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Palaeoenvironmental reconstruction based on palynofacies analysis of the Early to Middle Jurassic of the Lathi Formation, Jaisalmer Basin, India

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Twenty-four sedimentary samples collected from a succession of the Lathi Formation exposed near the Tamira Rai Temple, Jaisalmer Basin, western India, are subjected to palynofacies analysis for the palaeoenvironmental interpretations. Based on the quantitative composition of the various types of sedimentary organic matter, two distinct palynofacies associations (PF-I and PF-II) have been recognized, which are respectively reflecting over depositional settings in a proximal-distal suboxic-anoxic shelf and proximal oxic basin. The sediments are found rich in amorphous organic matter (AOM) through palynofacies analysis under the present investigation. PF-I is characterized by the dominance of AOM and sub-dominance of the opaque phytoclasts, and PF-II is dominated by the occurrence of the opaque phytoclasts. Dominant occurrence of the phytoplankton derived organic matter in the PF-I suggests its deposition in the marginal/shallow marine settings while the abundance of the opaque phytoclasts and rare presence of the phytoplankton-derived organic matter in PF-II suggests its deposition mainly in the continental settings. The present study suggests a marginal marine setting for the early phase of Lathi Formation contrary to the previous studies.

Keywords: Palynofacies, Sedimentary organic matter, Jaisalmer Basin, Lathi Formation, Depositional environment.

ARTICLE HISTORY

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INTRODUCTION

The stratigraphic study of the Mesozoic sediments of this basin has been carried out by several workers (Blanford, 1877; Oldham, 1886; La Touche, 1902; Ghosh, 1952; Swami Nath *et al.*, 1959 (See Singh, 2006); Narayanan, 1964; Rao, 1972; Das Gupta, 1975; Pareek, 1981, 1984; Krishna, 1987; Misra *et al.,* 1993 (See Singh, 2006); Singh, 2006; Bhandari, 1999). Lithostratigraphically, the Jurassic rocks are established in the form of Lathi, Jaisalmer (including Baisakhi Formation of Swami Nath *et al.*, 1959 (See Singh, 2006), and Bhadasar formations (Pandey and Krishna, 2002) (Fig. 1b).

However, the Lathi Formation was previously investigated by several researchers in various aspects but it is the world over known for its rich silicified gymnosperm fossil woods (Blanford, 1877; Ritcher-Bernberg and Schott, 1957 (See Singh, 2006); Madhav Rao, 1974 (See Pareek, 1981); Das Gupta, 1975; Bhatia, 1977; Sharma and Tripathi, 2002; Bonde, 2010). In addition, various other fossils from this succession have also been retrieved by other workers including, leaf impressions (Verma, 1960, See Singh, 2006), nannofossils (Kalia and Roy, 1989, Rai *et al.*, 2016), silicified nerineid gastropod from the Thaiat ridge (Das Gupta, 1975; Pareek *et al.*, 1977; Jodhawat, 1984; Pandey and Choudhary, 2007; Pandey *et al.*, 2012), and trace fossils (Parihar *et al.*, 2021). Very few palynological investigations have been carried out in this succession (Srivastava, 1966; Lukose, 1972).

Due to the insufficient recovery of the palynomorphs, it is difficult to achieve the palynostratigraphy in the present succession but for a better understanding of the palaeodepositional settings detailed palynofacies analysis has been taken up as the main objective of this work. The samples have been collected from Lathi Formation for the palaeoenvironmental investigations.

At present, palynofacies studies have become a significant tool due to their requirement in the petroleum industry. Palynofacies as a proficient tool have been widely utilized to define the palaeodepositional settings in the various sediments of different periods by several authors (Singh *et al.*, 1992; Tyson, 1995; Cazzulo-Klepzig *et al.*, 2009; Oboh-Ikuenobe *et al.*, 2005; Prasad *et al.*, 2013; Aggarwal *et al.*, 2019). Although some reports are available from Mesozoic sediments (Götz *et al.*, 2003; Schneebeli-Hermann *et al.*, 2012; Mueller *et al.*, 2014; Zhang *et al.*, 2015; Zobaa *et al.*, 2013; Carvalho *et al.*, 2013; Christoph *et al.*, 2019) but very few reports are available from India (Mishra *et al.*, 2018; Aggarwal *et al.*, 2019). This study is also an approach for the first time to understanding the palaeodepositional settings of the Jurassic sedimentary record belonging to the Lathi Formation of the Jaisalmer Basin.

GEOLOGY OF THE AREA

Western Rajasthan shelf is a turmoil zone in the north-western part of India (Fig. 1a). It includes four separate sedimentary basins, namely Bikaner-Nagaur, Jaisalmer, Barmer, and Sanchore basins. The Jaisalmer Basin has a long sedimentation history from the Precambrian to Quaternary that comprise marine sediments deposited over the Banded Gneissic Complex, Malani Igneous Suite, and Erinpura Granite Complex (Coulson, 1933; Heron, 1953) (Fig. 1d). Outcrops are mainly represented by the Early Jurassic to Quaternary (Das Gupta, 1975; Misra *et al.*, 1996). However, the sub-surface (boreholes) sediments are mainly confined to the Late Proterozoic-Early Cambrian along with the Triassic succession (Sigal *et al.*, 1970; Sigal and Singh, 1980; Mehrotra and Singh, 1968 (See Singh, 2006); Mathur and Mathur, 1968 (See Singh, 2006); Das Gupta, 1975, Lukose, 1974, Lukose and Misra, 1980, Singh, 1969 (See Singh, 2006), Singh, 1996, Misra *et al.*, 1996).

Jaisalmer Basin, located on the north-western slope of the Indian platform, covers a large part of around 30,000 km^2. It occupies the central part of the Rajasthan shelf. Tectonically, the Jaisalmer Basin is divisible into three zones, (1) the raised Mari-Jaisalmer Arch extending through the central part of the basin with an NW-SE trend, neighboured by (2) the synclinal Shahgarh Sub-basin to the south and south-west, and (3) the monoclinal Kishangarh Sub-basin to the north and north-east. Younger Jurassic outcrops are confined to the raised Mari-Jaisalmer Arch (Fig. 1d) (Oldham, 1886; Swami Nath *et al.*, 1959 (See Singh, 2006) in the Jaisalmer Basin.

The Lathi Formation (Fig. 1b) is the basal-most part of the Jurassic sequence of the Jaisalmer Basin. Near Devikot, an unconformable relationship between the basement rocks and the overlying Lathi Formation is well exposed. However, in the subsurface, this formation rests on the Permian-Triassic Bhuana Formation (Williams, 1959; Lukose, 1972; Lukose and Misra, 1980; Misra *et al.*, 1996) and extends toward the south up to the Barmer-Sanchor Basin. Eastwards, in the Bikaner-Nagaur Basin, the Lathi Formation has been correlated with the Triassic–Jurassic Mayakor Formation (Shrivastava, 1971). The Lathi Formation is underlain by the lower Hamira Member of the Jaisalmer Formation, with a conformable and 'interfingering' relationship (Pareek, 1984; Roy and Jakhar, 2002). The beds are either horizontal or towards the northwest, having gentle undulatory dips. The strike is roughly NE-SW (Roy and Jakhar, 2002). The sequence was initially designated as 'Lathi Beds' by Oldham (1886) after Village Lathi. Later Swami Nath *et al.* (1959, See Singh, 2006) grouped the beds into a formation. However, the formation is well-formed in the vicinity of Lathi Village

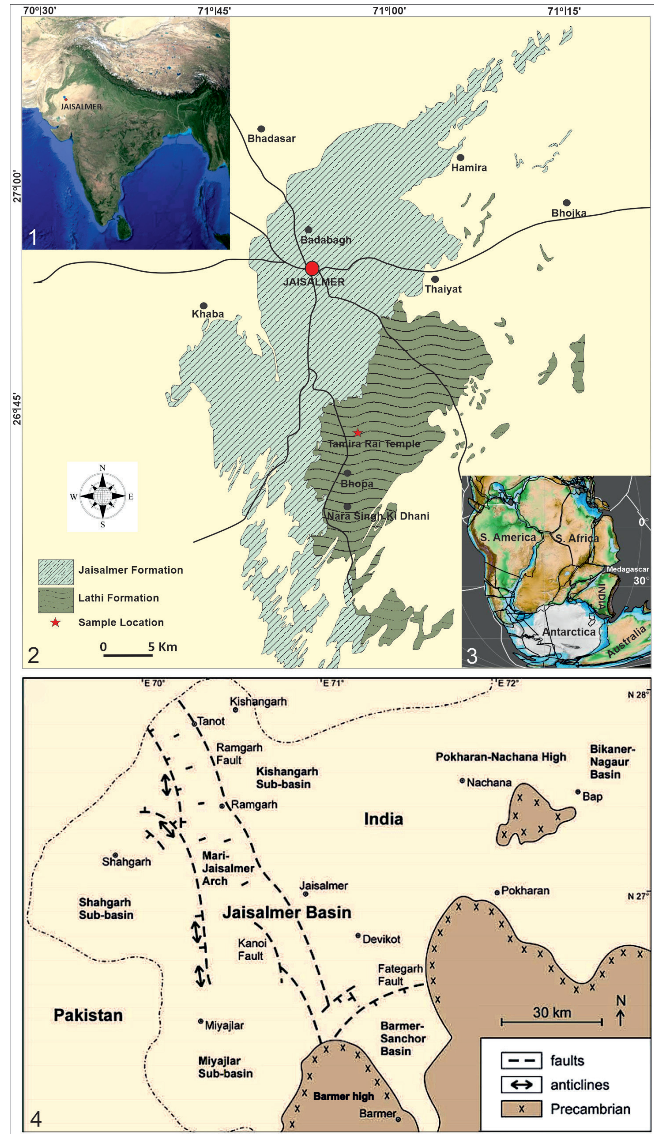
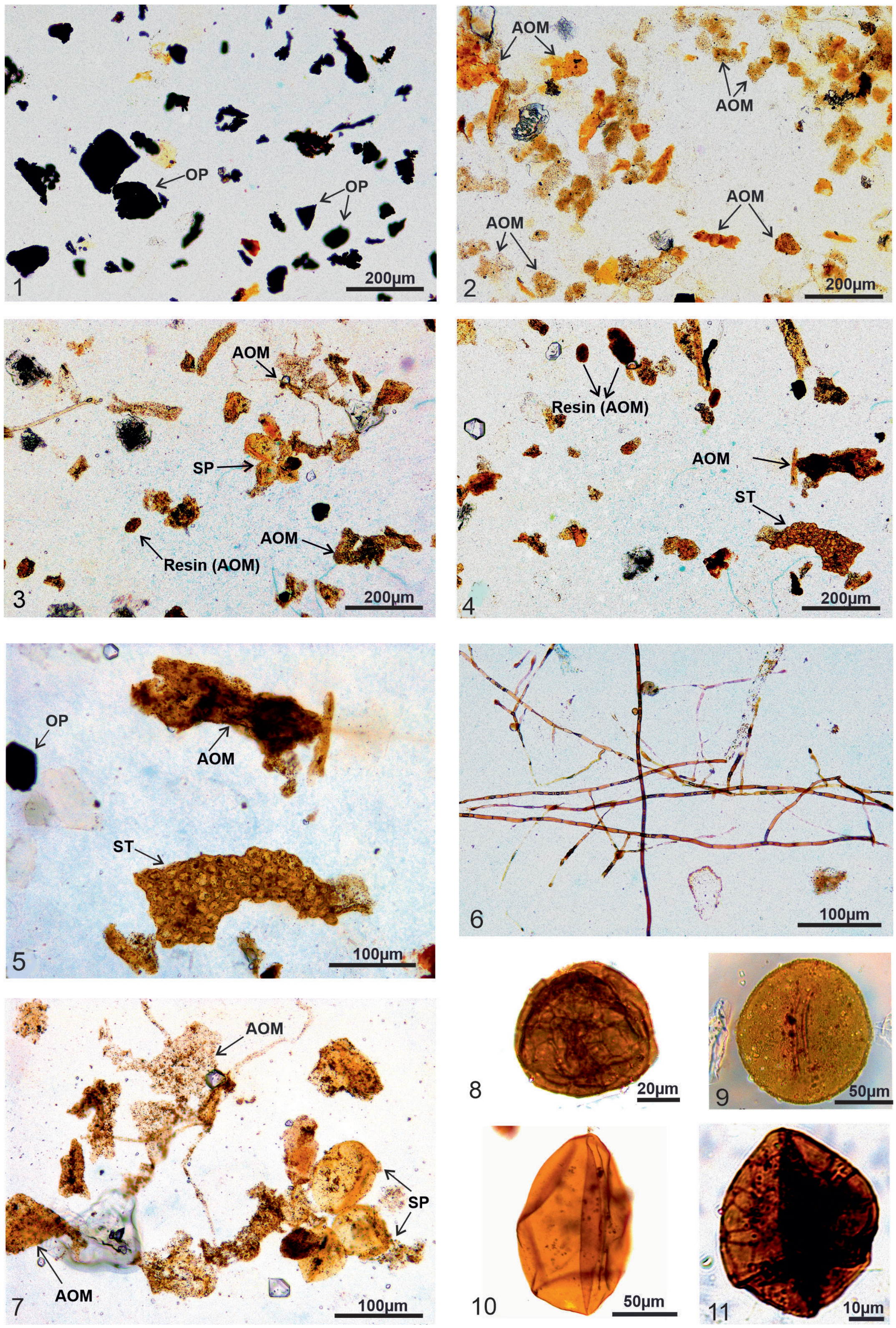


Figure 1. (1) Satellite map of India showing location of Jaisalmer Basin. (2) Geological sketch map of Lathi Formation and sample location of the study area (Modified after Rai *et al.*, 2016). (3) Palaeogeographic position of Jaisalmer Basin during Jurassic. (4) Structural units of the Jaisalmer Basin (modified after Rao, 1972; Misra *et al.*, 1993).

(27°01′N: 70°30′E) on Pokaran-Jaisalmer Road. The sporadic outcrops of this formation also occur in the south, southeast, and east of Jaisalmer (Roy and Jakhar, 2002).

The Lathi Formation in outcrops predominantly comprises sandstones and arenaceous facies and hence this formation was described as Lathi Sandstone by Pareek (1984). Based on surface analysis, Madhav Rao (1974, See Pareek, 1981) and Das Gupta (1975) subdivided the Lathi Formation into two members *viz.,* the lower Odania Member and the upper Thaiat Scarp member. The Odania Member is further split into lower Odania Member and upper Odania Member. The basal part of Odania Member, which is well exposed in the Lathi-Odania Section, commences with a conglomeratic bed overlying the Bilara Limestone of the Marwar Supergroup. The overlying rock unit comprises low to high-angle cross-bedded, well-cemented, poorly sorted



EXPLANATION OF PLATE I

Palynofacies association retrieved from the Lathi Formation of Tamira Rai Temple section (1) Opaque phytoclast, Slide No. 16895, V-45/4. (2) AOM, Slide No. 16896, Q-34. (3) AOM along with palynomorphs, Slide No. 16894, Q-49/3. (4) Structured phytoclast along with AOM, Slide No. 16894, R-26/4. (5) AOM, structured phytoclast along with Opaque phytoclast, Slide No. 16894, Q-49/3. (6) Fungal hyphae, Slide No. 16892, N-48/3. (7) palynomorphs along with AOM, Slide No. 16894, S-26/2, BSIP. (8) *Callialasporites*, Slide No. 16893, R-36/3. (9) *Calamospora*, Slide No. 16894, S-36. (10) *Classopollis,* Slide No. 16894, A, K-50. (11) *Monosulcites,* Slide No. 16894, N-39/4.

ferruginous sandstone and is followed by a sequence of white to maroon, sandy siltstone, dark ferruginous sandstone, and arkosic, poorly sorted, coarse-grained sandstone. Another conglomeratic bed tops this sequence with a large fossil tree trunk and several small wood fossils in coarse sandstone beds. The upper part of Odania Member is typically exposed in and around Akal National Park. The rock sediments are poorly cemented, poorly sorted, medium to coarse-grained, mica bearing, cross-bedded calcareous to ferruginous sandstone with occasional concretion conglomerate bed overlying the top of this unit. Another conglomerate bed is present with large fossil tree trunks in coarse sandstone bands. The Thaiat Member is best exposed in the Scrap section, characterized by fine-grained, well-sorted, cross-bedded white and grey sandstone with siltstone bands. In comparison to the Odania Member, the Thaiat Member is predominantly composed of siltstones.

MATERIALS AND METHODS

The present study includes 24 samples obtained from a 2.5 m thick succession exposed at Tamira Rai Temple Section of Lathi Formation (Fig. 2), located on a diversion just before Khuri Road, 25 km south of Jaisalmer (26°44'13.1"N: 70°84'17.6"E) (Fig. 1a). Both the Odania and the Thaiat Members of this formation (Figs. 2a–f) are exposed in this section and comprise a sequence of variegated, grey-yellow shale and red, reddish-yellow sandstone intercalation in the basal portion, succeeded by a massive bed of planer and cross-bedded sandstone (Figs. 2a, d), which in turn overlain by friable, burrowed, conglomeratic bed of sandstone. This conglomeratic layer (Figs. 2a, d) also shows many scattered silicified wood fossils without any anatomical details. The upper portion of the sequence contains grey, brown shale, grey sandy shale, and reddish iron-rich shale, which is capped by a massive layer of limestone (Figs. 2a, b), marking the contact between Lathi and the Jaisalmer formations. No other body fossil could be found in this section other than fossil wood. In gritty sandstone beds, scanty trace fossils are observed.

Only 13 samples, out of 24 samples of the present contribution, were rich in organic matter, and the rest 11 samples were utterly barren or poor in organic matter. Processing of the samples for palynofacies investigation was done by using the standard non-oxidative procedure (Faegri and Iversen, 1989; Tyson, 1995; Prasad *et al.*, 2013; Aggarwal *et al.*, 2019). After maceration, the digested material was washed with water through a 500 mesh strainer. The sieved organic residue with polyvinyl alcohol (PVA) was spread and dried on a coverslip, and finally, the permanent slides were prepared by mounting the dried coverslip using Canada Balsam. Two slides from each sample were routinely examined under transmitted light and incident light fluorescence microscopy and photomicrographs were taken by Lecia MC 190HD and Leica DFC 420 C Camera attached to Leica DM 2000 LED and Lecia DM 5500 microscope respectively. The relative proportion was determined by way of counting at least 500 organic matter particles per sample at

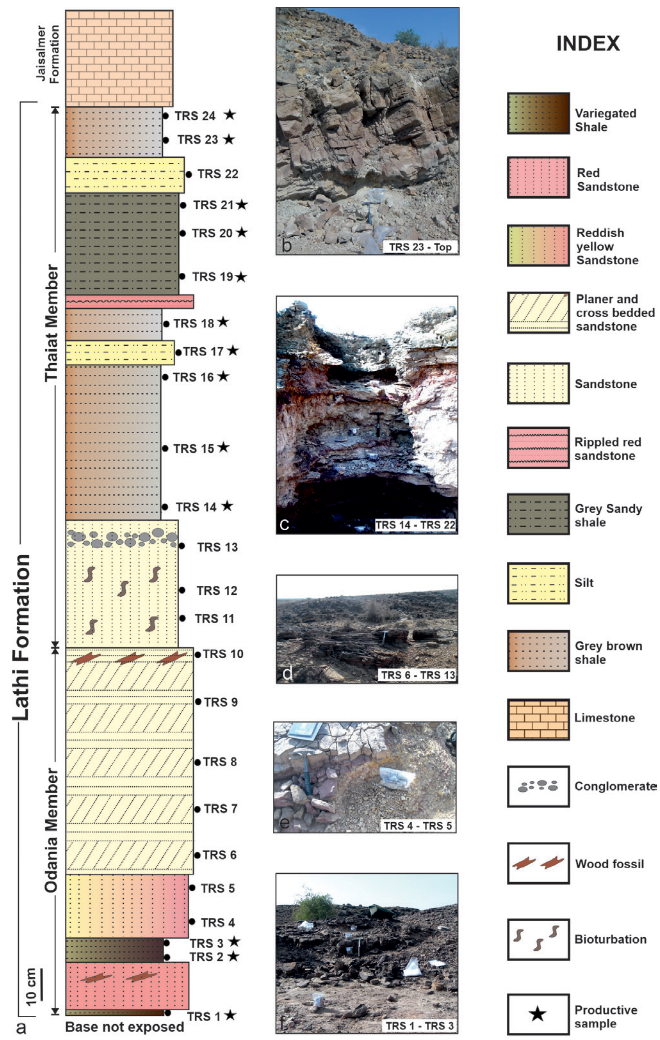
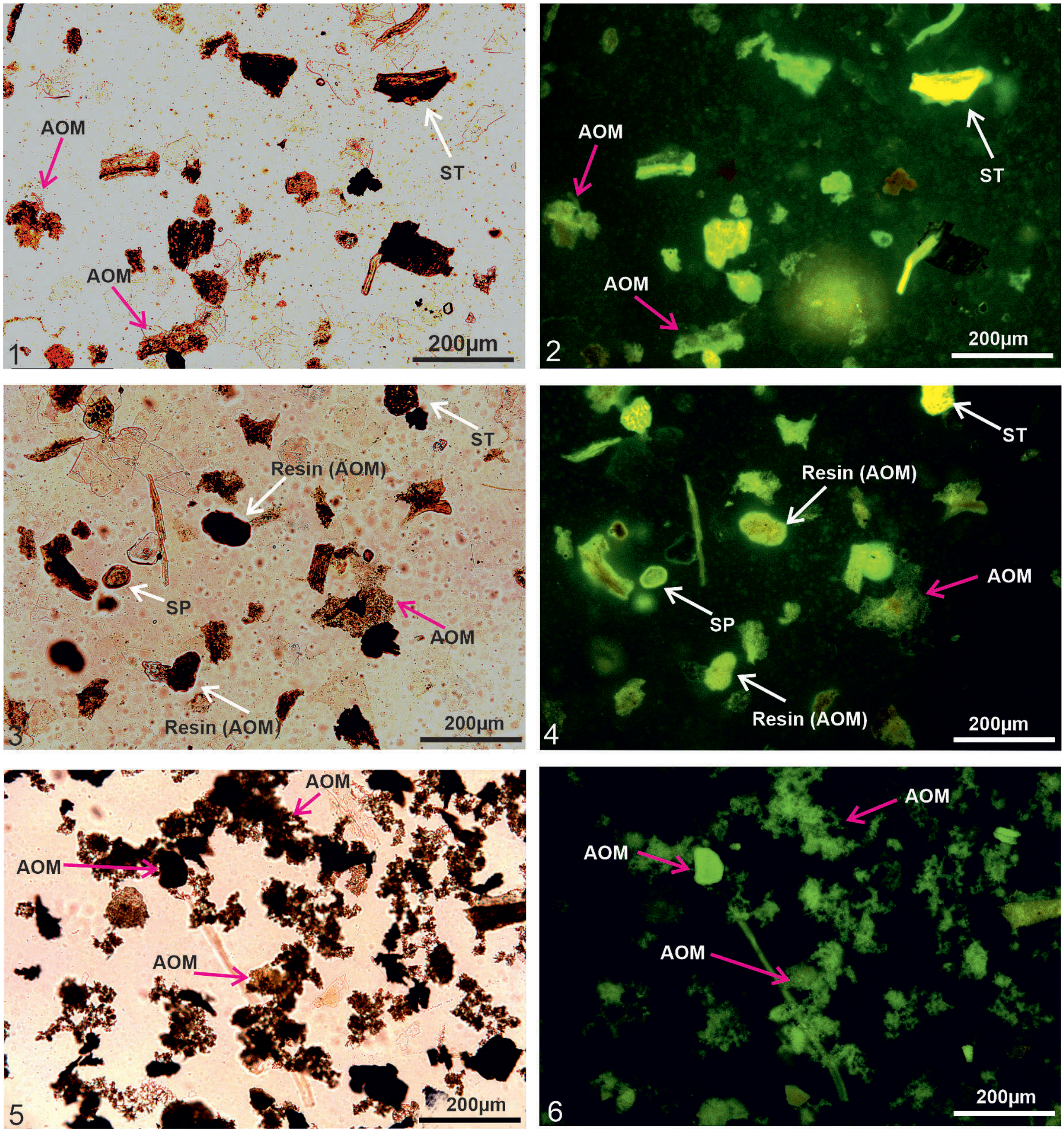


Figure 2. Measured litho-section of Lathi Formation at fossil locality exposed in Tamira Rai Temple.

various magnifications (10X/ 20X/ 40X/ 63X) to generate a qualitative and semi-quantitative assessment of the dispersed organic matter (OM). An England Finder reference follows the sample number for each figured specimen. All microscopic slides are kept in the repository of BSIP Museum, Lucknow, India. The identification of the different types of sedimentary organic matter has been made with the help of the classical literature provided by various researchers (Tyson, 1993, 1995; Traverse, 1994; Oboh-Ikuenobe *et al.*, 2005; Carvalho *et al.*, 2006; Mendonça Filho *et al.*, 2011; Aggarwal *et al.*, 2019).

The studied sedimentary organic matter was classified into four main categories: 1) palynomorphs (SP), 2) structured phytoclasts/ translucent phytoclasts (ST), 3) opaque phytoclasts (OP) and 4) amorphous organic matter (AOM). Palynomorphs include all recovered spores and pollen grains and fungal spores. The structured phytoclasts envisage poorly- to well-preserved woody material, cuticles, tracheids, and fungal hyphae. The opaque phytoclasts include exclusively black opaque phytoclasts. AOM is attributed to the microbial reworking of structured organic matter which is finally converted into structureless, porous/spongy, dark,



EXPLANATION OF PLATE II

(1) under transmitted light, translucent beige dark brown structure phytoclast (white arrow), light-brown granular AOM with sharp outlines (pink arrow), Slide No.16894, M-36/2. (2) under blue-light fluorescence, complex organic matter associated with variable strong fluorescence, ST (white arrow), strongly fluorescent AOM (pink arrow), Slide No.16894, M-36/2. (3) under transmitted light, translucent beige dark brown structure phytoclast (ST), Palynomorphs (SP), Resin (AOM) (white arrow), light-brown granular AOM with sharp outlines (pink arrow), Slide No.16894, Q-35. (4) under blue-light fluorescence, complex organic matter associated with variable strong fluorescence, ST, SP, Resin (AOM) (white arrow), and strongly fluorescent AOM (pink arrow), Slide No.16894, Q-35. (5) under transmitted light, dark brown to light brown AOM with sharp outlines (pink arrow) Slide No.16894-B, E-28. (6) under blue-light fluorescence, strongly fluorescent AOM, Slide No.16894-B, E-28.

or slightly translucent amorphous mass. Several workers have recently introduced the gelified particles in palynofacies studies (Graz *et al.*, 2010; Ţabără *et al.*, 2015; Zhang *et al.*, 2015). Resins also lie under AOM (Tyson, 1995). The scanty presence of the palynomorphs is represented by *Callialasporites*, *Calamospora*, *Classopollis,* and *Monosulcites* (Pl. I, Figs. 8-9). Algae are scarce, but fungal elements are very rare. The present study incorporates AOM as the main component. After calculating the percentage of different organic matter types, the quantitative distribution has been presented in a ternary plot (Fig. 3). The various identified forms of organic matter types have been illustrated in Table 1 and Pl. II, Figs.1-6 & Pl. III, Figs. 1-6.

PALYNOFACIES ASSEMBLAGES

Although the occurrence of the common marine elements (foraminiferal linings, scolecodonts, dinoflagellates, marine algae, etc.) are completely missing in the Lathi sediments, phytoplankton-derived organic matter is abundantly present in most of the samples. The AOM Phytoclasts-Palynomorphs (APP) ternary plot after Tyson (1993, 1995) has been comprehensively applied to infer the depositional settings and the transport pathways of the sedimentary organic matter in various successions and the same APP plot has also been applied in the present study to decipher the depositional settings. The plot (Fig. 3) shows two different palynofacies associations (PF-I and PF-II).

Palynofacies-I (PF-I)

This palynofacies is represented by the predominance of the AOM (48.61-71.83%; avg. 59.43%) and sub-dominated by phytoclasts (26.69-50%, avg. 39.43%). Phytoclasts are mainly constituted by OP (18.2-43.4%; avg. 33.19%) along with ST (0.65-7.2%. avg. 4.76%). Other constituents of PF-I are SP (0.7-3.75%; avg. 1.94%) and fungal remains (0-11.81%; avg. 1.48%). It has been documented exclusively in shales (sample no.s TRS-1-3, TRS-14-16, TRS-18-21, and TRS-24). This is one of the most occurred palynofacies in the succession.

Palynofacies-II (PF-II)

This palynofacies is represented by the predominance

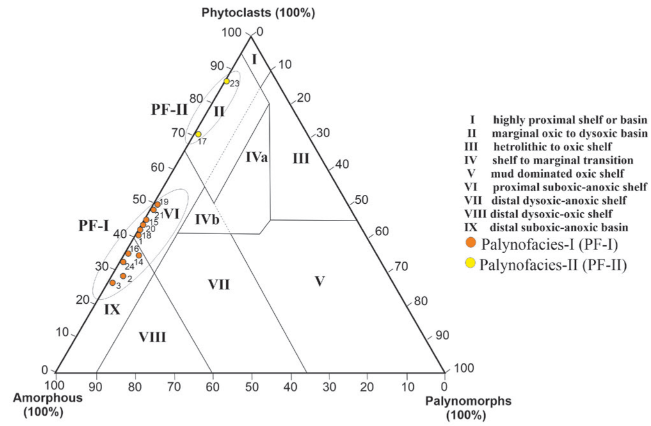


Figure 3. Distribution of the different identified palynofacies in the ternary diagram (modified after Tyson, 1993 and 1995).

of the phytoclasts (70.75-87%, avg. 78.87%) mainly OP (66.25-77.98%, avg. 72.11%) and sub-dominated by the AOM (12.98-28%, avg. 20.49%). The rare occurrence of the palynomorphs (0-1.25%, avg. 0.625%) and structured phytoclasts (4.50-9%, avg. 6.63%) have been documented. PF-II has been documented in shale and siltstone sediments (TRS-17 and TRS-23).

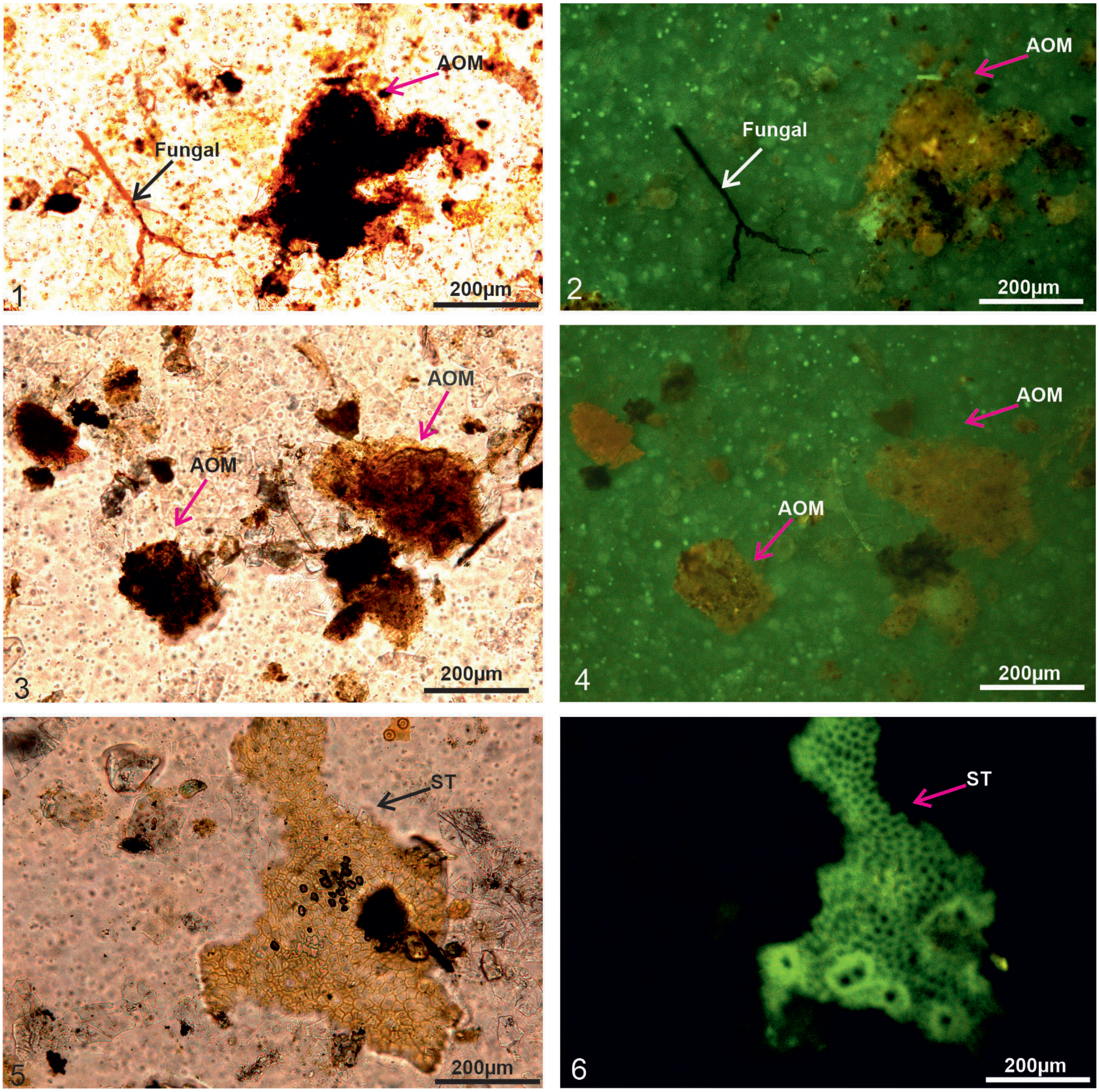
PALAEOENVIRONMENTAL RECONSTRUCTION

PF-I (Proximal-distal suboxic shelf)

The high percentage of AOM along with the sub-dominance of OP characterizes PF-I. The AOM is formed by the microbial activity on the translucent phytoclasts (woody elements, cuticles, plant tissues, etc.) in low-energy settings such as standing/ waterlogged bodies (Tyson, 1993; Atta-Peters *et al.*, 2013). Deposition of the AOM is usually

Table 1. Classification of sedimentary organic matter of Tamira Rai Temple section (Lathi Formation) (modified after Tyson, 1995; Bombardiere and Gorin, 2000; Mendonça Filho et al., 2002, 2011; Carvalho et al., 2006; Ţabără et al., 2015).

Group	Subgroup		Origin
Palynomorphs (SP)	Sporomorph	Spores	Terrestrial palynomorph produced by pteridophyte, bryophyte and fungi.
Structured Phytoclasts (ST)	Structured/Translucent	Cuticle	Higher plants' leaf-epidermal tissue
		Woody remains	Gymnospermous and angiospermous woody tissues
	Fungal remain	Fungal hyphae	Derived from fungi
	Resin		Higher plant secretions
Opaque Phytoclasts (OP)	Opaque	Equidimensional Lath	Derived from woody higher plants or fungi
Degraded Organic Matter (DOM)	Degraded structured phytoclsats (DT)	Partially to thoroughly degraded structured organic matter (DT) due to the bacterial and fungal activities. Various preservation states have been observed, partially to fully deteriorated	
	Amorphous organic matter (AOM) Degraded organic matter	Amorphous organic matter (AOM) is formed due to the microbial reworking on partly degraded structured phytoclasts finally converted into structureless, porous/spongy, dark or slightly translucent amorphous mass. Material without structure with no morphology or shape	



EXPLANATION OF PLATE III

(1) under transmitted light, light brown fungal remain (black arrow) and dark brown to light brown AOM (pink arrow) Slide No. 16897, Q-44/1. (2) under blue-light fluorescence, fungal remain show black colour (black arrow), and AOM show light fluorescence, (pink arrow), Slide No. 16897, Q-44/1. (3) under transmitted light, dark brown AOM (pink arrow) Slide No. 16897, D-28/2. (4) under blue-light fluorescence, AOM less fluorescent matrix (pink arrow), Slide No. 16897, D-28/2. (5) under transmitted light, light brown ST (black arrow) Slide No. 16897, P 37/3. (6) under blue-light fluorescence, structure phytoclast show variable strong fluorescence (pink arrow), Slide No. 16897, P 37/3.

taking place in high water level conditions (Aggarwal *et al.*, 2019). AOM is formed by freshwater algae, phytoplankton, and bacteria and is generally deposited in deficient oxygen environments/ reducing conditions with low energy and high preservation rate (Batten, 1983; Tyson, 1993; Pacton *et al.*, 2011; Ţabără *et al.*, 2015). Anoxic-dysoxic conditions are mainly associated with the preservation of AOM (Zhang *et al.*, 2015; Pacton *et al.*, 2011; Aggarwal *et al.*, 2019). Aerobic microbes and algal blooms enhance the organic matter input, which is an important source of AOM. Algal blooms are mainly associated with anaerobic depositional settings (Liu and Wang, 2013). Laminated structures in most of the rock samples are primarily related to anoxic bottom settings (Liu and Wang, 2013), as a result, this palynofacies type has been attributed to the shale deposits exclusively in the present study. The usual presence of moderate to small-sized phytoclasts in PF-I denotes its deposition in the proximal to distal settings (Tyson and Follows, 2000). The abundant occurrence of AOM along with the moderate presence of the opaque phytoclasts suggests the disposition of this palynofacies in suboxic-anoxic settings. In Fig. 3 sample nos. TRS-2, TRS-3, TRS-14, TRS-16, and TRS-24 denote more distal settings as compared to sample nos. TRS-1, TRS-5, TRS-18–21. The same inference has also been drawn based on the size of the phytoclasts as sample nos. TRS-2, TRS-3, TRS-14, TRS-16, and TRS-24 are dominated by the small and equidimensional phytoclasts while sampling nos. TRS-1, TRS-5, TRS-18-21 are comparatively larger and lath-shaped. Thus, the palynofacies infer a proximal-distal suboxic-anoxic shelf environment (Figs. 2a-c, f). The absence of common marine elements but the abundance of phytoplankton-derived organic matter (fluorescent AOM: 10.35-61.61%, avg. 39%; non-fluorescent AOM: 4.56-46.59%, avg. 20.43%) in this palynofacies directly denotes its deposition in marginal/ shallow marine low energy settings (exclusive occurrence in shale deposits). This palynofacies lie under the IX and VI zones of the APP diagram suggested by Tyson, 1995 (Fig. 3).

PF-II (proximal oxic basin)

The OP predominates in PF-II. It is mainly derived from the oxidation of structured phytoclasts (tracheids, translucent brown wood, cuticle, etc.) at normal or elevated temperatures (Cincotta *et al.*, 2015). The predominant incidence of opaque phytoclasts possibly replicates high freshwater inundation with oxidizing settings that resolute OP at the proximal site (Tyson, 1989; Cincotta *et al.*, 2015). Although, the composition and the size of the phytoclasts are usually predicted to be associated with the distance from the terrestrial influx (Tyson and Follows, 2000). Woody elements are mainly originated from the terrestrial plant xylogen and have a large volume that tends to be deposited in proximal settings (close to the source). In addition, the occurrence of the low AOM also denotes the deposition of these palynofacies types in the oxic environment. The concurrence of the larger size of the phytoclasts elements also indicates deposition of PF-II in proximal settings. Sample no. TRS-17 is represented by coarse-grained rock such as siltstone, which usually occurs in shallow lake or delta settings (Zhang *et al.*, 2015). On the other hand, sample no. TRS-23 is represented by the shale which may be caused by the profuse terrigenous clastic sediments owing to fluvial supply due to seasonal flooding. As the palynofacies is predominated by the occurrence of the opaque phytoclasts and the rare occurrence of the phytoplankton derived organic matter (fluorescent AOM: 9.89-11.41%, avg. 10.65%; non-fluorescent AOM: 3-16.59%, avg. 9.84%) suggest its deposition mainly in the continental set up. PF-II lies under the II zone of the APP diagram suggested by Tyson, 1995 (Fig. 3).

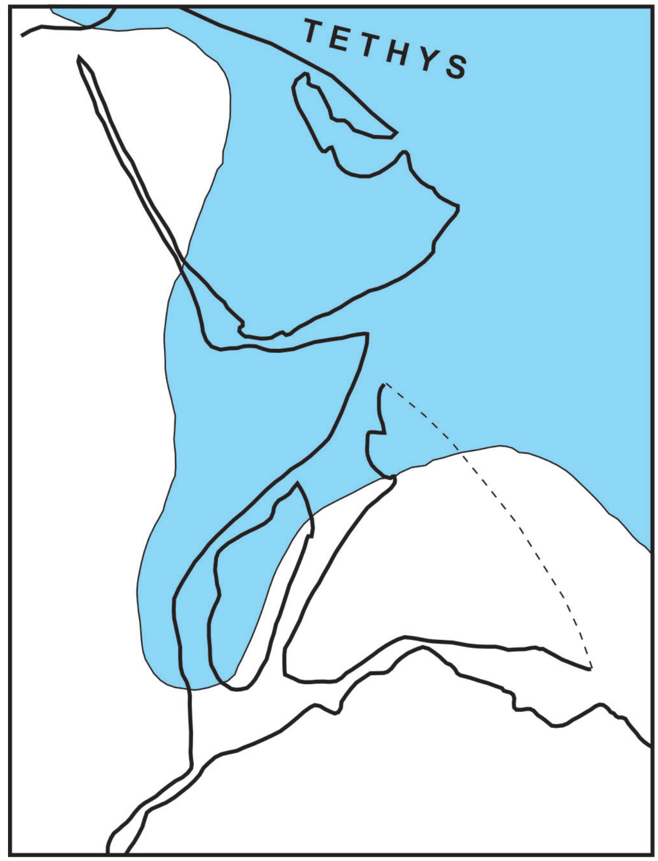


Figure 4. Predrift reconstruction showing site of the 'Trans-Erythrean Trough' or the 'Ethiopian Gulf' (after Hallam, 1971).

DISCUSSION

Biostratigraphic age

The sedimentary successions of the Lathi Formation are best seen in quarries around Lathi village consisting of numerous silicified and ferruginous gymnospermous fossil woods (Blanford, 1877, Ritcher-Bernberg and Schott, 1957 (See Singh, 2006); Das Gupta, 1975; Bhatia, 1977; Madhav Rao, 1974 (See Pareek, 1981); Sharma and Tripathi, 2002; Bonde, 2010). In a small area of 10 m^2 near Akal, more than 15 very large fossil logs were recovered so that the area is transformed into Fossil Wood Park. The common occurrence of gymnosperm wood fossils in this formation is suggesting the existence of flourishing forests during the Early Jurassic.

The vegetative part of the plant in the form of leaf impressions of *Pterophyllum* sp., *Ptilophyllum acutifolium,* and *Equisetites* sp. has also been reported from a locality near Devikot in Barmer District by Verma (1960, See Singh, 2006). Srivastava (1966) recorded the presence of rich microfloral assemblage from the subsurface samples of the Lathi Formation collected from the well drilled near the town of Jaisalmer and Barragaon viz., *Cyathidites australis rimalis*, *C. australis*, *C. minor, Osmundacidites wellamanii*, *Dictyotriletes (Ischyosporites) crateris*, *Cingulatisporites lathiensis*, *Trilobozonosporites*

Table 2. Botanical affinity of palynotaxa recorded from Lathi Formation, Jaisalmer Basin by Srivastava, 1966 and Lukose, 1972.

Name of the genus	Botanical affinity
Trilobozonosporites	Lygodiaceae (Fern)
Cyathidites australis rimalis	Cyatheaceae (Fern)
Osmundacidites	Osmundaceae (Fern)
Dictyotriletes (Ischyosporites)	Dicksoniaceae (Fern)
Gleicheniidites	Gleicheniaceae (Fern)
Dictyophyllidites	Dipteridaceae (Fern)
Matonisporites cooksoni	Matoniaceae (Fern)
Polypodisporites	Polypodiaceae (Fern)
Monosulcites	Pteridosperm
Cycadopites	Peltaspermales (Pteridosperm)
Cupressacites	Cupressaceae (Conifer)
Inaperturopollenites	Taxodiaceae (Conifer)
Araucariacites	Araucariaceae (Conifer)
Callialasporites	Araucariaceae (Conifer)
Podocarpidites	Podocarpaceae (Conifer)
Spheripollenites	Taxodiaceae (Conifer)
Classopollis	Cheirolepidiaceae (Conifer)
Gliscopollis	Cheirolepidiaceae (Conifer)
Ginkgocycadophytus	Cycadales (Cycads)

verrucatus, *Triangulatisporites mathurii, Polypodiisporites rajasthanensis*, *Ginkgocycadophytus deterius* var. *majus*, *G. inkgocycadophytus nitidus*, *Monosulcites couperi*, *Monosulcites* sp., *Cupressacites ramachandrae*, *Araucariacites ghoshii*, *Inaperturopollenites indicus*, *Callialasporites dampieri*, *C. trilobatus*, *C. jaisalmerensis*, *C. barragaonensi*, *Podocarpidites* sp., *Classopollis classoides*, *C. minor, Classopollis* sp. Based on the correlation of recovered palynoflora with that of the other Gondwana continents (Western Australia: Balme, 1957; Western Siberia: Bolkhovitina, 1959; Western Canada: Pocock, 1962), and dominance of *Classopollis classoides* with a recorded range from Lower to Middle Jurassic, the Lathi Formation has been assigned as Early to Middle Jurassic age. Later, Lukose (1972) also recovered a rich pollen assemblage from the subsurface sediments of Chor Well-Section, which comprises *Spheripollenites*, *Classopollis minor, C. classonides, C. itunensis, Gliscopollis*, *Araucariacites* and *Inaperturite* in predominance along with the scanty presence of *Cyathidites, Lophotriletes, Gleicheniidites, Osmundacidites, Dictyophyllidites, Endosporites, Matonisporites cooksoni, Laricoidites, Clavatipollenites, Cycadopites, Psilospora*. Based on the recovered palyno-assemblage, the sediments have been considered older than the Jurassic Salt Range sediments and the Liassic age (Late Triassic-Early Jurassic) has been assigned to this formation.

Recently, based on the occurrence of the reworked nannofossil taxa the sediments of the Lathi Formation (Odania and Thaiat members), have also been dated as Early-Middle Jurassic (Pliensbachian-Aalenian) by Rai *et al.* (2016).

Based on the presence of the characteristic Bajocian coral *Isastraea* (d'Orbigny) in the lower part of the overlying Jaisalmer Formation (Pandey and Fürsich, 1994; Pandey *et al.,* 2006a), the upper age limit of the Lathi Formation should be Bajocian or Pre-Bajocian, therefore the age of the Thaiat Member ranges from Early Jurassic to Bajocian.

Palaeoecology and depositional environment

The recovered palynomorphs (Table 2; Srivastava, 1966; Lukose, 1972) are represented basically by ferns and conifers. However, ferns are low in quantity but represent spore types having an affinity with various families, viz., Cyatheaceae, Osmundaceae, Dicksoniaceae, Schizaeaceae, Selaginellaceae, and Polypodiaceae. *Callialasporites*, which have been correlated with plants of the conifer family Araucariaceae are fairly well represented in the assemblage. However, coniferous disaccate grains are very rare in the microfloral assemblage but grains belonging to the conifer family Cheirolepidaceae i.e., *Classopollis* probably produced by coniferous taxa like *Cheirolepis*, *Brachyphyllum,* and *Pagiophyllum* are dominant representative of microflora. A pollen grain of the family Taxodiaceae is also present and identified as *Inaperturopollenites* and *Spheripollenites*.

Coniferous pollen grains like *Callialasporites, Classopollis*, *Inaperturopollenites,* and *Spheripollenites* are not suited for wind transportation to long distances, so it is reasonable to suppose that the plants which produced them were located very close to the sedimentation. Very few diasaccate grains belonging to *Podocarpidites* are carried to very long distances by wind and their scarce presence shows that they are not indigenous to the place of deposition. Dominance of *Classopollis* (cheirolepidian) pollen and a good representation of other conifer pollen (araucarian, taxodiacean) along with some pteridophytic spores suggests a warm and humid environment. *Classopollis*, representing the dominant microflora, which has a recorded range from Lower to Middle Jurassic. *Spheripollenites* pollen also has an acme during the Early to Late Torchian age (Dybkjær, 1991; Batten *et al.*, 1994; Koppelhus and Nielsen, 1994; Koppelhus and Batten, 1996). The dominance of *Classopollis* and *Spheripollenites* points towards the Lower to Middle Jurassic age of the Lathi Formation.

An abundance of conifers pollens along with a fair representation of fern pollen, perceiving that in quite a considerable area, adjoining the depositional site may have the existence of a forest, dominated with large-sized conifers trees and under the shade of these tall trees there are a variety of damp lovers fern plants were grown in the palaeomire. The occurrence of an abundant silicified tree trunk and wood fragments provides additional evidence for the existence of conifers forest. Investigation of these tree trunks suggests that most of them belong to the conifer family viz., Podocarpaceae, Cupressaceae, and Araucariaceae. Considering all this evidence viz. an abundance of conifers (with the dominance of *Classopollis* pollen) and a variety of pteridophytic pollen a warm and humid palaeoclimate is suggestive of Lathi Formation.

According to prior studies, the Lathi Formation shows a gradual change from continental to epineretic environment. The previous assumption that lower Lathi was deposited in the fluvial, deltaic or lacustrine depositional environment has been confronted with the recent report of the nannofossil study (Rai *et al.,* 2016), which suggested that the earliest epeiric sea transgression has occurred in western India during the Early Jurassic. Foraminiferal occurrence by Verma (1982) also points towards the marine depositional basin. Moreover, by Khan *et al.* (2021), Lathi sediments were found to be tentatively correlated with the Datta Formation of the Potwar Basin, Pakistan, which was deposited in a palaeo-depositional setting on the NW margin of the Indian plate affected by Neo-Tethys realms. This study also suggests suboxic-anoxic, nearshore fluvio-deltaic depositional settings for the Lathi Formation. A similar type of inference has also been drawn by the present study as the recovered palynofacies data advocates that the Lathi Formation was chiefly deposited in the marginal/shallow marine realm.

During Jurassic (Lower Toarcian) times, Tethys, the ancestral World Ocean, spread southwards over the Gondwanaland through the 'Trans-Erythrean trough' or 'Ethiopian realm' or 'Province' (Arkell, 1956; Stevens, 1963, 1973; Hallam, 1971) that extended off the central Tethys across Arabia between the Indian subcontinent and the east coast of Africa down to Madagascar (Fig. 4). It was the site of a shallow marine gulf, the opening of which proceeded the final breakup of the eastern Gondwanaland. Due to this impact of transgression in the western Indian region parts of Rajasthan and Kachchh were inundated. Floral evidence (Srivastava, 1966; Lukose, 1972; Present report) and palaeogeographic position (Lees, 2002) also indicate that the Jaisalmer succession was laid down under a warm, shallow inner shelf marine environment (Fig. 1(3)).

CONCLUSIONS

A palynofacies study was conducted using 24 samples of the Lathi Formation from the Tamira Rai Temple Section in the Jaisalmer Basin, India. This study is the first to combine palynofacies for source rock evaluation of Jurassic sediments in the Jaisalmer Basin. The analysis can be summarized as follows:

1. Palynofacies analysis of the Lathi Formation suggests that the sediments are mainly dominated by AOM. Based on the estimation of the different types of sedimentary organic matter, two distinct palynofacies assemblages have been identified (PF-I and PF-II).
2. The abundant occurrence of the AOM, along with the presence of the moderate to the small size of the phytoclasts in shale deposits, suggests the deposition of PF-I in a suboxic to anoxic shelf. PF-II is distinguished by the dominance of the opaque phytoclasts along with large and lath-shaped phytoclasts, which directly suggests its deposition in proximal and oxidizing conditions. Mainly the succession is predominated by PF-I. As per the lithological attributes, the sediments of the present study are mainly represented by the shales, sandstone, siltstone, and sandy shales, which directly corroborate with the palynofacies analysis.
3. The present palynofacies studies in this section are mainly documented by the abundant presence of the fluorescent AOM (Pl. II, Figs.1-6 & Pl. III, Figs. 1-6) but the absence of common marine components (prasinophytes, dinoflagellates, scolecodont, foraminiferal linings, etc.), directly denotes the marginal marine settings of these sediments. Therefore, the present study is contrary to the previous views of the continental to fluvio-deltaic deposition for the sediments of the early phase of Lathi Formation.

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