

# *Lockeia*: the bivalves resting trace fossils from Early Jurassic to Bajocian Thaiat Member of Lathi Formation of the Jaisalmer Basin, Western Rajasthan, India

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**This study focuses on the descriptions of well preserved numerous *Lockeia* traces of bivalves from the Early Jurassic to Bajocian Thaiat Member of Lathi Formation, Jaisalmer Basin, Western Rajasthan, India. Here, both ichnospecies *Lockeia siliquaria* and *Lockeia cunctator* have been recorded from the yellowish brown fine grained rippled calcareous silty sandstone in Thaiat Section. The *L. siliquaria* trace fossils are small, elongated almond-shaped and oval-shaped oblong body structures with smooth surfaces, occurring as positive hyporelief and more or less tapering at both ends. The *L. cunctator* trace fossils are small, almond-shaped oblong bodies with smooth surface structures, occurring as positive hyporelief with linear and club-shaped arrangement. The ichnotaxon *L. siliquaria* represents those places where the bivalve stopped temporally for feeding, whereas the *L. cunctator* are interpreted as locomotion traces with a resting or probing component of bivalves. Based on *Lockeia* trace fossil assemblages with associated fauna and trace fossils, we suggest shallow-marine environment for the upper part of the Thaiat Member of Lathi Formation.**

**Keywords:** Bivalves, *Lockeia*, early Jurassic to Bajocian, Jaisalmer Basin, Lathi Formation, resting trace fossils, Thaiat Member.

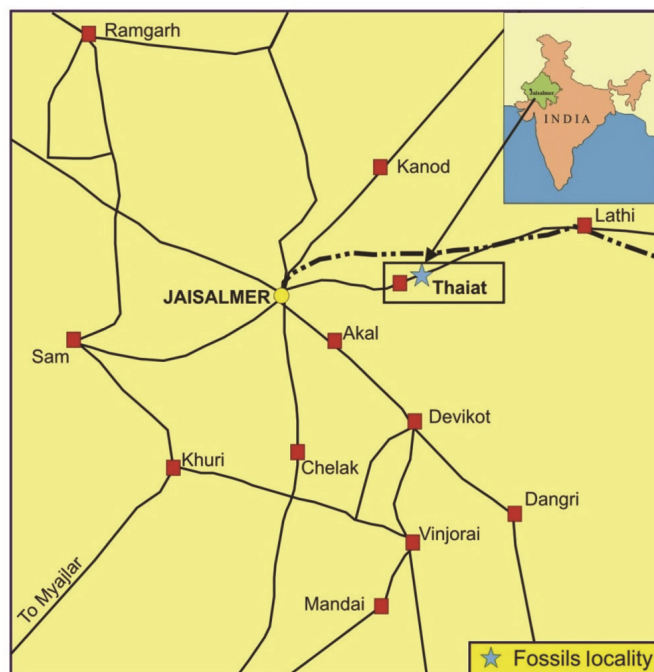
THE *Lockeia*<sup>1</sup> has been known as an ichnogenus of small almond-shaped, oval to rounded oblong bodies with smooth surfaces, normally preserved as convex hyporelief, tapering to sharp and obtuse points at both ends<sup>2</sup>. Its junior synonym is *Pelecypodichnus*<sup>3</sup>. Previously, the *Lockeia* was originally interpreted as an alga<sup>1</sup> and now it is considered as the resting traces of burrowing pelecypods/bivalves<sup>2-5</sup>. The *Lockeia* ichnogenus results from the activity or behaviours of cleft-foot bivalve as suggested<sup>6</sup>. It was also observed that *Protovirgularia* and *Lockeia* commonly occurred together and represent two different behaviours of the same individual organisms (bivalve) trace markers<sup>6-8</sup>. The behaviours of *Lockeia* indicate size, shape and ornamentation of the bivalve shells, where as the *Protovirgularia* indicates size and shape of the feet of

the animal<sup>9</sup>. Other traces of bivalves are *Lophoctenium* and *Ptychoplasma*<sup>10</sup>. The *Ptychoplasma vagans*<sup>11</sup> traces are elongated, irregularly meandering or looping, consisting of aligned series of amygdaloidal traces in convex hyporelief. The *Lophoctenium*<sup>12</sup> traces consist of a mass of closely spaced curved ridges, forming a feeble spreiten-like structures and represent repetitive lateral probing of sediments by labial palpal tentacles of bivalves<sup>9</sup>. The six ichnotaxa of *Lockeia* ichnogenus are known and recognized in the old literatures, viz. *L. siliquaria*<sup>1</sup>, *L. amygdaloides*<sup>3</sup>, *L. ornatus*<sup>13</sup>, *L. czarnockii*<sup>14</sup>, *L. elongata*<sup>15</sup> and *L. avalonensis*<sup>16</sup>. *L. elongata* are characteristically thin and elongated forms of *Lockeia*<sup>15</sup>. *L. ornatus* is characterized by surface ornamentation as suggested in its name<sup>10</sup> and *L. czarnockii* is characterized by large size and drop-shaped morphology<sup>14</sup>. Both ichnospecies (*L. ornatus* and *L. czarnockii*) are recorded only from their type localities. The more stout forms of *Lockeia* described as *L. amygdaloides*<sup>3</sup> whereas, the narrower forms referred as *L. siliquaria*<sup>1</sup> have shown the same morphology. Hence, both ichnotaxa are treated as the morphological variations of *L. siliquaria*<sup>1,6,17</sup>. The triangular forms of *Lockeia* described as *L. triangulichnus*<sup>18</sup> show preservational variants of *L. amygdaloides*. Therefore, *L. amygdaloides*<sup>3</sup>, *L. avalonensis*<sup>16</sup> and *L. triangulichnus*<sup>18</sup> are used as junior synonyms of *L. siliquaria*<sup>1,17</sup>. Recently, a new ichnotaxon known as *L. cunctator*, has been proposed<sup>17</sup> which is characterized by small, bilaterally almond-shaped oblong bodies mainly arranged or connected in a row or lines. Here the *Lockeia* trace fossils have shown cubichnia ethological class of cleft-footed bivalves. As the *Lockeia* traces have importance and significance in understanding and interpreting the ecology and depositional environments, this study discusses here the systematic taxonomy, palaeoecology and palaeoenvironment of *L. siliquaria* and *L. cunctator* traces recovered from the strata of Upper Thaiat Member of Lathi Formation of the Jaisalmer Basin, Western Rajasthan, India (Figure 1).

## Geological settings

Lathi Formation is the basal lithostratigraphic sequence of the Jaisalmer Basin, unconformably overlies on sub-surface

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**Figure 1.** Location map of the Thaiat Section of Lathi Formation of Jaisalmer Basin showing trace fossils locality.

Bhuana Formation<sup>19</sup>, and underlain by lower Hamira Member of Jaisalmer Formation<sup>20,21</sup>. Earlier, the Lathi Formation was known as the 'Lathi beds'<sup>22</sup> as its outcrops are well-exposed in the vicinity of Lathi village. The rocks or successions of the Lathi Formation are also exposed in and around Odania, Thaiat, Akal and near Devikote areas of Jaisalmer district. The Lathi Formation is about 350 m thick and its thickness increases towards north-west directions in western Rajasthan<sup>23</sup>. In the stratigraphic order, Lathi Formation is divided into Lower Odania Member and the Upper Thaiat Member<sup>24</sup> whereas, the Odania Member is further subdivided in Lower Odania Member and Upper Odania Member. The Lower Odania Member is exposed in the mainly Lathi-Odania area and represented by conglomerate, coarse grained arkosic sandstone grading to whitish maroon sandy siltstone and cross-bedded coarse grained sandstone facies at the top<sup>24,25</sup>. The outcrops and hillocks of Upper Odania Member are well exposed in and around Akal and Devikote area, and mainly comprise glauconitic sandstone, calcareous sandstone, dark brown ferruginous sandstone with cross-beddings, box works and concretionary sedimentary structures<sup>21,26</sup>. These facies have abundantly preserved petrified wood (mostly wood-fragments and tree trunks of gymnosperm) and trace fossils (*Thalassinoides suevicus*, *Thalassinoides paradoxica*, *Ophiomorpha nodosa*, *Ophiomorpha borneensis*, *Palaeophycus heberti*, *Palaeophycus tubularis*, *Gyrocrate* and *Phycodes palmatum*)<sup>26</sup>. Based on the stratigraphic position, Early Jurassic age was suggested for the Odania Member of the Lathi Formation<sup>21,25,26</sup>. The Thaiat Member is the upper member of Lathi Formation and well exposed

in scrap sections near Thaiat village and its surrounding areas (Figure 1). The lower part of the Thaiat Member is mainly composed of siliciclastic sediments with low CaO and MgO contents while the upper part is more calcareous with highly diversified fauna, trace fossils<sup>27-29</sup> and theropod dinosaur footprints<sup>30,31</sup>. Based on the flora and fauna recorded from Thaiat Member<sup>27-31</sup>, and occurrences of Bajocian coral in overlying Jaisalmer Formation<sup>25</sup>, Early Jurassic to Bajocian age is determined for the Thaiat Member of the Lathi Formation. The present studied *Lockeia* trace fossils were observed and collected from the Thaiat Section, near Thaiat village. It is located about 16 km east of Jaisalmer city on Jaisalmer-Jodhpur Highway. The Thaiat Section is about 18.5 m thick lithostratigraphic column and comprises inter-bedded sequence of mudstone/claystone and fine grained sandstone at the base followed by about 12.5 m alternate sequence of fine grained ferruginous sandstone and fine grained silty sandstone. Both *L. siliquaria* and *L. cunctator* ichnotaxa have been found in abundant and ideal forms in yellowish brown fine-grained rippled calcareous silty sandstone of upper part of the section. The generalized lithostratigraphic column of the Thaiat area of Lathi Formation is given below (Figure 2).

## Palaeontology

### Systematic Ichnology

Ichnogenus: *Lockeia*<sup>1</sup>

*Ichnospecies: Lockeia siliquaria*<sup>1</sup> (Figures 3, 4 e-g and 5).

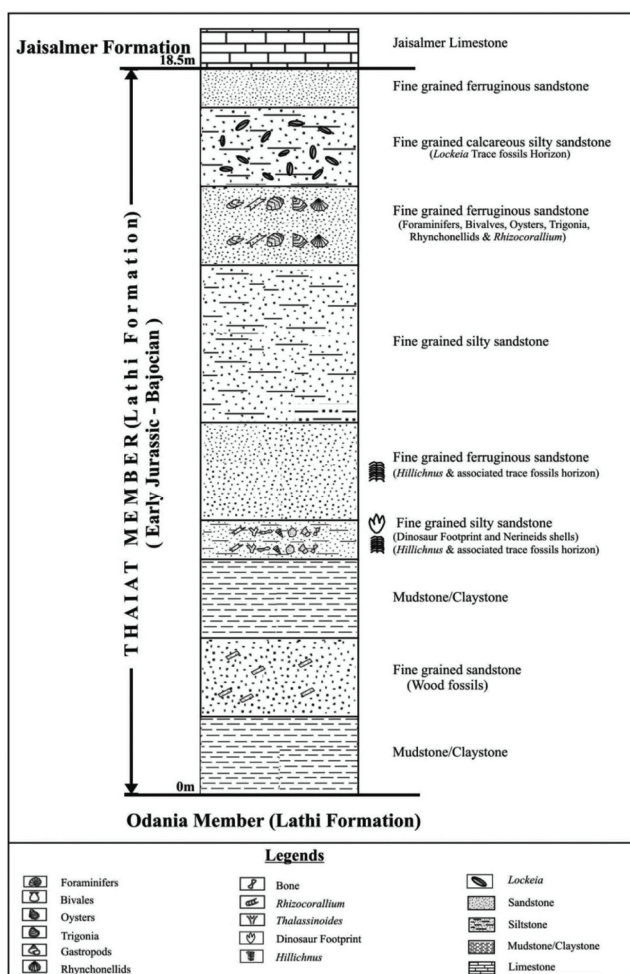
**Material:** DG/JNVU/TF/Thaiat Section of Lathi Formation/Jaisalmer/15 slabs containing 430 specimens.

**Diagnosis:** Thin, elongated to stout, almond-shaped bodies with smooth surfaces; preserved as convex hyporelief with tapering at both ends<sup>17</sup>.

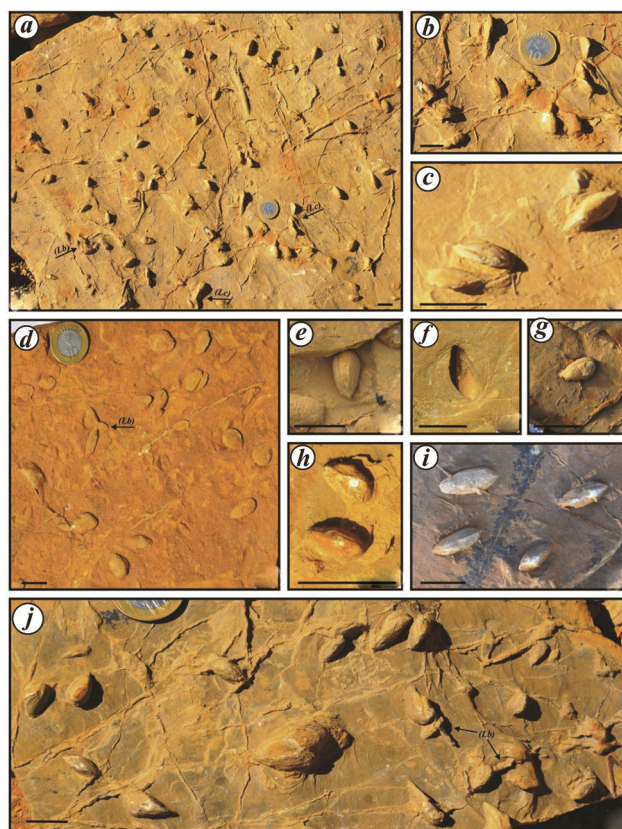
**Description:** Elongated and parallel to sub-parallel, bilaterally stout, relatively small almond-shaped and circular to ovate oblong bodies with smooth surfaces. These are preserved as convex or positive hyporeliefs being more or less tapering at both ends, whereas some specimens in one end are tapered and the other end rounded (Figure 3 a, e, g, h, j and 4 e–g). The median crest was observed in many *L. siliquaria* specimens in Thaiat Member (Figure 5) which provided the evidence of bilateral symmetry of the forms. Here, all the *L. siliquaria* specimens occurred as isolated specimens with observed length ranging from 15 to 19 mm, width 4–6 mm and relief from 9 to 10 mm. These trace fossils were formed and filled by rock sedi-

ments identical to that of the host. These were commonly gregarious animals and many *L. siliquaria* specimens did not show any preferred alignment on the bedding surfaces.

**Remarks:** The *Lockeia* ichnogenus is considered as the resting traces (cubichnia) of burrowing bivalves<sup>3,4,6,32</sup>. *L. siliquaria* are the bivalve temporally stopped feeding traces<sup>9</sup>, treated either as dwelling structures of suspension feeding or as fugichnial response to changing environmental conditions<sup>33</sup>. The present studied specimens were perfectly similar to the mode of occurrence and overall morphology of ichnospecies *L. siliquaria* proposed in earlier studies<sup>1,17</sup>, and therefore, they are assigned as *L. siliquaria* trace fossils. This ichnospecies is different from *L. ornata*<sup>33</sup> due to absence of ornamentation on the walls; *L. czarnockii*<sup>14</sup> due to lack of large size with drop-shaped morphology and from *L. cunctator*<sup>14</sup> due to absence of linear or connected arrangement of specimens. Regionally, this ichnotaxon is also correlated to *L. siliquaria* reported from the Badabag Member of Jaisalmer



**Figure 2.** Generalized lithostratigraphic column of Thaiat Member of Lathi Formation of the Jaisalmer Basin showing trace fossils bearing horizons<sup>30</sup>.



**Figure 3.** a, Photograph showing *Lockeia siliquaria* trace fossils preserved as convex hyporelief, small almond-shaped oblong bodies with more or less tapering at both ends, Lc indicates *Lockeia cunctator* and Lb, club-shaped morphology; b, Close-up view of *L. siliquaria* bed; c and e–i, Close-up view of well preserved *L. siliquaria* specimens; d, Close-up view of *L. siliquaria* specimens showing rounded and elongated morphology where Lb indicates club-shaped morphology; j, Close-up view of *L. siliquaria* trace fossils bed where Lb indicates club-shaped morphology. Scale: Bar is equal to 2 cm.

Formation, Rajasthan<sup>34</sup>, from the Jurassic of Kachchh, Gujarat<sup>35</sup> and from the Kala-Dongar Formation, Kachchh, Gujarat<sup>36</sup>. The specimens of *L. siliquaria* of the present study have been ideally preserved with more clear morphology and closely similar to such types of trace fossils of Badabag Member of Jaisalmer Formation<sup>34</sup>. Globally, these are also well compared with *L. siliquaria* recovered from HaB-berge area, Franconia, Southeastern Germany<sup>17</sup>, the Agrio Formation of the Neuquen Basin, Argentina<sup>37</sup>, the Early Jurassic Holy Cross-Mountain, Poland<sup>38</sup>, and from the Permian Teresina Formation of Cerro-Caveiras, South Brazil<sup>39</sup>.

**Occurrences:** Yellowish brown fine-grained rippled calcareous silty sandstone of Thaiat Member of Lathi Formation of the Jaisalmer Basin, Thaiat area, Jaisalmer, Western Rajasthan.

**Ichnogenus:** *Lockeia*<sup>1</sup>

**Ichnospecies:** *Lockeia cunctator*<sup>17</sup> (Figure 4 a–f and j).



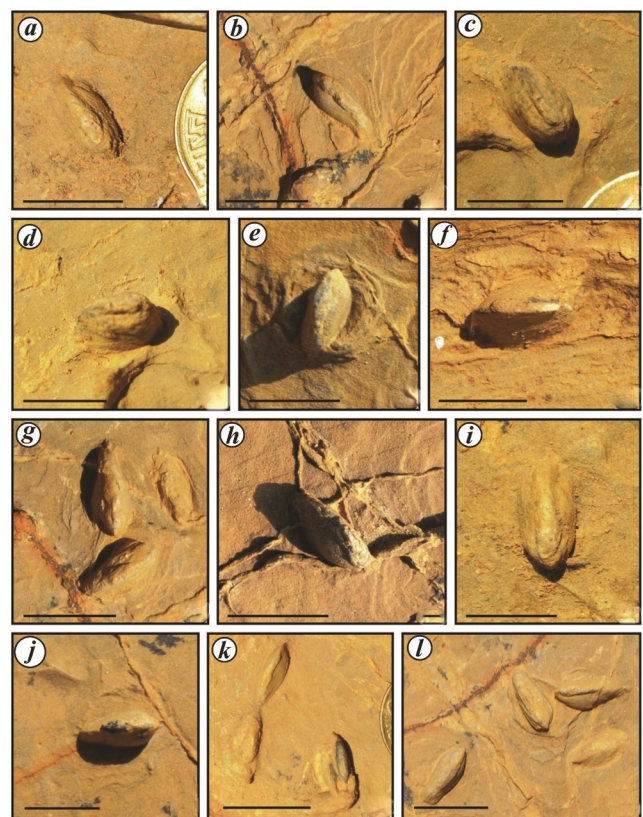
**Figure 4.** a–c, Close-up view *L. cunctator* which are arranged more or less in a row and diverging away from the main axis; d, e and j, Close-up view of *L. cunctator* preserved as hyporeliefs with more or less arranged in row or lines; f, Close-up view of *L. cunctator* and *L. siliquaria*; g, Close-up view of *L. cunctator* and *L. siliquaria* specimens; h and i, Close-up view of *Lockeia* traces showing club-shaped morphology. Scale: Bar is equal to 2 cm.

**Material:** DG/JNVU/TF/Thaiat Section of Lathi Formation/Jaisalmer/08 slabs containing 86 connected specimens in rows or lines.

**Derivation of name:** *Cunctator* (Latin) = waverer<sup>17</sup>.

**Diagnosis:** Elongated, almond-shaped or club-shaped oblong bodies with tapering at both ends which are more or less arranged in rows or lines and diverging away from the main axis<sup>17</sup>.

**Description:** The *L. cunctator* trace fossils are small, bilaterally stout with smooth surfaces, elongated, commonly almond-shaped, oval-shaped and club-shaped oblong bodies and tapered at both ends. They are preserved as convex or positive hyporeliefs, are more or less connected to each other and arranged in rows or lines. These trace fossils were found connected as two sets of 7–9 specimens, six sets of 4–6 specimens and twenty sets of 2–3 specimens in rows or lines in 8 slabs with average observed length of 15 mm, 4–6 mm width and 6–9 mm height of specimens. Here six sets of club-shaped morphology (*Lb*) of *L. cunctator* were also observed (Figure 3 a, d, j and 4 h, i) which indicate the diverging behaviours of animals in various directions from main axis. Normally,



**Figure 5.** a–f and h–j, Close-up views of well preserved *L. siliquaria* trace fossils with sharp median crest; g, k and l, Photograph showing of 3–4 *Lockeia* specimens with sharp median crest. Scale: Bar is equal to 2 cm.

these trace fossils were formed and filled by rock sediments similar to that of the host.

*Remarks:* The club-shaped arrangement of *L. cunctator* represents the locomotion or probing traces of bivalves in different directions<sup>17</sup>. These trace fossils ideally have similar mode of occurrence and overall morphology of ichnospecies *L. cunctator* proposed by earlier studies<sup>17</sup>, such as almond or club-shaped mounds arranged in rows or lines and diverging away from the main axis. Therefore, they are assigned as *L. cunctator* trace fossils. This ichnotaxon is quite different from *L. ornata*<sup>33</sup> due to lack of ornamentation on the walls; from *L. siliquaria*<sup>1</sup> which occur as isolated specimens and from *L. czarnockii*<sup>14</sup> due to absence of large sized and drop-shaped forms. These *L. cunctator* trace fossils also differ from the ichnogenus *Ptychoplasma*<sup>10</sup> as, generally it moves in directions away from the main axis, whereas the *Ptychoplasma vagans* traces are discontinuous, irregularly meandering or looping patterns and arranged in a single plane<sup>11,34,40</sup>. In Thaiat area, some small individual *Lockeia* specimens also occurred encompassing with *L. cunctator* (Figure 4 c–e and j) which indicated that they might be generated by smaller or younger bivalves.

*Occurrences:* Yellowish brown fine-grained rippled calcareous silty sandstone of Thaiat Member of Lathi Formation of the Jaisalmer Basin, Thaiat area, Jaisalmer, Western Rajasthan.

## Discussions

### Palaeoecology

The *Lockeia* trace fossils are significant to understand and interpret the life history, ecology and ethology of bivalves<sup>41</sup>, and so the sediments of the Thaiat Member of Lathi Formation were studied for palaeoecological aspects and described here in brief. Bivalves are considered as the main producers of *Lockeia* traces and their different morphologies have shown living and feeding strategies of bivalves<sup>33</sup>. The presence of heterodont bivalves, bakevelliid bivalves and other type of bivalves<sup>25</sup>, and deep-burrowing of bi-siphonate bivalves, the trace markers of *Hillichnus*<sup>42</sup> in the Thaiat Member also support this interpretation. Here, the *Lockeia* trace fossils appear in the fine-grained calcareous silty sandstone, and their morphological variations, and preservations are strongly controlled by substrate fluidity and sedimentation rates. The large occurrences of *Lockeia* indicate that the conditions would have been extremely favourable for the bivalve communities which, in several cubichnia were associated with repichnia. This means that the vast settings including food, oxygen and ideal substrate consistency permitted these bivalves to generate here when the silty layer was being deposited.

These bivalve trace markers were tolerant towards fluctuations in salinity, turbidity and sedimentation rates, as well as short periods of oxygen depletions. These tolerances reflect the opportunistic behaviours for the inhabitants in the stressful settings. The life position and vertical movements of bivalves also indicated that they were able to excavate and inhabit in shallow substrates<sup>33</sup>. The availability of traces of several epifaunal and infaunal organisms, body fossils, trace fossils and wood remains showing the existence of wide variety of herbivore, carnivore and detritivore habitats, might have contributed to an ecological system in shallow-marine environments in Thaiat Member of Lathi Formation of Jaisalmer Basin.

### Paleoenvironment

The lower part of Thaiat Member is mainly made of siliclastic sediments with low CaO and MgO contents containing wood remains and has shown fluvial environments<sup>25,30,43</sup>. The upper part is more calcareous with more diversified fauna such as nerineid gastropods, heterodont bivalves, bakevelliid bivalves, oysters, *Trigonia*, *Eomodion*, rhynchonellid brachiopods and crinoids indicating marine environment<sup>25,28</sup>. The traces of *Teichichnus*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Skolithos*<sup>27</sup> and *Hillichnus agriensis*, *Jamesonichnites heinbergi* and *Ancorichnus ancorichnus* trace fossils reported from strata or beds of upper Thaiat Member also suggested shallow-marine environment<sup>42</sup>. The *Lockeia* are well represented trace fossils and are important in environmental interpretations. The records of *Lockeia* traces have been more common in marine, deltaic and estuarine deposits<sup>44–48</sup>. They have also been found in marine to non-marine<sup>16</sup> and shallow to deep water environments<sup>33</sup>. In the present study, both ichnotaxa *L. cunctator* and *L. siliquaria* have been recovered in abandoned nature and diverse forms in yellowish brown fine-grained rippled calcareous silty sandstone of upper Thaiat Member of Lathi Formation. The abundant occurrences of *Lockeia* suggest that the conditions would have been extremely favourable for the bivalve communities. Sedimentologically, this facies showed well cemented, moderated to well sorted, fine to massive fine grains, and made of 1.22 m thick bed or strata with ripple marks and appeared in shallow water depositional environment. Based on the presence of *Lockeia* trace fossils with the above mentioned associated fauna and trace-fossils<sup>25,27,28,42</sup>, shallow-marine environment is suggested for the Upper Thaiat Member. Thus, this finding (*Lockeia* traces) adds a new evidence of shallow-marine environment for the upper part of the Thaiat Member of Lathi Formation of the Jaisalmer Basin as suggested by earlier researchers<sup>25,27,28,30,31</sup>.

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