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# Paleoenvironmental Reconstruction of Quaternary Sedimentation in Eastern Sri Lanka: An Ichnological Study

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## ABSTRACT

**Quaternary sediment deposits are well exposed along the eastern coastal margin of Sri Lanka. Systematic trace fossil studies along with sediment characteristics have been carried out for the first time to interpret the paleoenvironment that prevailed during Quaternary sedimentation in eastern Sri Lanka. The trace fossils *Thalassinoides, Skolithos* and *Polykladichnus* have been recognized about 5m above the present mean sea level. Features of the major trace fossil, *Thalassinoides,* indicate that it was formed by Thalassinidean shrimp *Calianassa*. Isolated, vertical to steeply inclined, cylindrical to sub cylindrical tubes with thin internal wall lining and inner wall striations of *Skolithos* and *Polykladichnus* show that they were formed by polychaetes. The typical characteristic of *Polykladichnus* is Y-shaped branching with slight enlargement at junctions. Morphology and association of burrows as well as mineralogy, grain size and roundness of sediments indicate that the environment prevailed was marine soft grounds of the intertidal zone. Presence of preserved fine-scale features of burrows indicate that the bioturbated sandy tidal flat was suddenly exposed to the tropical environment due to sea level regression in Quaternary periods. Due to the microbial activities of wall linings, burrows were preserved and it was supported by other microbial activities that produced secondary iron bearing minerals that suffered subsequent oxidation. The bio-origination of red sediments of eastern coastal area of the present study can be used to interpret the debatable origin of the red beds found in northwestern and southeastern coastal areas of the island.**

## INTRODUCTION

Quaternary sediments are widespread along the eastern and northwestern coastal belts of Sri Lanka where they classified as older and younger Quaternary sediments (Cooray and Katupotha, 1991). Basal ferruginous gravel, red beds and terrace gravel are classified in to the older Quaternary deposits. The younger deposits have been categorized as alluvial, lagoon and estuarine sediments as well as unconsolidated and consolidated beach sediments. These sediments are characterized by varieties of fossils which can be utilized to reconstruct the eustatic-isostatic changes in the coastal environment (Katupotha, 1989, 2007).

Quaternary deposits consisting of shells and traces of fossils in the western, northeastern and southwestern coastal belts of Sri Lanka have been studied in depth (Swan, 1983; Katupotha and Fujiwara, 1988; Katupotha and Wijayananda, 1989; Cooray and Katupotha, 1991, Weerakkodi, 1992). Chronological studies on compositional and depositional events of shell deposits revealed that they piled up initially in emerged coastal embayments by wave actions and further rose up with marine transgression during mid-Holocene (Katupotha and Fujiwara, 1988; Katupotha and Wijayananda, 1989; Katupotha, 1989). A sea level rise during Pleistocene period was also identified with the evidences of the reddish gravel deposits extending along the southeastern and northwestern regions of the country (Cooray and Katupotha, 1991).

Fine grained, well rounded, polished quartz grains which referred as 'red earth' overlie the reddish gravels in both regions. Dahanayaka and Jayawardhane (1979), Weerakkodi (1990) and Cooray and Katupotha (1991) interpreted them as aeolian deposits. However, the source materials for the sediments as well as iron concentration of these deposits are still uncertain.

Similar types of reddish sedimentary deposits have been discovered in the eastern coast around Thuraineelavanai village in the Batticaloa district by the authors (Fig.1). However, these deposits are characterized by trace fossil burrows which were not recorded from other similar types of sediments within the country.

Trace fossil burrows have many advantages for identification of sedimentary environment and recognition of past sea level fluctuations (Carnoma et al., 2009; Buatois et al., 2010, Gandini et al., 2014; Villegas-Martin et al., 2014). Animal burrows are habitat controlled. Many studies have revealed that the morphology of burrows, degree of bioturbation, burrow association and cross cutting relationships are the basic proxies for the interpretation of paleoenvironment (Curran and Martin, 2003; Netto, 2007, Gingras et al., 2012). Further, several studies have focused to interpret the animal behavior (ethology) and ecological significance of present environments by correlating the traces of burrows and their characteristics (Curran and Martin, 2003; Gingras et al., 2008; Melchor et al., 2010). Thus, an attempt has made in this study to decipher the paleoenvironment using the trace fossil evidences and sediment analysis. Present paper is the first documentation of the trace fossils found in the partially consolidated sediments in the eastern coast as well as in the Quaternary deposits of Sri Lanka.

## GEOLOGICAL AND MORPHOLOGICAL SETTING

The Batticaloa lagoon has been formed due to isolation of the water bodies by complex barrier systems and further developed by shoreline changes (Katupotha, 2007). The width of the sediment bands of the lagoon barriers is narrow and they are associated with weathered to fresh basement bed rocks which could be traced more than 2km distance from the present coast line. The exposed rocks are Precambrian metamorphic rocks of Vijayan complex (Cooray, 1994) and they are biotite and granitic gneisses.

Traces of animal burrows are widely spread in Thuraineelavanai village and the environment is distinctive with mounded topography of burrows that are open or grass-covered. Animal burrows are preserved within the exposedred dish sediment deposit which is essentially composed of homogeneous sandy sediments. The surface mounded topographic features of fossils are well oxidized showing a

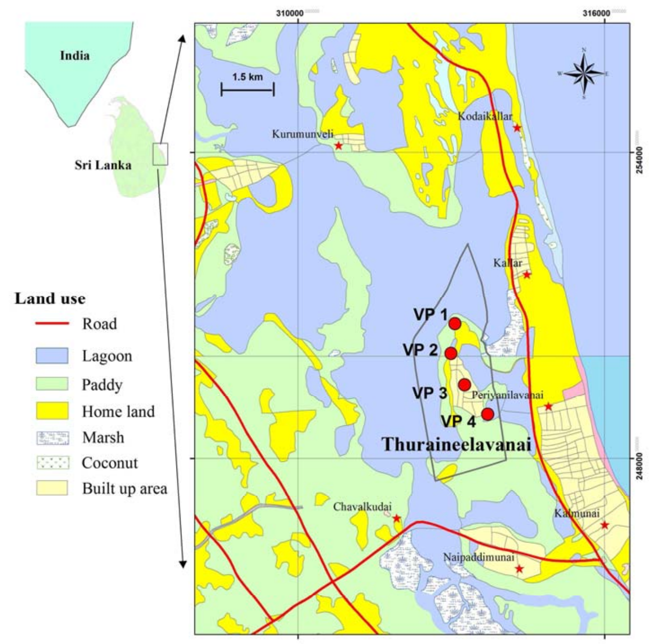


**Fig.1.** Map of Thuraineelavanai, Batticaloa district, Sri Lanka, showing the area of trace fossil burrows. VP1, VP2, VP3 and VP4 are the locations of vertical pits.

partially consolidated sedimentary bed, however, most of the original surface mounds are damaged due to human activities. Unconsolidated sediment layer that contains reddish yellow patches at top levels is retained in between the surface mounds of trace fossils and the weathered basement bedrock (Fig.2).

Generally the area falls in the dry zone of the country having an average temperature of 22.5-32.5°C and annual rainfall of 1500-2000 mm (Department of Meteorology, Sri Lanka, 2015). Present humid tropical environment is favorable for rapid oxidation of iron bearing minerals.

## MATERIALS AND METHODS

The field investigations were carried out during November and December, 2014. Field observations were made and described on the exposed trace fossils highlighting the general borrow morphology, burrow walls and branching (Villegas-Martin et al., 2014). Since the trace fossils are within partially consolidated oxidized sediments, sampling and molding was problematic as the sediments slack off easily. Certain consolidated broken parts of fossils were collected and studied in the laboratory.

Characteristics of sediments of the bioturbated area were analyzed for compositional and textural characteristics of sediments. Four vertical pits (VP1, VP2, VP3 and VP4) with an average height of 1m were dug within the partially consolidated fossil bearing sediment bed and sub-samples were collected in each pit with 30cm intervals for sedimentological analysis (Fig. 1). The sampling intervals were decided considering the homogeneity of sediments. The trace fossils are found within the top 30cm. About 250g of the samples were oven dried at 60°C for 24 hours. Stiff dried samples were disaggregated using porcelain mortar and pestle. Mechanical sieving was done on each sample in quarter phi intervals for 20 minutes using Retsch AS 200 digital sieve shaker and weight percentages were calculated. Mean size and sorting values were calculated following Folk and Ward method (1957). About 10g of 0.125mm sediment fractions were boiled and washed by 30% dilute HCl to remove the iron and carbonate coatings for shape analysis (Vos et al., 2014). Then they were thoroughly washed in distilled water and oven dried at 60°C. Sediments were mounted on glass slides for mineralogical and roundness analyses by optical means (following Powers, 1953).

## RESULTS

### Trace fossils of Eastern Quaternary Sediments

#### *Thalassinoides suevicus*

The burrows constitute complex branching system with horizontal and predominantly vertical sections. The length and the diameter of the horizontal burrows are less when compared to the vertical shafts. These horizontal burrows are connected to the main shafts through a gently upside curved bifurcations. The internal wall of the horizontal sections is smooth and mostly circular in cross section. The shape of the edge of them is U shape.

The diameter of the vertical shafts ranges from few millimeters to about 4 cm (Fig.3). Surface mounds were observed in most of the vertical shafts. One or more horizontal branches are connected to the high diameter shafts. The internal wall of the vertical shafts are smooth but the vertical sections are irregular, rather circular (Fig.3a). Upper edge of some vertical shafts show two handled cup shape with inner circular tube (Fig.3b). The ending of the vertical shafts is U shaped and overall well developed burrow has I- or L- shape.

The distinguishing features of this ichnogenera are predominant vertical orientation with anastomosing networks, U-shaped edges, absence of internal wall lining, irregular wall diameter and overall I- or L- shape borrow structure. Hence the burrow architecture defines the ichnogenera as *Thalassinoides suevicus* Rieth, 1932 (Myrow, 1995; Yanin and Baraboshkin, 2013).

#### *Skolithos linearis* and *Polykladichnus irregularis*

Vertically or near vertically arranged simple tube like structures are the common features of these trace fossils (Fig.4). The maximum length of the tubes is about 20cm. The external diameter of the tube is less than 1cm and internal diameter being in few millimeters. They generally appear as cylindrical bodies with respect to the external area. However, the internal burrow wall is distinct with irregular formation and thin wall lining (Figs. 5 a, b and c). In the cross sections, circular red to orange coloured rims are

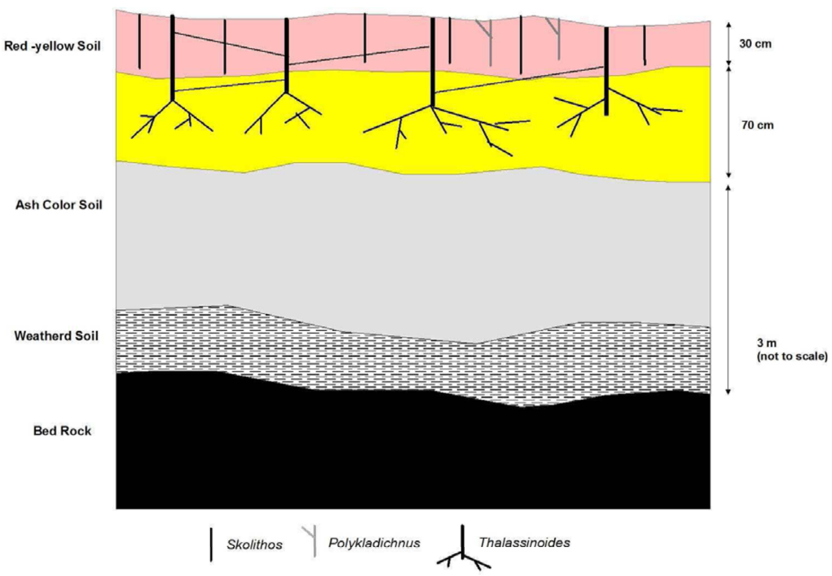


**Fig.2.** Diagram of vertical profile showing co-occurrence of *Thalassinoides*, *Skolithos* and *Polykladichnus* within 1 m height. Measured sediment characteristics of 1 m height are almost similar and further extensions also indicate similar nature.

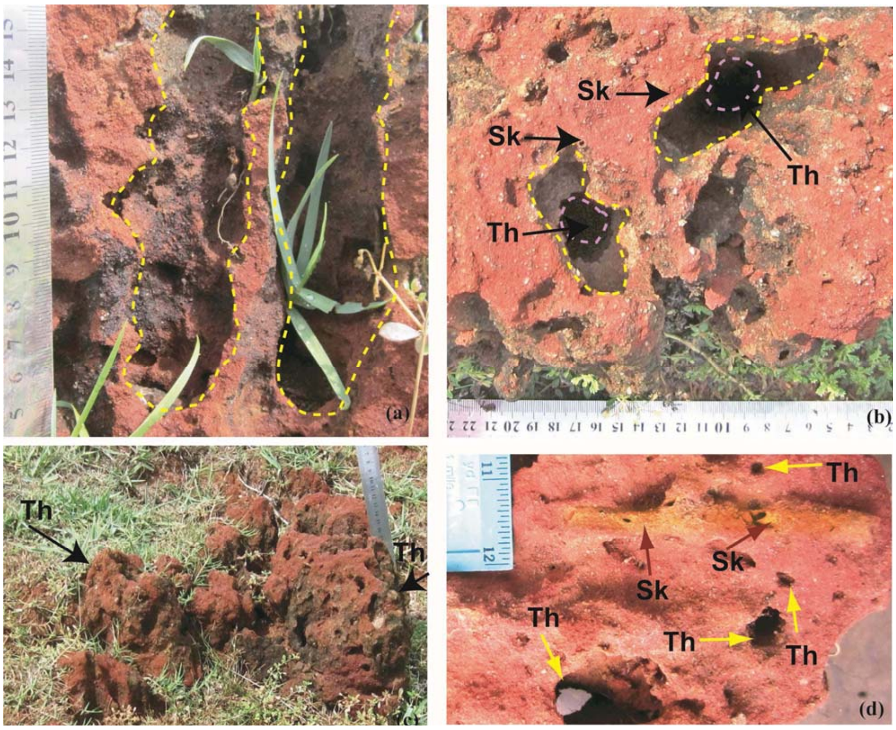


**Fig.3.** *Thalasinoides*. (**a**) Longitudinally cut section showing the swelling, unlined burrow walls with U shape edge. (**b**) Cross sectional view indicating the two handled cup shape with circular internal tube. (**c**) Sediment mounds around the top of the vertical shafts (**d**) Sample showing co-occurrence of *Skolithos* and *Thalassinoides*; brown colour arrows shows the tubes of *Skolithos* and yellow colour arrows shows the *Thalassinoides.*

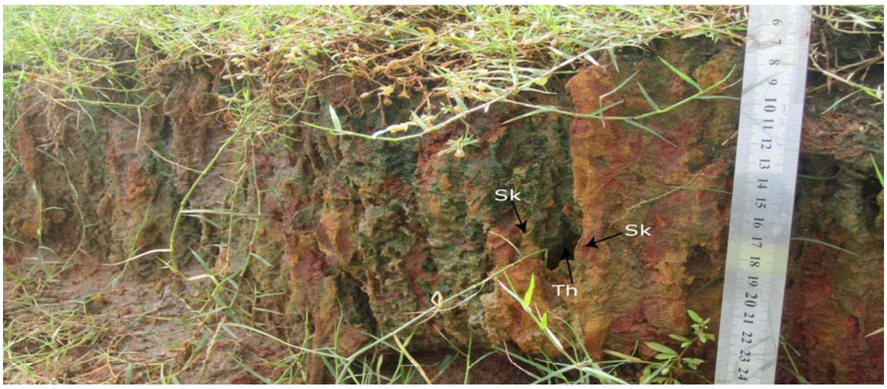


**Fig.4.** Field photograph of co-occurrence of *Skolithos* and *Thalassinoides.*

present. The bottom of the tube is V or U shaped (Fig.5 e). Three dimensionally the irregularities are elongated striations that recorded oblique or perpendicular to the tube axis. Compared to burrows of *Thalassinoides* this tube like structures are not densely crowded. Very few trace fossils of similar characteristics show Y shape branching with slight enlargement at the junctions (Fig.5d).

All the diagnostic features such as simple, vertical tube like orientation and ornamentation of the internal wall help in identifying the ichnogenera as *Skolithos linearis* Haldeman 1840 and rare Y shaped branching of similar simple vertical tubes indicate the presence of *Polykladichnus Irregularis* Fursich, 1981 (Schlirf and Uchman, 2005; Desai and Pattel, 2008; Mork and Bromley, 2008).

### Characteristics of sediment association

Sediments at this locality consisted of fine to medium grained and moderately well sorted to poorly sorted sediments (Table 1). About 90% of the sediments have quartz grains with rounded to sub-rounded edges (Fig.6) which indicates that the maturity of sediments is high.

Stratifications or laminations could not be observed within the 1m sediment layer. The top 30 cm of the studied layer is highly bioturbated with red and yellow patches. Below 70 cm is ash colour having some yellow colour stains within the upper 30 cm of it (Fig. 2). This indicates the burrow extension is more than 50 cm.

## DISCUSSION

### Paleoenvironmental significance

The morphological characteristics of the traces of animal burrows of *Thalassinoides, Skolithos* and *Polykladichnus* at Thuraineela vanai, in the study area indicate soft sediment intertidal paleoenvironment. The large vertical shafts and anastomosing network suggests variety of lifestyles of the trace-maker. Large vertical fabric from deep shafts of the *Thalassinoides* displays suspension feeding activity of trace-maker in shallow marine environments (Bromley, 1996). However, tidal environments also record vertical to inclined large diameter shafts with J to U shaped exhibiting interface feeding nature (Gingras et al., 2012). The sediment mounds around the top of the vertical shafts (Fig.3c) indicate the deposit feeding nature of the trace-maker (Griffis and Suchanek, 1991; Jin et al., 2012). In deep burrows, sediments are mined to exploit foods and then brought to the surface to form the mounds. Further, large diameter shafts with complex structures of *Thalassinoides suevicus* suggest that fluctuation of the salinity was not high compared to the most of estuarine environments (Curran and Martin, 2003; Gingras et al., 2012). The rhythmic pattern of tidal environments deposit organic matter in sub-strate laminations which are favorable for horizontal deposit feedings (Gingras et al., 2012). The anastomosing network of the present trace fossils might be such horizontal feeding activities following the nutrient sediment-water interface in tidal fluctuations. On the other hand, these galleries have been used by the trace-maker for well oxygenation below water- sediment interface (Griffis and Suchanek, 1991).

Generally *Thalassinoides* are considered as dwelling structures of decapod crustaceans (Myrow, 1995). The swelling structure or the enlargements of the burrow walls of large vertical shafts illustrate the turn around points of the shrimp or shrimp like organism that is not recorded on other decapods such as lobsters and crabs (Myrow, 1995). The two handled cup shape of the upper edge of the vertical shafts might be the body outline of such shrimp probably resting for interface

**Table 1** Mean and sorting values of sediments obtained from vertical pits of trace fossil burrows

| Sampling Depth (cm) | Mean particle size (ϕ) | | | | Sorting (ϕ) | | | |
|---|---|---|---|---|---|---|---|---|
| | VP 1 | VP 2 | VP 3 | VP 4 | VP 1 | VP 2 | VP 3 | VP 4 |
| 30 | 1.4 | 1.9 | 1.7 | 1.4 | 0.6 | 1.1 | 1.2 | 0.7 |
| 60 | 1.4 | 2.3 | 1.7 | 1.1 | 0.6 | 0.8 | 1 | 1 |
| 90 | 1.6 | 2.3 | 1.7 | 1.8 | 1.1 | 0.8 | 1 | 0.9 |

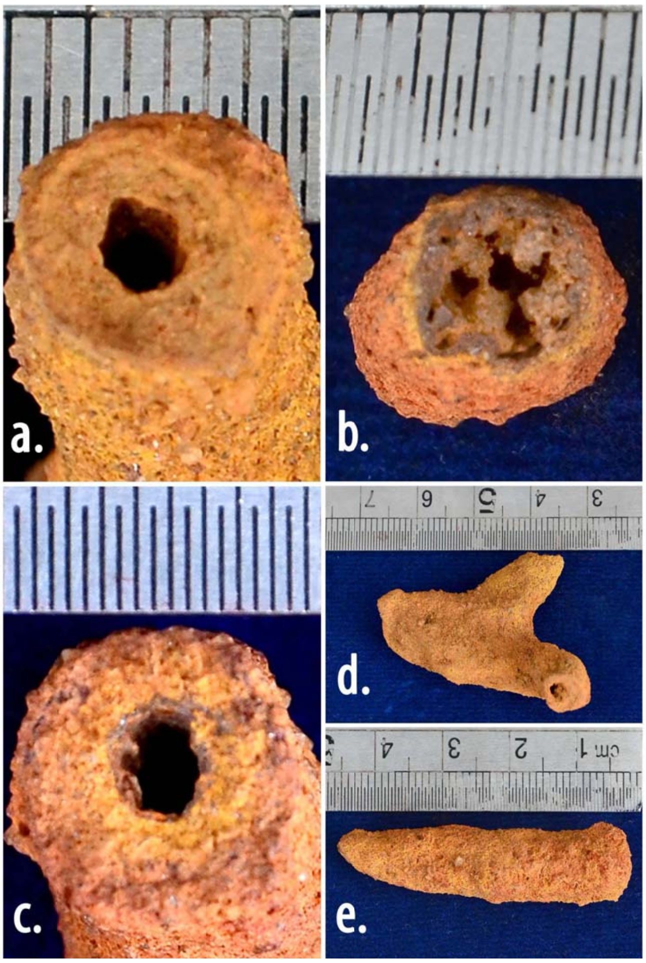


**Fig.5.** *Skolithos* and *Polykladichnus.* (**a**), (**b**) and (**c**) showing colour rims, internal wall irregularity and lined internal walls of the cross sectional view. (**d**) *Polykladichnus* with Y-shape branching with slight enlargement at the junction. (**e**) The bottom of the individual vertical tube has V-shape.

feeding (Fig.3b). Therefore, the trace-makers of the present locality should be Thalassinidean shrimps *Callianassa* that are common in tropical or sub-tropical temperate regions (Griffis and Suchanek, 1991). The Thalassinidean shrimps are typical of intertidal and shallow sub-tidal environments (Griffis and Suchanek, 1991; Myrow, 1995; Bromley, 1996; Buatois and Mangano, 2011). The greater depth of burrows of the Thalassinoides (>50cm) implies that the environment is most favorable for intertidal rather a sub-tidal environment (Griffis and Suchanek, 1991).

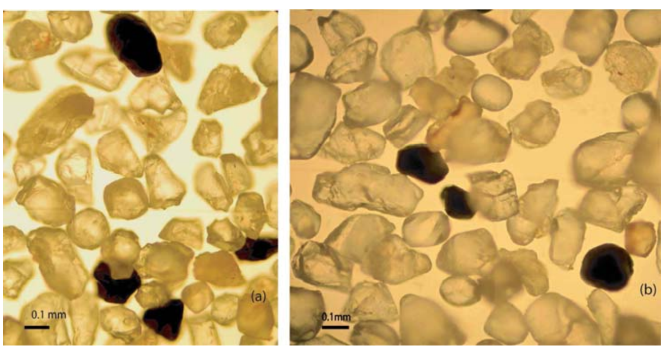


**Fig.6.** Cleaned sediments of tracefossil burrows: 0.125 mm size fraction X10. (**a**) Sediments of *Skolithos* (**b**) Sediments of *Thalassinoides.* About 90% of the sediments are quartz grains that having rounded to sub-rounded shapes.

*Thalassinoides suevicus* are characteristic for soft ground substrate and burrows were maintained by mucus linings (Myrow, 1995). However, there is no record of wall lining for the present samples. Instead of that, exposed burrows and substrate burrow margins of present locality show red to yellow color rims. Griffis and Suchanek (1991) explained burrows made by *Callianassa* species have wall lining with highly elevated bacterial numbers and high growth rates of microbial communities. Hence, the colour rims around burrow walls of *Thalassinoides* might be due to microorganism mediated alterations of wall linings forming iron bearing secondary minerals (Schieber, 2002; Virtasalo et al., 2012; Ahnand Babcock, 2012).

The intense bioturbation can be a result of high availability of nutrients and dense population in low sedimentation rates in tidal environments (Gingras et al., 2012). Since the tidal variation of Sri Lanka is not high (< 6cm), microtidal environments are generally present and therefore, low sedimentation rates that is favorable for dense population, can be expected.

The tube like recurrent geometry and wall lining of *Skolithos* also support the soft ground tidal environment that was suggested by *Thalassinoides*. Presence of lining and internal wall irregularities of *Skolithos* show that the tubes were constructed in soft sediments and secreated organics of the burrower prevent the collapses by binding the sediments around the dwell (Wetzel and Uchman, 2012; Wang et al., 2014). The trace maker of *Skolithos* probably worms or polychaetes in tidal sands or shallow marine settings that having tiny spines to make internal wall striations and sclerite to bind the sediments around it (Chamberlain, 1975, Han et al., 2007; Gingras et al., 2008). The vertical elongated nature of *Skolithos* implies us that interface feeding was prevailed in the intertidal environment (Gingras et al., 2008; Onuigbo et al., 2012). Similar feeding manners and burrows of polychaetes have been recorded in other countries (Frey, 1975; Chirananda, 2005). On the other hand *Skolithos* are restricted into smaller isolated areas and occur as individual vertical tubes of polychaetes. This isolated nature is characteristic for a beach or near high water line zones and only dense populations of *Skolithos* are recorded in sub tidal environments (Patel and Desai, 1999; 2008). Y shaped bifurcated *Polykladichnus* are rarely found and associated with *Skolithos*.

*Thalassinoides, Skolithos* and *Polykladichnus* preserved in eastern Quaternary deposits of Sri Lanka are co-occurring trace fossils at equal depths having intertidal paleoenvironments with soft ground (Figs.3b and d, and Fig.4). Similar co-occurrence has been recorded in Quaternary deposits of western India and interpreted the paleo-environment as lower intertidal flats (Chirananda, 2005). The trace-makers of these trace fossil burrows are significant in marginal marine conditions (Gingras et al., 2000).The bioturbation structures of the *Thalassinoides* have been accompanied by the tubes of *Skolithos* which indicate that *Thalassinoids* were the dominant type and *Skolithos* always follow the structures made by *Thalassinoides* at the same stage (Figs.3b and d).

The mineralogy, grain size and roundness of associated sediments (30cm depth) has further confirmed the paleoenvironmental analysis from the animal traces. Constant sedimentological characteristics of 1m thick layer in fossilized area indicate similar vertical depositional environment. Rhythms or the common sedimentary feature of tidal environments was not observed within the 1m height. Perhaps the low tidal variation may have affected due to sedimentary variations of burrowing bed. The mineralogical composition and texture in 1 m depth is significant for long term reworking and winnowing of sediments. However, medium sized sediment fractions indicate the beach environment in the burrow suites preferred medium energy conditions. The medium sandy nature of the location is favorable for irregular branched burrow systems of the species *Callianassa* (Griffis and Suchanek, 1991).

**Fossil environment with the sea level**

The altitude of the locality is above 5m from the present sea level and this might be a result of sea level changes in the Quaternary period (Katupotha and Fujiwara, 1988; Katupotha and Wijayananda, 1989, Ranasinghe et al., 2013). These sea level changes of the Quaternary period have been recorded either as eustatic (global) or isostatic (local) changes. Local changes of sea level in the eastern coastal areas of Sri Lanka in recent history are mainly due to tectonic activities and intra-plate deformations of Indo-Australian plate (Munasinghe et al., 2013). Global changes of sea level also have been recorded during the Quaternary period (Miller et al., 2012). Therefore, the type of sea level change of the present environment can be by both ways. Therefore, the altitudinal position of the present location is mainly affected by a sea level regression during the Quaternary period. Similar, sudden sea level regressions in late Pleistocene-early Holocene period have washed out the loose sediments in and around the burrows of India and elevated the tidal environments (Chirananda, 2005). Preserved in situ fine structures of trace fossils of the present locality indicate such sudden sea level regression.

The natural exhumation and oxidation of subaerial tidal sandy flats to the tropical climate might have influenced the burrow preservation. The wall linings of the burrow makers of the present location probably have high number of microbial mediated growth of bacteria and hence secondary iron rich minerals were formed (Griffis and Suchanek, 1991). Reddening and concretions of exposed sediments and sub-strate burrow walls ought to be affected by alterations of wall linings. Similar reddening and concretion of burrow associated sediments may be due to alteration of pyrite (Schieber. 2002; Virtasalo, et al., 2012; Ahnand Babcock, 2012).

The red sediment deposits (red earth) of northwestern and southeastern coastal regions of Sri Lanka have being recognized as reworked dune deposits that occur in the dry zone and the dry climatic conditions prevailed during Quaternary period assisted the formation (Cooray, 1967; Dahanayaka, 1978; Weerakkodi, 1990). However the source materials for the sediments are still debatable. These deposits have rounded, well sorted, fine sediment grains that are embedded in clayey matrix (Cooray, 1967). Majority of the grains are quartz with minor amounts of ilmenite and magnetite.Geochemically, red earth contains high amount of iron oxides and aluminium oxides (Vithanage et al., 2006). The prominent iron oxides are hematite that gives the red colour for the formation (Dahanayaka and Jayawardhane, 1979). Sediment grain size, roundness, sorting, and mineralogy of the red trace fossil bearing deposits of Thuraineelavanai, Batticaloa district have similarities with the northwestern and southeastern red earths. The spread of red earth deposits of Sri Lanka is around the coastal margins of the country having different elevations. Red earth deposits of southeastern region have partially consolidated sediments which are above 10m from the present sea level (Weerakkodi, 1990). The Northwestern deposits occur as long ridges and the maximum height reaches up to 40m (Katupotha, 1994). However, the local elevation of the Thuraineelavanai bio-originated red earth deposits is comparatively low.

The origin of the reddish iron oxides of northwestern and southeastern red earths is still uncertain. Though the sediment characteristics of all locations are similar there is no record of trace fossil evidences in other locations of the country. The trace fossil association and characteristics of sediments of the present red sediment deposits of eastern coast can suggest a biogenic origin resulting in the reddening of iron bearing minerals. Probably, the changes of the elevation, reworking of sediments and weathering processes may have interrupted the preservation of the trace fossil burrows in such localities. Further studies combining geochemistry, micropaleontology and geochronology are needed to interpret the relationship with the present study environment and the other red earth deposits of Sri Lanka.

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