding the depositional setting of the studied basin likeformerly interpreted fluvio-lacustrine depositional model to recently reinterpreted fluvio-tide-wave dominateddepositional model.Several invertebrate traces have been recorded from the study area namely *Planolites*, *Thalassinoides*, *Ophiomorpha*, *Palaeophycus*, *Cylindrichnus*, *Diplocraterion*which indicatesdiverse environmental settingsranging from supratidal/intertidal/subtidal to continental shelves whereasother solo/uniform traces observed like *Chondrites*, *Skolithos*,*Rhizocorallium*etc. are indicator of shallow subtidal to marine quite water setting. Here the additional challenges include the lack of ample exposures, weathered exposed rock sections, inaccessible mine cut sections, absence of body fossils and controversial identification of trace fossils in differential erosive surfaces. This chapter in short has tried to mitigate these problems by the integrated sedimentary and ichnological facies association studies indelineating the depositional environment of the studied basin.

Keywords: Barakar Formation, Raniganj basin,trace fossils, sedimentary facies, depositional environment.

1. Historical Background

Sedimentary rocks may hold record of organism activities in the form of burrows, trails, tracks, boring etc. As a result, the study of the trace fossils thereafter evolved looking into the different aspects on the behavioral pattern of the trace makers and trace fossil assemblage with response to different sedimentary depositional setting. For an ichnologist (a special branch of palaeontology) it is a challenge to interpret the organism-sediment interaction from the study of the trace fossils preserved in the ancient rock record. Sediments are bioturbated for numerous reasons and among various types of bioturbations, burrows are the prime topic of discussion in this chapter. Organisms may produce traces intentionally or accidently, for suspension/deposit/surface feeding, dwelling, resting, respiratory, ploughing, escaping processes etc. [1]. However, traces produced by burrowing for protection is also very common where sediments may shield the organism's giving protection from the predators [1]. The ichnological study since its inception bears two-fold manifestations in respect of biology and sedimentology [2]. There is distinct sedimentological, morphological, biological and other physico-chemical contrast between burrows within softground, looseground, soupground, firmground and hardground where organisms accustomed to a particular habitat may not survive in different one [1,2]. The tendency of assessing paleo-depositional environment with the aid of ichnology is much older and examples of interpreting trace fossils for entitling the sedimentary succession of Apennines by Leonardo da Vinci as marine may be cited [3]. These biogenic structures have been classified as toponomically – in connection with preservation within the substrate, biologically – in connection with the responsible organism, ethologically – in connection with organism's behavioral response and systematically – in connection with morphology[4]. So, the concept and modern methodology on the ichnology/trace fossil study has started taking its shape from 1950s and 1960s and after that many modifications have been made into the classification system [5,6]. Among these four classifications only the systematically one is known as ichnotaxonomy and is used for providing names to these biogenic activities [2].Initially, the standardized terminology was used[7] for describing a trace fossil and subsequent development was seen in the manuscript of many workers [8,9,10].Recent development ofichnological studies have penetrated the limit of facies interpretation, palaeo-environmental reconstruction, identifying discontinuities and prospecting and exploring hydrocarbon resources [2].Ichnologist, who works with the trace fossils must pay attention during diagnosis at places where the absence of body fossils imparts partial knowledge about the trace making organisms. Vertebrates are not as sensitive as invertebrates to environmental conditions [11,12], and their behavioral traits preserved as traces (e.g., trackways) cross environments with different physicochemical characteristics.Sedimentary processes that lead to the formation of sedimentary rock record simultaneously affect the biological remnants (both fossils and trace fossils) [2] and so the substrate properties determining different habitat of organism is of outmost importance [13]. There are several concepts regarding the depositional setting of the Barakar Formation, Raniganjbasin, India,from formerly interpreted as fluvio-lacustrine depositional setting[14-21]to recently reinterpreted fluvio-tide-wave dominated depositional model [22-29]. The sedimentary rocks of Barakar Formation from other basins of India hosts evidences of trace fossils [30-33]. Since the above mentioned sedimentary depositional setting of the recent study reflect a mixed fluvio-estuarine environment [34]reassessment of the inferred model from ichnological point of view seems essential.

2. General Geology of the Study Area

The Raniganj basin in the eastern part of peninsular India within Son-Damodar Valley lineament which hosts approximately 2000 meters thick rock successions of lower and upper Gondwana supergroup [35]. The study area of Barakar Formation, Raniganj Basin, India encompassing the major river section of the Barakar and Khudia and few mine cut sections (Figure 1) holds partly enriched and partly impoverished trace fossils and imprints of some Gondwanan flora (lower Permian) within the sedimentary rocks hosting huge reserves of coal.The E-W trending southern boundary fault of Raniganj basin extends between Panchet hill in the west to Andal in the east. This fault is normal fault produced by rifting [36] is responsible for the development of half-graben type basin for which the thickness of the basin increases towards south. Apart from this, intrabasinal growth faults [37,38] formed during the process of sedimentation is evident by sudden appearance of coarser sediments, splitting of the coal seams across faults etc. within this basin. There are several concepts regarding the depositional setting of the studied basin like formerly interpreted fluvio-lacustrine depositional model [14-21]to recently reinterpreted fluvio-tide-wave dominated depositional model [22-29]. The lower Barakar is characterized by alternate sandstone-shale-coal with finer clastics predominates in the upper part of the Barakar Formation [27,28].

3. Sedimentary Facies

Along with the study of trace fossils understanding the sedimentary facies and stratigraphy is also essential. A single or multiple distinctive sedimentary rock bed/ beds formed under certain conditions, reflecting particular process is known as sedimentary facies [39]. The lithofacies of the study areas are classified on the basis of bulk composition of the sediments where the dominant sedimentary structures, bed dimension, geometry, palaeocurrent directions, bed contacts and alternating coal horizon have become the benchmark for the characterization of different facies. The sedimentary facies observed here are (i) channel-fill cross-bedded sandstone facies (F1), (ii) trough cross-stratified sandstone facies (F2), (iii) massive to faintly laminated sandstone facies (F3), (iv) plane-parallel laminated sandstone facies (F4), (v) planar cross - stratified sandstone facies (F5), (vi) ripple laminated sandstone facies (F6), (vii) hummocky cross- stratified sandstone facies (F7), (viii) wavy-laminated siltstone-mudstone facies (F8), (ix) heterogeneous mudstone-siltstone facies (F9), (x) laminated mudstone facies (F10), (xi) lenticular laminated siltstone-mudstone facies (F11) and (xii) coal facies (F12).

4. Systematic Ichnology

The rock samples collected from the study area showing abundant traces are cut by rock cutting machine which is then polished and scanned for better identification. The photographs used in this chapter are either actual field photographs or aforesaid scanned photographs. Within the Barakar Formation, Raniganjbasin several invertebrate traces have been recorded from the study area namely *Planolites*, *Diplocraterion*, *Skolithos*, *Palaeophycus*, *Rosselia*, *Rhizocorallium*, *Thalassinoides*, *Ophiomorpha*, *Chondrites*, *Cylindrichnus*ichnotaxons. The traces that are obtained within the study area are seen to be concentrated within some particular horizons, especially in F6, F8, F9, and F11. But its maximum concentration is seen within F8 and F9. The identification and figure of these ichnotaxons is represented in Table 2 and Figure 2.

5. Discussion

The sedimentary rocks as observed from the upstream towards downstream of the Barakar and Khudia Nala sections show characteristic changes. So, the sedimentary facies are grouped into four facies associations based on textures, structures, geometry, palaeo-current indicators and lateral facies transition and position of the facies on the dip-oriented transact downdip.

The basal part of the Barakar Formation begins with the coarse-grained channel filled pebbly sandstone units representing fluvial channel facies association (FA-1). Whereas the upper part is characterized by tidal sand bar facies association (FA-2). In each sequence the thickness of individual bed decreases upward and is in the range of millimeter scale alteration. Tidal flat facies association (FA-3) is constituted of tide dominated sedimentary facies which include siltstone-mudstone heteroliths, lenticular wavy laminated siltstone-mudstone facies. Heterogenous mudstone-siltstone facies, wavy laminated siltstone-mudstone facies and hummocky cross-stratified sandstone facies characterize most of the upper Barakar Formation and is represented as central estuary facies association (FA-4). The interpretation of the depositional environment on the basis of sedimentary facies association characterizing the Barakar Formation, Raniganj basin, India is given in Table 1.

Similarly, depending upon the presence of the trace fossils within different lithounits they are broadly clubbed into three ichnofacies assemblages viz. IFA 1, IFA 2 and IFA 3. The interpretation from the ichno-assemblage studies may indicate the palaeo-environmental condition [40,41,42]. Hence, Table 2. is constructed to analyze the environmental settingafter proper identification of the ichnofaciesandstudying their ichnofacies-assemblages.

This integrated sedimentary facies association and icho-facies assemblages together reflects a depositional / environmental setting where there are ample noises of tide and wave. Looking into the sedimentary facies association where the FA-1 represent the lower part of the Barakar succession is ascribed as fluvial dominated sedimentation. The further up-sections are successively represented as sedimentation within tidal sand bar, tidal flat and central estuarine system.

Likewise, the ichno-facies assemblages viz. IFA 1, IFA 2 and IFA 3 are indicative of lower intertidal to shallow subtidal, permanently subtidal and intertidal to subtidal settings respectively.

The generalized sedimentary log of the Barakar Formation, showing sedimentary facies associations and ichnofacies-assemblages exposed along the Barakar river and Khudia Nala, Raniganj basin, India, is given in Figure 3. Now, after seeing the arrangement of the sedimentary facies associations with respect to the ichofacies-assemblage it could be narrated that the FA-1 is devoid of ichnofacies because of the higher energy, fresh water condition and less supply of organic detrital that it might have received further downstream by tide/wave action. But, further upward in the succession within tide/wave derived sediments depauperate and sometimes enriched ichnotaxons have been observed.

6. Conclusion

- The sedimentary rocks of the Barakar Formation, Raniganj basin, holds ample signatures of tide and wave, especially from the upper part of the Barakar succession. Likewise, report of such marginal marine activities within sediments of Barakar Formation from other Gondwana basins of India are also obtained[25,26].
- The trace fossils so obtained and their ichnofacies-assemblages signifies inter-tidal to sub-tidal setting. Similar representations are also obtained by the analysis of the trace fossils study from Barakar Formation of other Gondwana basins of India as well[30-33].
- The sedimentary facies coupled with the analyses of the ichno-facies assemblages recorded within the sedimentary successions of Barakar Formation, Raniganj basin, India, further strengthen the evidences of tide-dominated partly wave influenced associated with the fluvial sedimentation.

- After careful consideration of the variation of the processes inducing sedimentary structures and distribution of the ichnofacies-assemblages which are controlled by various factors like process operating, rate of sedimentation,variability of food etc. it may be concluded, that the Barakar Formation, Raniganj basin, was a part of tide-dominated estuarine setting.Similar tide dominated settings has been recorded during Carboniferous-Permian time from USA Midcontinent and are preserved within equatorial carbonate / siliciclastic cyclothems.

Table 1: Establishing the relationship between sedimentary facies, sedimentary facies association and sedimentary depositional environment of Barakar Formation, Raniganj basin, India[43].

Sl. No.	Sedimentary facies	Sedimentary facies Association	Sedimentary depositional environment
1	F1, F2, F3, F4,F10	Fluvial channel facies association (FA1)	The small-scale fining upward depositional units of dominantly cross-stratified sandstone with erosional and concave-up base indicate deposit within channels [44,45]. The scattered unidirectional palaeoflow pattern suggests meandering fluvial nature of the channel. Presence of basal pebble or granular clasts followed by cross stratification, parallel laminated sandstone and laminated mudstone within channel geometry is the results of high and low energy flow fluctuations of fluvial environment. Moreover, numerous erosive bases of episodic channel incision, palaeocurrent data indicates often shifting of the channel.
2	F4, F5, F11	Tidal sand bar facies association (FA2)	The sand / silt lenses, bi-directional cross-strata, reactivation surfaces, sigmoidal bedding indicates deposition from tidal currents with fluctuating current speed and direction [46-49].The heterolithic stratification and high mud content in the distal part of the tidal channel indicates lower energy conditions and suggests deposition along the flanks of the tidal channels [50]. Such bars are characteristics

			of seaward portions of most macrotidal environment [51,52,53]. The overall geometry and sediments indicate it to be a part of tidal sand bar.
3	F4, F6, F9	Tidal flat facies association (FA3)	The mm to cm scale cross strata bundles characterized by sandy foresets and mud drapes are interpreted as tidal bundles produced by migration of bedforms. Mud drapes indicate pause planes formed during slack water phases. Reactivation surfaces are the products of velocity asymmetry of tidal energy.Vertically accreted tidal bundles with planar laminated interbeds attest to the development in the upper intertidal-flat domain [54,55].Sandy ripple troughs with mud flasers signify periodic flow fluctuations in subtidal to intertidal zones [25,46]. Presence of combined flow ripples and association with other facies associations having combined flow signatures indicate that the wave ripples actually formed in tidal flat.
4	F8, F6, F4, F7	Central estuary facies association (FA4)	Wave dominated condition exists in the seaward flanks of the outer estuary [56,57]. The wave dominated part indicates open coast adjacent to an estuary[58,59]. Wave ripples forming the above wave base with flat topped and presence of ladder-back ripples suggest intermittent exposure of the rock so the rocks are of shallow coastal origin.The upper inter-tidal and supra-tidal parts of the tidal flats, with very low gradients and a muddy substrate, dampen storm waves significantly [60] and may preserve tide-generated structures under a thick cover of wavy or hummocky laminated deposit [61].

Table 2. Showing the observed ichnotaxons, their identification, ichnofacies assemblages and their environmental interpretation.

Ichnotaxons	Identification	Ichnofacies-assemblage	Environment
Ophiomorpha [62] (Figure 2H)	Ophiomorpha burrow may be horizontal / inclined or vertical lined with agglutinated pelletoidal sediments. Interiorly smoothly lined but mammilated exteriorly. It is a simple to complex burrow system [63] lined at least partially with agglutinated pelletoidal sediment [modified after 64].	IFA-1 Skolithos	Lower intertidal to shallow subtidal settings, tidal inlets and channels, sandy shoals and bars. [64,65,66]
Palaeophycus [67] (Figure 2E)	Essentially cylindrical, predominantly sub-horizontal, straight or slightly curved or slightly undulose, ornamented or smooth, branched or unbranched, lined burrows. Bifurcation is not systematic, nor does it result in swelling at the ramification points. The burrows do not wind or coil. Burrow filling typically massive, similar to host rock.		
Planolites [68] (Figure 2D)	Unlined, rarely branched, straight or tortuous, smooth or ornamented, irregularly walled or annulate burrows, circular to elliptical in cross-section, predominantly horizontal, but bedding penetrative. The dimensions and configurations are variable and the fill is essentially massive.	IFA-2 Cruziana	Permanently subtidal settings. [65,80,81]
Diplocraterion [69] (Figure 2A)	(After 76) “Vertical U-shaped spreiten burrows; dwelling burrows of suspension-feeders.”		
Cylindrichnus [70] (Figure 2G)	Vertical subcylindrical to subconical constitute of a central core and an exterior wall concentrically laminated. Circular to elliptical in		

	cross-section [77].		
Thalassinoides [71] (Figure 2C)	Commonly cylindrical to elliptical burrows of variable diameter forming three-dimensional network connected where vertical shaft connects to the surface. Burrows show T- or Y-shaped bifurcations and swellings at branches.		
Planolites Nicholson, 1873	Already mentioned above.	IFA-3 Skolithos-Cruziana	Intertidal to subtidal settings. [64,65,80,81]
Diplocraterion Torell, 1870	Already mentioned above.		
Rosellia [72] (Figure 2I)	Conical to irregularly bulbous or funnel shaped structures, vertical to horizontal, consisting either of a small central burrow surrounded by broad, concentric, cone-in-cone laminae, or of spreite-like helicoid swirls surrounding a cone, both tapering downward to a concentrically walled, subcylindrical stem. Interpreted as feeding structures of vermiform animals.		
Chondrites [73] (Figure 2B)	Branched tunnel system forming dendritic pattern consisting of fewer master shaft [78, 79].		
Palaeophycus Hall, 1847	Already mentioned above.		
Rhizocorallium [74] (Figure 2J)	U-shaped endichnial burrow, unbranched with protrusive sprietened burrow. Limbs more or less parallel and distinct; tube diameter / diameter of spreite>1:5 [after 76].		
Skolithos [75] (Figure 2F)	Straight tubes or pipes perpendicular to bedding plane, shafts parallel to each other. Burrow wall distinct or indistinct, smooth to rough, some specimens annulated.		

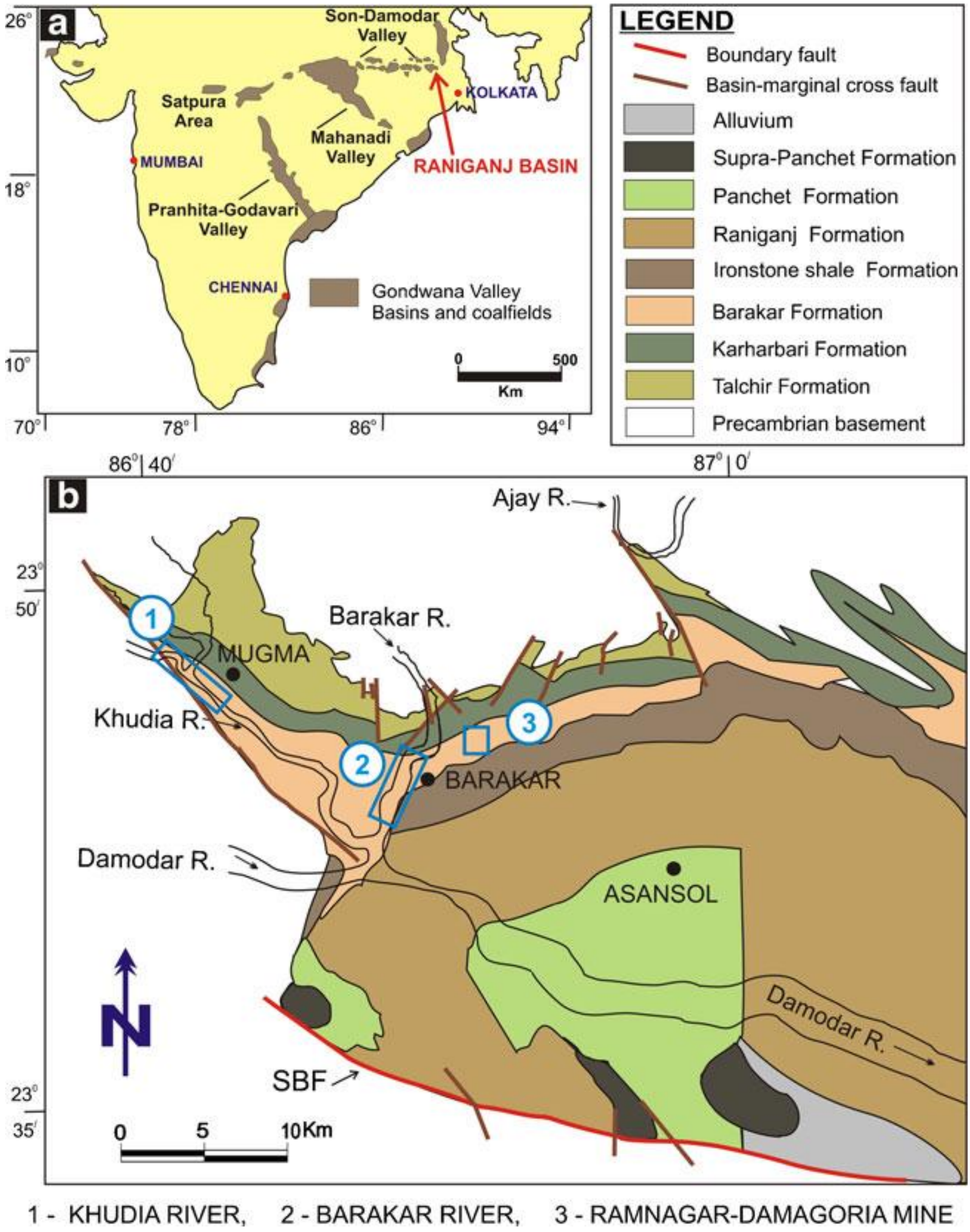

Figure 1. (a) Map of India showing distribution of Gondwana provinces in Peninsular India [modified after 82]. Note the location of Raniganj basin.
(b) Generalized geological map of the Raniganj basin [modified after 27,83]. The study areas are marked as 1: Khudia River, 2: Barakar River, and 3: Ramnagar–Chapatoria open pit area.

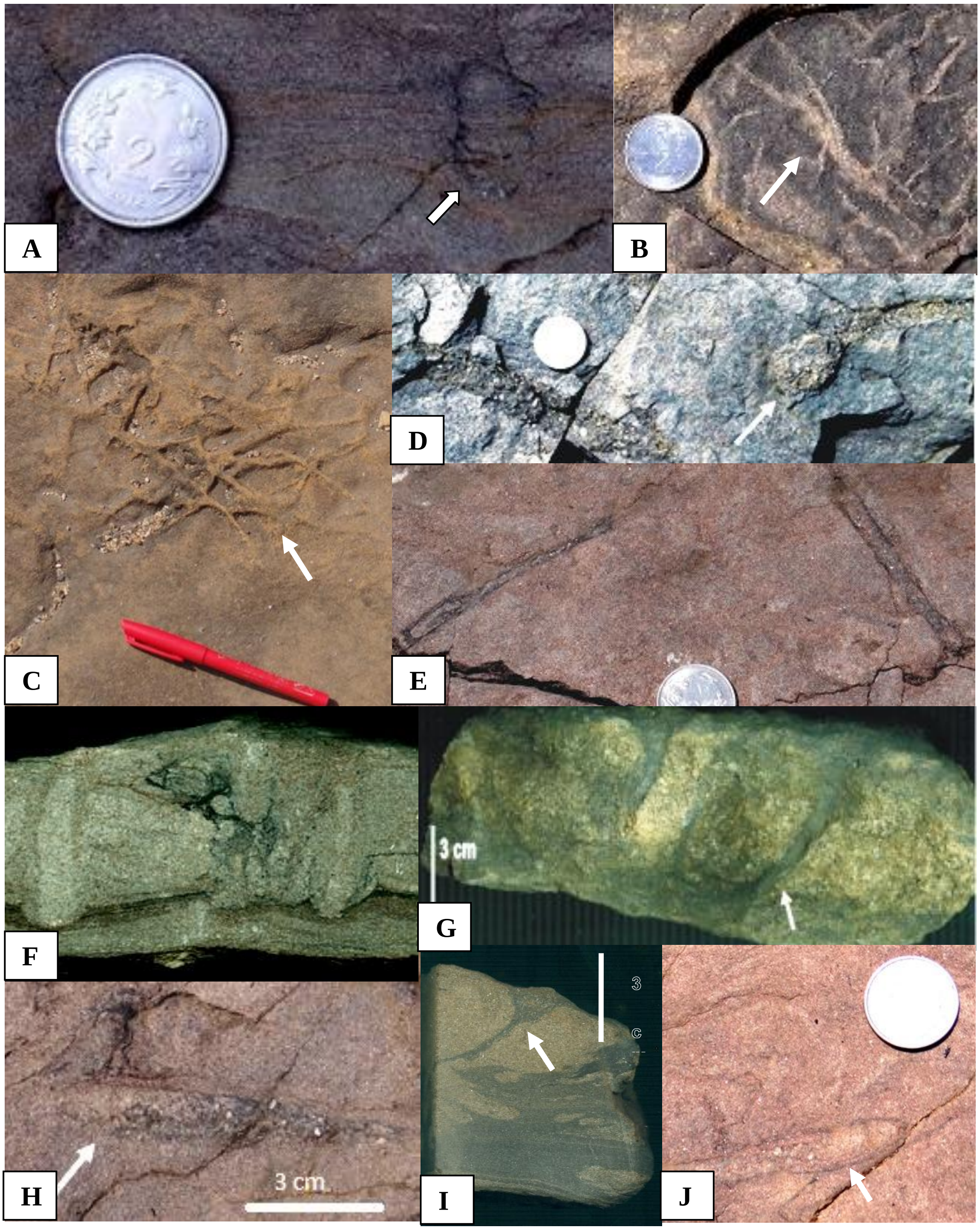

Figure2. Identified ichnotaxons from Barakar Formation, Raniganj basin, India. A – Diplocraterion, B – Chondrites, C – Thalassinoides, D – Planolites, E – Palaeophycus, F – Skolithos, G – Cylindrichnus, H – Ophiomorpha, I – Rosselia and J – Rhizocorallium.

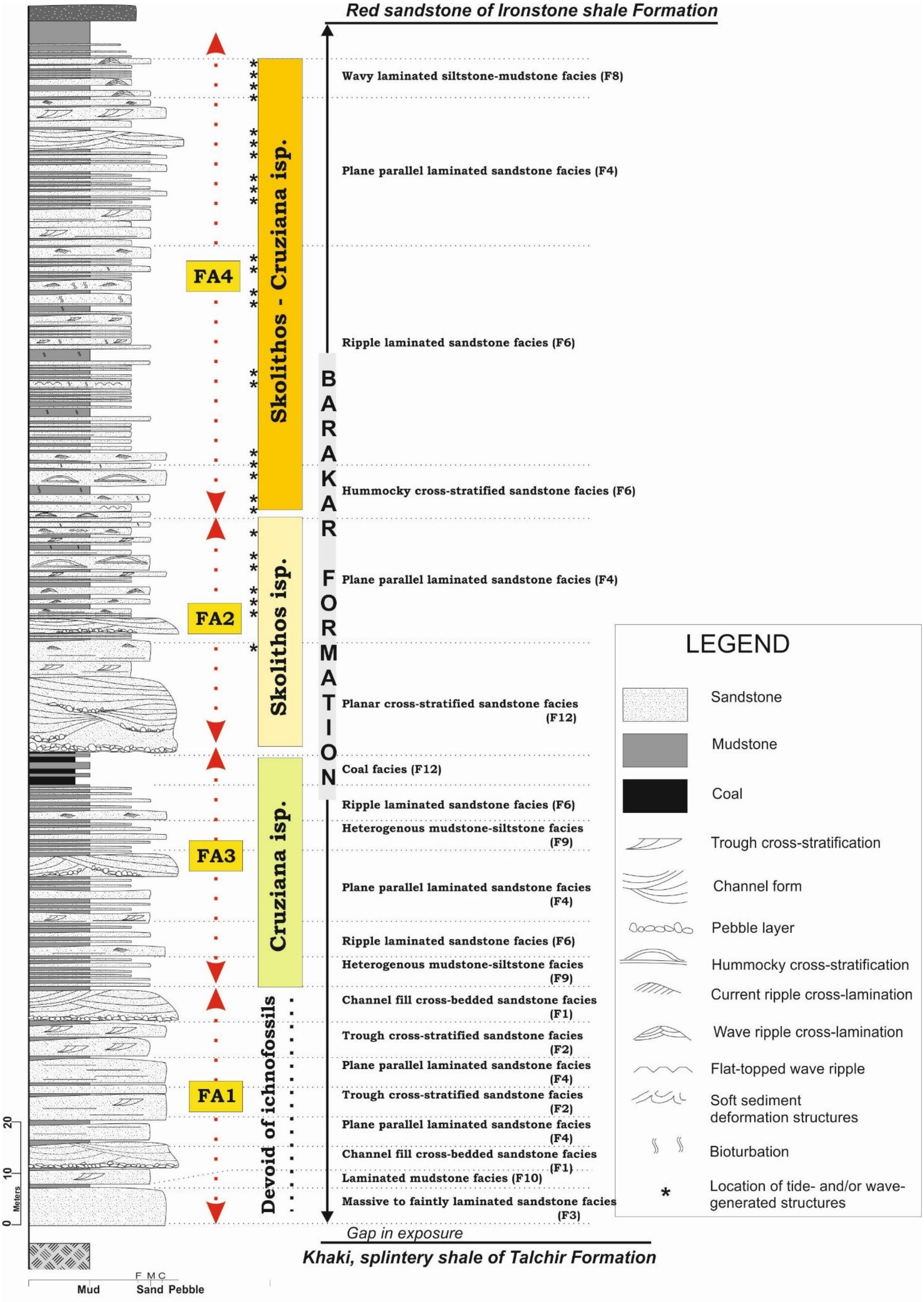
Red sandstone of Ironstone shale Formation
Wavy laminated siltstone-mudstone facies (F8)
Plane parallel laminated sandstone facies (F4)
Ripple laminated sandstone facies (F6)
Hummocky cross-stratified sandstone facies (F6)
Plane parallel laminated sandstone facies (F4)
Planar cross-stratified sandstone facies (F12)
Coal facies (F12)
Ripple laminated sandstone facies (F6)
Heterogenous mudstone-siltstone facies (F9)
Plane parallel laminated sandstone facies (F4)
Ripple laminated sandstone facies (F6)
Heterogenous mudstone-siltstone facies (F9)
Channel fill cross-bedded sandstone facies (F1)
Trough cross-stratified sandstone facies (F2)
Plane parallel laminated sandstone facies (F4)
Trough cross-stratified sandstone facies (F2)
Plane parallel laminated sandstone facies (F4)
Channel fill cross-bedded sandstone facies (F1)
Laminated mudstone facies (F10)
Massive to faintly laminated sandstone facies (F3)
Gap in exposure
Khaki, splintery shale of Talchir Formation
BARAKAR FORMATION
Skolithos - Cruziana isp.
Skolithos isp.
Cruziana isp.
Devoid of ichnofossils
FA4
FA2
FA3
FA1
0
10
20
Meters
Mud
F M C
Sand
Pebble
LEGEND
Sandstone
Mudstone
Coal
Trough cross-stratification
Channel form
Pebble layer
Hummocky cross-stratification
Current ripple cross-lamination
Wave ripple cross-lamination
Flat-topped wave ripple
Soft sediment deformation structures
Bioturbation
Location of tide- and/or wave-generated structures

Figure4. Generalized sedimentary log of the Barakar Formation, showing sedimentary facies associations and ichnofacies-assemblages exposed along the Barakar river and Khudia Nala, Raniganj basin, India.

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