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ICHNOLOGY OF THE PANAMANIAN MIOCENE CHAGRES FORMATION: AN ADDITIONAL PALEOENVIRONMENTAL PROXY

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Abstract

The paleobathymetry of the Late Miocene Chagres Formation in Panama has been subject of debate. Past paleobiological surveys have resulted in contrasting interpretations of the paleo depths recorded by this formation. This study proposes the use of trace fossils as an additional proxy to narrow the possible conditions under which the Chagres was deposited. A census of the trace fossils present in the Chagres was performed in 10 localities along its coastal exposure, covering its three members: Toro Limestone, Piña Sandstone and Rio Indio Siltstone. Fifteen ichnogenera were identified: *Asterosoma, Aulichnites, Chondrites, Diplocratherion, Ophiomorpha, Paleophycus, Rhizocorallium, Rosselia, Siphonichnus, Scolicia*, *Schaubcylindrichnus, Skolithos, Teichichnus, Teredolites* and *Thalassinoides*; which coupled with the sedimentological data place the Chagres Formation in a shallow marine setting ranging from high energy conditions in the Toro Member, moderate energy in the Piña Sandstone, to low energy in the Rio Indio Siltstone. The Toro Member represents a subtidal dune migration field generated by the action of a unidirectional current, and the Piña Sandstone and Rio Indio Siltstone record the lateral transition to lower energy facies as the distance from the current increases.

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1. Introduction

The complex uplift history of the Isthmus of Panama has been a subject of great interest due to the global oceanographic, climatological and biological implications that have been associated with its formation. This local event joined previously isolated land masses and separated two oceans that were connected in the past by the Central American Seaway (CAS), playing major role in establishing modern ocean circulation patterns (e.g., Murdock et al., 1997; Maier-Reime & Mikolajewicz, 1990; Nisancioglu et al., 2003) and triggering biological processes such as the diversification of newly separated Pacific and Caribbean marine faunas and the Interchange between the North and South American land mammal faunas known as the Great American Biotic Interchange (Woodbourne, 2010; Whitmore & Stewart, 1965; Webb, 1976).

The Isthmus of Panama grew as an intraoceanic island arc beginning about 66 Ma (Wörner et al., 2009; Wegner et al., 2011), as a result of the subduction of the Farallon plate under the young Caribbean plate. Isthmian arc magmatism has had few interruptions from its inception until today (MacMillan et al., 2004; Wegner et al., 2011; Montes et al., 2012a). Most notably, magmatic activity stopped east of the Canal Basin after Lutetian times, probably as a result of left-lateral deformation and orocline formation (Montes et al., 2012b). It is the middle Eocene that marks the time of initiation of sub-aerial sedimentation in the Gatuncillo and Tonosi formations (Woodring, 1964; Buchs et al., 2011). Since then, the Isthmian stratigraphy seems to have gone through periods of alternating marine and terrestrial sedimentation, culminating in marine deposits of the Gatun and Chagres formations (Collins et al., 1996; Coates et al., 2004).

The Chagres Formation has been pinpointed as the location where the last connection existed between the Caribbean and the Pacific oceans during the late Miocene (Collins, 1996). However, the paleodepth of this connection is not clear. While the paleobathymetry derived from benthic foraminifera indicate bathyal depths (Collins, 1996), the molluscan fauna indicates shallower environments (Hendy et al., in review).

In this contribution, we use trace fossils as an additional proxy to determine the paleoenvironmental context of the Chagres Formation. Trace fossils are considered the evidence of animal behavior, typically as a response of subtle changes in physicochemical conditions in the environment, and thus represent a powerful tool for paleonvironmental reconstruction (Buatois and Mangano, 2011; Pemberton et al., 2001). Fifteen ichnogenera were identified along the Chagres Formation, including *Asterosoma, Aulichnites, Chondrites, Diplocratherion, Ophiomorpha, Paleophycus, Rhyzocorallium, Rosselia, Siphonichnus, Scolicia, Skolithos, Teichichnus, Schaubcylindrichnus, Teredolites and Thalassinoides* .The distribution of these ichnogenera along the different members of the Chagres Formation was integrated with sedimentological data, providing useful information to reconstruct the sedimentary environments where the structures were formed.

2. Geologic Setting

The Panama Canal Basin is a Cenozoic sedimentary basin formed over a Cretaceous volcanic basement (Woodring, 1957; Kirby et al., 2008; Montes et al., 2012a) along the tectonic boundary of the Chocó and Chorotega Blocks of the Panama microplate. The Canal Basin is located over a very complex tectonic area, evidenced by the extensive northeast-southwest faulting systems (Mann, 1995; Pratt et al., 2003). Ages of the sedimentary succession range from Eocene to Pliocene, comprising sediments of marine and terrestrial origin and volcanic rocks (Woodring, 1957). This succession is overlaid unconformably by Quaternary unconsolidated deposits referred to as "Pacific Muck" and "Atlantic Muck" (Woodring, 1957).

The late Miocene Chagres Formation (MacDonald, 1915) is the youngest unit in the Cenozoic Canal Basin. The unit unconformably overlies the Gatun Formation (Woodring, 1957) and its outcrop area is restricted to the northern part of the Canal Basin in the Colón province of Panamá, on the west side of the Panama Canal, and forms gently and uniformly dipping coastal exposures extending southwest from Toro Point to the Gobea River (Fig.1).

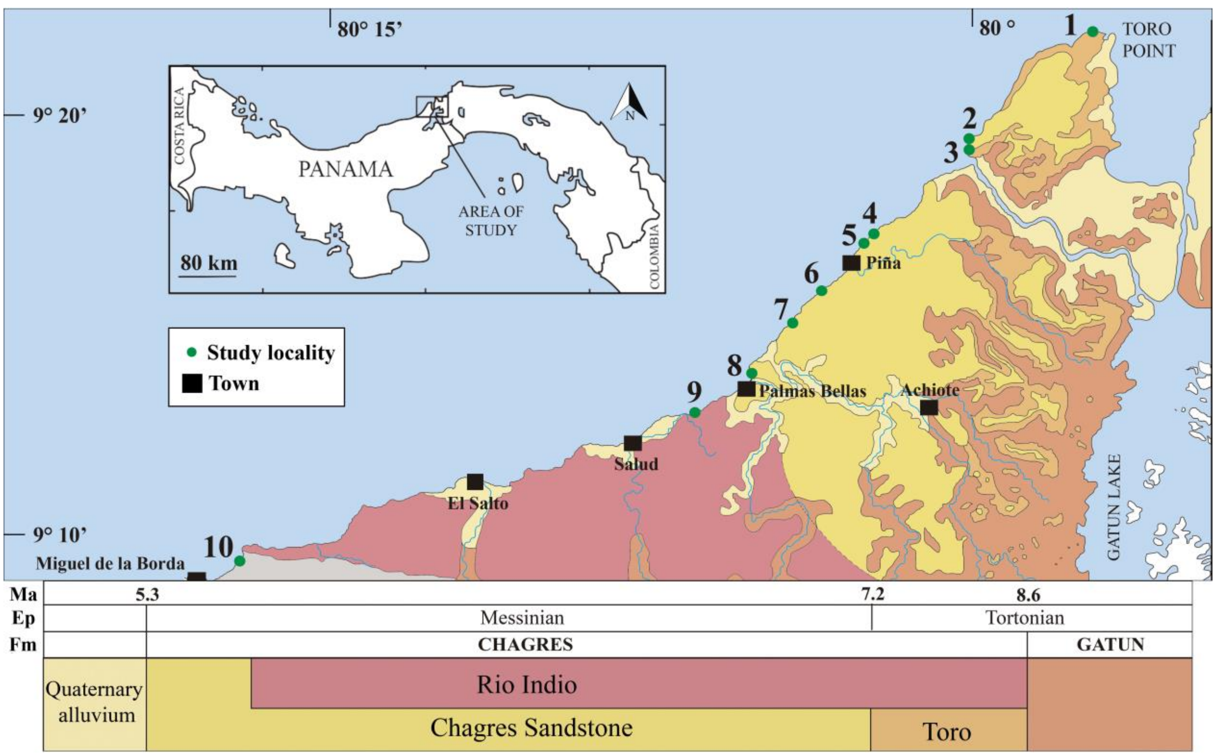

Figure 1. Geologic map of the Caribbean Coast of Panamá, modified after Collins et al. (1996).

The estimated thickness of the unit is 250 m (Collins et al., 1996), and has been divided into three members (Fig. 1), which represent the lithological variation as the outcrop extends towards the southwest, namely the Toro Member (Woodring, 1957), the Piña Sandstone or Chagres Sandstone Proper (Jones, 1950) and the Rio Indio Siltstone facies (Aguilera & de Aguilera, 1999; Coates, 1999; Collins and Coates, 1999). The Toro Member exposed at Toro Point, is the basal segment of the formation and consists of lime-cemented coquina composed by barnacle plates, echinoid spines, pectinid fragments and coral fragments, interbedded with coarse-grained sandstone beds with abundant mollusk fragments (Woodring, 1957; Collins, 1996, Coates, 1999). Cross bedding is common in this member, representative of high-energy currents (Coates, 1999; Hendy, 2013). Towards the southwest, the Toro Member is replaced by the Piña Sandstone facies (deepwater sandstone facies in Collins et al, 1996, refer to Fig.1), characterized by massive sandstone and siltstone beds with little evidence of bedding (Jones, 1950). Lithologically, it is a medium- to fine-grained volcanic, silty sandstone, which grades laterally into the siltstone-sandstone Rio Indio Facies (Collins, 1996; Coates, 1999).

The paleobathymetry of the Chagres Formation is a matter of debate; the estimates derived from benthic foraminifera indicate paleodepths of 200-500 meters, having an important affinity to modern species found in the Pacific Ocean (Aguilera & Aguilera, 1999; Collins, 1999). Other estimates based on fossil fish assemblages give a broader 100-700 meters range (De Gracia et al., 2012). However, the lithology and sedimentary structures seem to suggest a shallow, high-energy environment in the Toro Member and shallow (0-100m) depths in the siltstone Rio Indio Member. Additionally, the molluscan fauna (Hendy et al., in review) and the presence of shallow marine Gatunian Fauna throughout the formation as documented by Woodring (1957), indicate a shelfal (150 m at most) depositional paleodepth.

3. Study Location & Methodology

This study was performed on ten localities spread approximately 35 kms along the coastal exposure of the Chagres Formation on the Caribbean coast of Panama; extending southwest from Toro Point at the mouth of the Panama Canal to the town of Miguel de la Borda (Table 1, Fig. 1).

Locality number	Name	Coordinates	Sediment Samples in Panama Paleontology Proyect
1	Toro Point	9°22’17.4’’N, 79° 57’ 14.4’’W	1172-1174
2	Playa Tortuguillas	9° 19' 36.1200" N, 80° 0' 13.6080" W	1091
3	Fuerte San Lorenzo	9° 19' 21.4680" N, 80° 0' 13.0320" W	1076, 1088-1090, 1093
4	Piña Norte 1	9° 17' 36.1320" N, 80° 2' 16.0080" W	1649-1651
5	Piña Norte 2	9°17’27’’N, 80°02’23’’W	“ “
6	Piña Sur	9°16’27’’N, 080°03’11’’W	-
7	Balneario Tommy	9° 15' 19.9440" N, 80° 4' 13.1880" W	1646 – 1647
8	Monasterio Palmas Bellas	9°14'8.52"N, 80° 5'13.78"W	-
9	Palmas Bellas	9°, 13' 13.6200" N, 80° 6'33.41"W	1644-1645
10	Rio Indio	9° 9' 25.4880" N, 80° 17' 34.5120" W	158-160

Table 1. Localities used in this study, along with the reference number of the sediment samples used in previous paleobiological studies performed in the Panama Paleontology Proyect (Collins et al., 1996; Collins & Coates, 1999), collected at these approximate locations.

These localities were selected based on previous paleobiological surveys conducted throughout the formation and on accessibility of outcrops. In each locality, a stratigraphic section was measured and described in order to place the observed trace fossils in a sedimentological context. The degrees of bioturbation in each section were quantified using the Bioturbation Index proposed by MacEachern & Bann (2008) (Fig. 2). Traces present throughout the formation were identified using Pemberton’s Atlas for Identification of Trace Fossils.

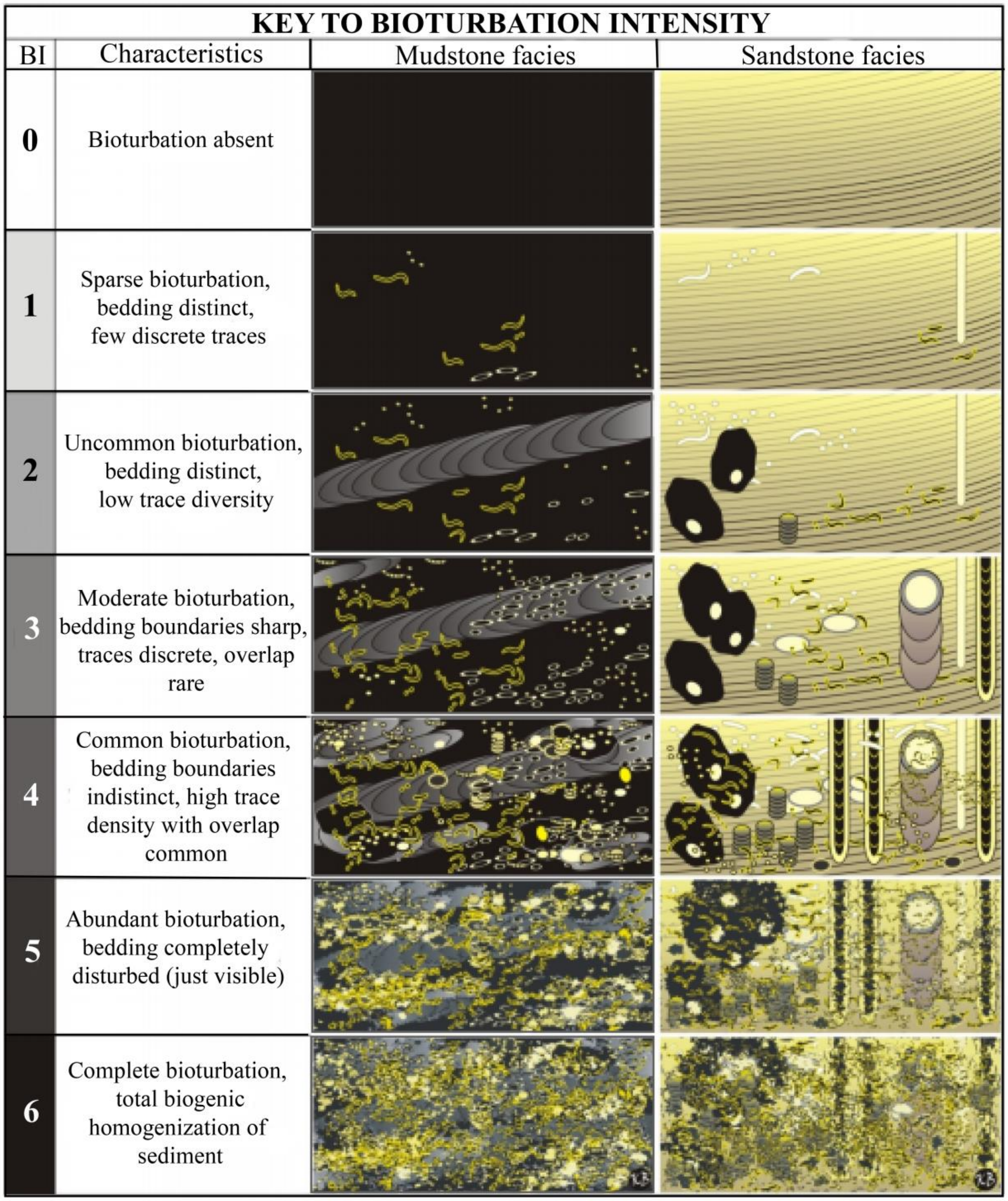

Figure 2. Diagram illustrating the use of the Bioturbation Index (BI), modified after MacEachern & Bann (2008). Based on the works of Reineck (1963), Taylor and Goldring (1993) and Taylor et al. (2003).

4. Results

Seven main sedimentary facies were described occurring in the outcrops studied along the coastal exposures of the Chagres Formation (Table 2).

Facies	Description	Occurrence and Contacts	Sedimentology/Accessories
F1	Coquinas *(Bioturbated)*	- Underlies F2 with sharp to diffuse contact. - Overlies F2 with erosional contacts.	- Barnacle and echinoid dominated coquina. Pectinid fragments are abundant. Skeletal fragments are invariably fragmented -Massive coquina with discrete 5-30 cm intervals of oriented coquina with incipient cross bedding - Silty coarse grained lithic sand matrix
F1A	Coquina and Sandstone Cross beds *(Bioturbated)*	- Found between layers of F2. Lower contacts are erosional, upper contacts are interfingering. - Found only at the base of the formation.	- Thinly bedded cross beds with truncated steep prograding foresets, cross beds are alternating shelly barnacle coquina with silty matrix and very coarse grained silty sandstone - Bioclast proportion decreases in the layers found towards the top of the section.
F2	Massive Coarse Grained Sandstone *(Bioturbated)*	- Found above F1 with erosional contact. Is found between F1A and F1B occurrences. Contacts between F2 and F1B may be sharp or erosional.	- Poorly sorted coarse grained silty lithic sandstone, no internal structures can be observed. Occurrences in lower section pinch out towards the west.
F2A	Fining Upward Coarse Grained Sandstone *(Bioturbated)*	- Gradational inferior contact with F1A, sharp contact with F1B. - Single occurrence in measured section.	- Poorly sorted silty coarse grained sandstone, grading up to very fine grained muddy sandstone at the top of the layer.
F3	Massive Medium Grained Sandstone *(Bioturbated)*	- Erosional contact when overlaid with F3A is observed, wavy contact with F3B is observed. Sharp contacts with F8, wavy contacts with F5 and F4A. - Dominates throughout the lower section of the formation.	- Medium to fine grained muddy lithic sandstone. No internal structures can be observed. Abundant calcareous grains.
F3A	Massive Medium Grained Sandstone *(Not bioturbated)*		Medium to fine grained muddy lithic sandstone. No internal structures can be observed. Abundant calcareous grains. Discrete lenses of mud, possibly tuffaceous, are present.
F3B	Hummocky Bedded Medium Grained Sandstone *(not bioturbated)*	- Erosional contact with underlying F3, superior contact gradational into F3.	- Medium to fine grained muddy lithic sandstone. Base of layer always presents a concentration of disarticulated shell material, fish otoliths and shark teeth. The layers may then have variable thicknesses of hummocky bedding with proportionally less skeletal material.
F3C	Fining Upward Medium Grained Sandstone *(Bioturbated)*	- Gradational contact with underlying F3A. Erosional contact with F3. - Single occurrence in the section.	- Moderately sorted medium to fine grained muddy lithic sandstone. No internal bedding can be observed.

F4	Massive Fine –Grained Sandstone *(Bioturbated)*	- Erosional contacts when underlying F4B. Wavy contacts when overlying F4B. - Wavy contacts with F4A. - Sharp contact with F8. - Contacts with F5A may be wavy or sharp. -Oxidation surfaces are common between F4 layers towards the top of the section.	- Moderately sorted fine grained lithic sandstone supported by a gray silty matrix. No internal bedding.
F4A	Cross and swaley Bedded Fine Grained Sandstone *(Not bioturbated)*	- Erosional contacts with underlying F4 or F8, which may be straight or curving. - Wavy contact with F4. - Straight contact with planar bedding occurs only once overlying F4.	-Planar cross beds of fine grained muddy lithic sandstone. - Undulating layer of fine grained muddy lithic sandstone, with a high concentration of fossil material.
F5	Massive Very Fine Grained Sandstone *(not bioturbated)*	- Sharp contacts with F3.	- Very fine grained light gray lithic sandstone.
F5A	Massive Very Fine Grained Sandstone *(Bioturbated)*	- Sharp or wavy contacts with F4.	- Very fine grained light gray lithic sandstone. No internal bedding or structures can be observed. Discrete layers of cemented material are present but rare.
F6	Siltstone with concretions *(Bioturbated)*	- No contacts with other facies could be observed.	-Gray siltstone with cemented burrows forming layer-like concretions. - Plane lamination can be observed between burrows
F7	Gray Siliceous Mud *(Bioturbated)*	-Sharp contacts with F4, erosional contact when underlying F4B, wavy contact when overlying F4B. - Occurs in lenses	-Massive dark gray mud, no internal bedding structures, very bioturbated. Burrows infilled with coarser grained sediments of lighter color.

Table 2. Seven main sedimentary facies observed along the studied localities, subdivisions based on sedimentary structures and level of bioturbation.

4.1. Sedimentology & Ichnology

Fifteen ichnogenera were identified along the Chagres Formation. (Fig. 3, Table 3)**.** The ichnological assemblages of the presented ichnogenera were combined with the sedimentological data collected to reconstruct the environments in which these structures were generated.

Ichnogenus	Ethology	Trophic Group	Possible Originator
Asterosoma	fodichnia	deposit feeder	Annelid
Aulichnites	pasichnia	deposit feeder	Gastropods
Chondrites	fodichnia	deposit feeder	nematode or siphunculid
Diplocratherion	domichnia	suspension feeder	crustacean (amphipod)
Ophiomorpha	domichnia	suspension feeder	crustacean (thalassinid decapod)
Paleophycus	domichnia	Carnivore	Annelid
Rhizocorallium	domichnida/fodichnia	suspension/deposit feeder	crustacean/annelid
Rosselia	fodichnia	deposit feeder	annelid or other worm-like phyla

Siphonichnus	fodichnia	deposit feeder	endobenthic bilvalves
Scolicia	pasichnia	deposit feeder	spatangoid echinoids
Schaubcylindrichnus	domichnia/fodichnia	suspension/deposit feeder, carnivore	maldanid polychaetes, foraminifera
Skolithos	domichnia	suspension/deposit feeder, carnivore	annelid, phoronid or other worm-like phyla
Teichichnus	fodichnia	deposit feeder	annelid, phoronid or other worm-like phyla
Teredolites	domichnia/fodichnia	suspension feeders	wood boring bilvaves
Thalassinoides	fodichnia/domichnia	deposit feeder	crustacean (thalassinid decapod)

Table 3. Ethological classification, modified after Pemberton et al., (1992) to include all the ichnogenera present in the Chagres Formation.

Toro Member

The Toro Limestone is the coarsest grained member of the Chagres Formation. It can be divided into a medium- to coarse-grained sandstone (F2) and coarse-grained barnacle and echinoid coquinas (F1). These alternations grade upward into a dominance of monotonous sandstone facies, with complete absence of coquinas and only one discrete layer of siliceous (possibly tuffaceous) mudstone (F7).

Within the coquina (F1), there is some lithological and sedimentological variability. Terrigenous contents increase while shell content decreases towards the top of the section, marking an overall fining upward tendency. The lower part of the section is dominated by 0.5-5 m thick beds of coquinas with trough cross-stratification, grading upward and westward into a nearly massive coquina beds. Within this upper portion, discrete sheet-like intervals 5-30 cm thick, contain shell fragments oriented parallel to bedding, with the local development of incipient cross stratification. The basal contact of this coquinoid body is erosional with underlying massive sandstones (F2).

The cross-stratified coquina beds (F1A) are overlain and underlain by sandstone layers (F2 & F2A), having erosive, basal contacts and sharp to transitional upper contact. The foresets of these cross-bedded coquinas dip towards the southwest, and locally display convolute bedding along the outcrop.

Bioturbation is sparse throughout the lower section. The ichnofossil association includes *Thalassinoides*, *Schaubcylindrichnus, Scolicia* and *Aulichnites.* The trace fossils occur in the sandstone facies (F2) interbedded with the massive and cross-bedded coquina beds, and represent the *Cruziana* ichnofacies (e.g. Seilacher, 1962; Crimes, 1970; Frey & Seilacher, 1980, MacEachern & Bann, 2008). Fossil logs bearing the shipworm boring *Teredolites isp*. occur in the sandstone facies interbedded with the coquina (Fig. 3).

Degree of bioturbation increases towards the upper part of the Toro Member as it transitions into a monotonous sandstone. The assemblage is dominated by *Thalassinoides*, with localized occurrences of vertical *Skolithos* in the interface between F7 and F2 and *Asterosoma* within F2. This assemblage contains elements of both the *Skolithos* and *Cruziana* ichnofacies, meaning it represents a transitional facies between either shifting energetic or environmental conditions. The decrease in shell content and grain size indicates that the currents forming the dunes in the lower section are no longer effective in moving this grain size. This means that it may represent a more distal environment or could be adjacent laterally to the high energy zone in which the dune migration field is generated.

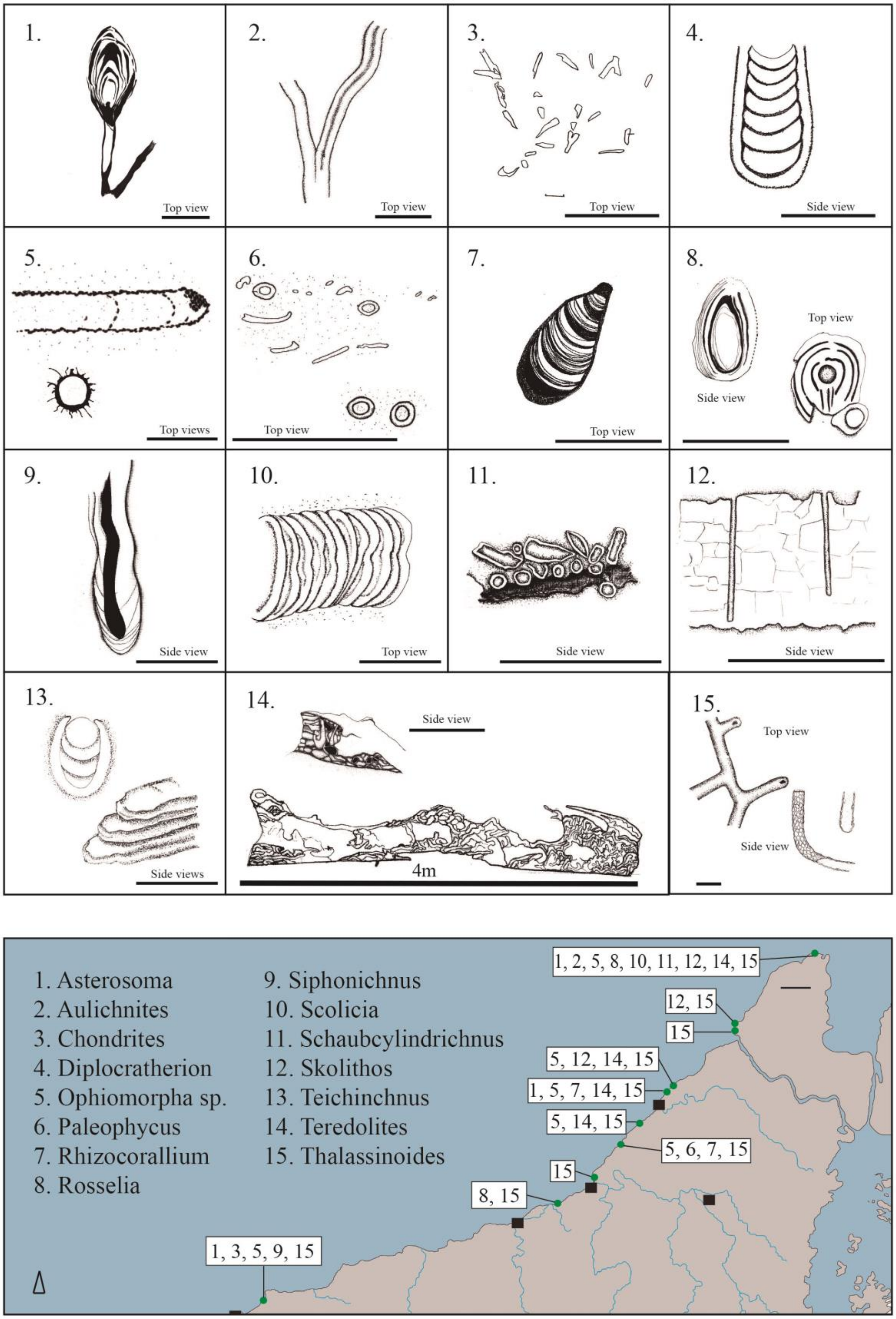

Figure 3. Ichnotaxa found along the Chagres Fm. and their distribution among the studied localities. Map modified after Collins et al. (1996). Scale bars are set to 5 cm for each trace.

Piña Sandstone

The Piña Sandstone member is dominated by medium- to fine-grained lithic sandstones (facies F3 & F4) with silt content increasing westwards. Interbeddings of thin, coarse grained sandstone beds (facies F5) can be found near the base of the member, and two layers of bioturbated sandy mudstone that pinch out laterally (facies F7) are found in the Piña town area. The San Lorenzo and Tortuguillas localities (Fig 1) are interpreted as transitional between the Toro and Piña members. The member in both localities consists of medium-grained sandstones.

The lower part of the section measured at San Lorenzo is a homogeneous layer of medium-grained lithic sandstone (facies F3) with moderate degree of bioturbation, similar to that of the Tortuguillas section. The upper San Lorenzo is sparsely bioturbated and is composed of interbedded coarse- to medium-grained sandstone (facies F2-F3). These beds are dipping gently towards the west.

The Tortuguillas section consists of medium grained lithic sandstones (F3) separated by sharp or erosive contacts. Near the base of the section, a thin bed of hummocky cross-stratification (F3B) with an erosive basal contact and lag concentrations of shell fragments is found.

Further west along the outcrop, the sections measured at the Piña Norte, Piña Norte 2, Piña Sur, Balneario Tommy and Palmas Bellas Monasterio localities present very similar ichnological and sedimentological characteristics. Grain size decreases westward, ranging from medium-grained sandstone (F4) to silty fine- to very fine-grained sandstone (F5). Sedimentary structures are scarce, which can be attributed to the pervasive bioturbation along the outcrop.

The two mud lenses found in the Piña Sandstone outcrop are comparable to those found in Toro Member in sedimentological and ichnological content (facies F7). In both cases sedimentary structures are lacking, and were pervasively bioturbated by burrows descending from the upper contact, infilled by the sediment from the overlying layer. These were interpreted as representatives of the *Glossifungites* ichnofacies, resulting from the colonization of the substrate after an erosive event.

Ichnologically, Tortuguillas is described as an intercalation of layers presenting moderate or high degrees of bioturbation produced by a monospecific suite of *Thalassinoides*, with the occurrence of *Skolithos* exclusively along one horizon between occurrences of facies F3. The infill of *Thalassinoides* towards the top of the section consists of an alternation of sand and silt.

The lower part of the section measured at San Lorenzo is moderately bioturbated by a monospecific suite of *Thalassinoides*, similar to that of the Tortuguillas section. Degree of bioturbation decreases towards the top of the section, grading into the sparsely bioturbated beds.

Degree of bioturbation throughout the Piña Norte, Piña Norte 2, Piña Sur, Balneario Tommy and Palmas Bellas Monasterio sections is high to moderate. In the Balneario Tommy locality, alternations of sandstone and thin mudstone laminae are found in the Thalassinoides burrows fill. The ichnofossil assemblage observed in these sections contains elements of both the *Cruziana* and *Skolithos* ichnofacies, being composed of *Thalassinoides isp.*, *Ophiomorpha nodosa*, *Ophiomorpha irregulaire*, *Skolithos isp.*, *Asterosoma isp.*, *Diplocratherion isp.*, *Paleophycus heberti* and abundant wood logs bored by *Teredolites isp.* (Fig. 3).

Rio Indio Siltstone

Only the Palmas Bellas locality can be assigned with certainty to the Rio Indio Siltstone facies of Collins (1996). Nevertheless, the Rio Indio locality has been included in the analysis because its lithology is consistent with a finning westward sequence. Based on the map by Collins (1996), this locality would be part of Coates's (1999) Unnamed Formation.

The section measured at the Palmas Bellas locality is composed of very fine grained mud sandstone (F5). The Rio Indio section consists of a massive sandy siltstone with nodular layers. Relict plane-parallel lamination can be observed in the lower and upper parts of the section, and coarser grained lenses are present and overlie finer grained mudstone or siltstone. These muddy and silty beds are pervasively bioturbated by vertically dominant burrow systems, possibly *Thalassinoides isp*., which are infilled with the coarse-grained sediments.

The section measured at the Palmas Bellas locality is moderately to highly bioturbated and is dominated by *Thalassinoides*, with possible occurrences of *Rosselia,* although it is not clear if the concentrical structures that may be diagnostic of this trace fossil correspond to alteration, considering the highly oxidized surfaces between layers. These trace fossils are common components of the *Cruziana* ichnofacies.

The assemblage found at the Rio Indio locality consists of *Thalassinoides isp.*, *Ophiomorpha isp.*, *Asterosoma*, *Chondrites*, *Siphonochnus*, *Rhizocorallium* and *Rosselia*. This assemblage is also representative of the *Cruziana* ichnofacies.

5. Environmental and paleobathymetric interpretation

Ichnological and sedimentological information was coupled in order to reconstruct the environments in which the three facies of the Chagres Formation were deposited.

Toro Member

Based on its sedimentological characteristics and ichnological content of the cross stratified coquinas, the Toro member can be interpreted as a tidal dune migration field (Olariu et al., 2012; Desjardins et al., 2010). Interbedding of F1, F1A and F2 is consistent with these studies' description of the facies association of a migrating subtidal dune field; F1A corresponding to Olariu's Bioclastic cross-bedded sandstone facies (Bcst) and the interbedded F2 to the Bioturbated muddy sandstone (Bms). The low degrees of bioturbation (BI 0 -1) and ichnodiversity of this succession may be a product of stressful conditions (MacEachern & Pemberton, 1994), caused by continuously migrating subtidal dunes that hinders the colonization of the substrate (Mángano & Buatois, 2004). Following this interpretation, the sharp contacts between F1 and F2 represent reactivation surfaces along the dunes.

Alternatively, facies F1A can be classified as a channel lag deposit (following the nomenclature of Brenner & Davies, 1973, Table 2) formed as a response to a period of tidal or storm action in which high energy conditions were concentrated in gouges. These gouges may have flowed obliquely to bar ridges or may have cut perpendicularly (to the southwest) to ridges parallel to the coastline, generating rip currents, which transported coarser grained material seawards (Gruszczynski et al., 1993).

Aulichnites isp., a gastropod grazing trace, confirms shallow marine conditions It has been reported in shallow marine near-shore environments (Zawiskie et al., 1983; Hakes, 1976), occurring on channel floor sediments during periods of low flow (Zawiskie et. al, 1983). The interface between the mudstone lens (F7) and the overlying sandstone (F2) contains elements of the *Glossifungites* ichnofacies, suggesting an erosional event such as storm action, or a regressive event (e.g. MacEachern et al., 1992, 2007; Pemberton et al., 2004).

The succession observed at the Toro Member is similar to the Facies Association 4 described by Dejardins et al. (2010); amalgamated cross-stratified sets of 30-80cm thick interbedded with wavy and lenticular-bedded sandstones. The bioturbation patterns are also similar with those described for this facies association: bioturbation is scarce in the lower section and increases towards the top, with *Skolithos* and *Rosselia*, along with *Asterosoma* appearing towards the top of the section as it transitions into a monotonous sandstone sequence (F2). According to Desjardins et al., this sedimentological and ichnological association records the migration of medium to large 2D and 3D dunes under unidirectional flow. These high energy conditions led to the permanent suspension of smaller particles.

Piña Sandstone

Following Pemberton et al. (1992), the sedimentological and ichnological evidence found in this member is similar to a lower shoreface setting. Erosive contacts, hummocky cross beds (F3B) and lag concentrations in the Tortuguillas section indicate the sporadic occurrence of high-energy conditions, which could be a product of storm action (Dott & Burgeois, 1982; McCrory & Walker, 1986). However, these events seem to be isolated and the dominantly highly bioturbated (BI 4-6) intervals present throughout the Piña Sandstone, suggest low sedimentation rates and low energy conditions, and a distal or lateral location with respect to the Toro Member dune field (Olariu et al., 2012).

The presence of *Ophiomorpha irregulaire* is of special importance. This trace fossil is extremely rare and has been reported solely on shallow marine deposits (Bromley & Ekdale, 1998). This trace fossil is generally reported in fine to medium-grained muddy sandstones similar to those found in these localities, interpreted as shallow marine, middle to lower shoreface deposits (e.g. Pedersen & Bromley, 2006; Gani et al., 2009; Howard & Frey, 1984). Laminated sands present in the infill of *Thalassinoides* burrows, reported in both Tortuguillas and Balneario Tommy could be the product of storm generated rhythmic events as shown by Reineck & Singh (1972), or be the result of tidal action further supporting the shallow marine hypothesis.

Similar ichnological assemblages to those present at the sections measured at the Piña Norte, Piña Norte 2, Piña Sur, Balneario Tommy and Palmas Bellas Monasterio localities have been reported in the Upper Cretaceous Cardium Formation in Alberta; representative of a shallow marine shelf deposit (Pemberton & Frey, 1984) and of middle shoreface deposits (Howard & Frey, 1984).

Rio Indio Siltstone

The *Cruziana* ichnofacies found at both localities, could be located in a range from lower shoreface to offshore settings (Pemberton, 1992). The Palmas Bellas locality can offer no additional environmental information due to its lack of sedimentary structures. On the other hand, the lithological description of the Rio Indio locality together with its ichnological content, would contain elements described by Pemberton et al. (1992) for both distal lower shoreface and proximal offshore setting; coarser grained lenses with finer grained partings are associated to lower shoreface, while laminated heterogeneous layers are generated in proximal offshore environments within maximum storm wave base. The development of parallel lamination described in the section could be associated with storm associated currents The *Cruziana* ichnofacies in this section is most consistent with the proximal offshore depositional conditions of Pemberton et al. (1992), suggesting that this is the deepest environment of the three members. The intense bioturbation of these sections (BI-5) indicates low energy and low sedimentation rates, allowing for burrowing organisms to build extensive burrow systems and obliterate most primary sedimentary structures.

6. Synthesis & Discussion

Both sedimentological and ichnological characteristics present in the Toro Member and Piña Sandstone indicate that the Chagres Formation could have been deposited in either a wave or tide influenced platform subjected to periodic storm action. Comparison with previous studies for siliciclastic shallow marine environments (e.g. Mángano & Buatois, 2004; Howard & Frey, 1984; Pemberton et al., 1992), narrows down the depositional setting for the Chagres Formation to a shallow marine setting; ranging from high-energy nearshore environments represented in the Toro Limestone Member, to lower shoreface in the Piña Sandstone, deepening to the lower shoreface – upper offshore transition in the Rio Indio facies.

The large scale cross beds presenting low ichnodiversity and sparse bioturbation are both reported for tide-dominated shorelines (Mángano & Buatois, 2004) as the expression of a tidal channel or a subtidal dunes. These possibilities set the Toro Limestone Member in a shallow marine environment, which is consistent with the findings of Hendy et al. (in review), classifying the Toro Limestone Member as inner shelf (<50m deep) based on the molluskan assemblage. This interpretation contrasts with the previous paleobathymetric reports (200-500m) based on foraminifera by Collins (1996), in which the Toro Limestone was interpreted as having been deposited in bathyal settings.

The Piña Sandstone member also contains evidence of possible tidal or wave influence. Swaley and planar bedded beds scattered in the section along with the characteristic ichnofossil assemblage similar to that described by Pemberton et al. (1992), allow for this member to be classified as the middle to lower shoreface of a shallow marine shoreline, in agreement with the findings of Hendy et al., (2015, in review), whose results indicate shallow shelfal conditions (75-150m). Condrichtyan assemblages of the Chagres Formation studied by Carrillo-Briceño et al. (2015), suggest bathymetric ranges that could stand between 200-300m, or a second most probable range of 50-200m. The results of this study are most consistent with the second hypothesis. This indicates that the fossil, sedimentological and ichnological evidence set the Piña Sandstone as shallow marine, contrasting with the previous interpretations that classify it as deep water facies (Collins et al., 1996).

Little other than describing a highly bioturbated low-energy regime can be said about the depositional environment of the Rio Indio facies if only the Palmas Bellas locality is taken into account. However, the locality referred to as Rio Indio in this study is near a locality used by Collins et al. (1996) to the East of Miguel de la Borda. The assemblage in this locality is most similar to that of a lower shoreface-upper offshore transition influenced occasionally by storms, as described in the synthesis by Buatois & Mángano (2011). No evidence for tidal influence was found in this member. These results favor the shallow depositional environment proposed by Hendy et al. (in review) (25-75m water depth), Collins et al. (1996) (50-80m water depth), Aguilera & Aguilera (1999) (0-100m water depth) & Carrillo-Briceño et al. (2015) (<100m).

The paleobathymetry of the Chagres Formation derived from benthic foraminifera analyses and the important affinity of these species to modern Pacific species (Aguilera & Aguilera, 1999; Collins et al., 1996), support Coates & Stallard's (2013) hypothesis that proposed the Chagres Fm. as the evidence that proves that by 6 million years, deep-water connections between the Pacific and the Caribbean were still possible. However, the results of this study suggest a much shallower depositional environment for the Toro and Piña Sandstone members than previously suggested; supporting previous findings by Hendy et al. (in press).

The underlying Gatun Formation was deposited at around 25m depth (Collins et al., 1996), therefore, if the Chagres Formation was accumulated at bathyal depths (>200m), then a rise in global sea level would not be enough to explain the paleodepth change and instead some tectonic mechanism should be invoked to explain subsidence and uplift in the order of several hundred meters. However, the absence of any signal of tectonic deformation in these units makes this tectonic activity unlikely (Woodring, 1957).

Carrillo-Briceño et al. (2015) described condrichtyan faunas from both deep and shallow waters found in the Piña Sandstone Member. This assemblage most likely reflects the migration of deep-water fauna towards shallow waters. Given the elevated densities of fish remains, Carrillo-Briceño proposes an association with a highly productive upwelling setting. This could be one possible explanation for fossil fauna indicating a wide range of bathymetries (Carrillo-Briceño et al., 2015; Collins et al., 1996; Aguilera & Aguilera, 1999; Hendy et al., in press). This hypothesis is consistent with the shallow water setting proposed by this study.

The paleoenvironmental reconstruction obtained from the sedimentological and ichnological analysis does not support the deep marine strait hypothesis for the Chagres Formation. However, the dune migration field interpreted in the Toro Member points to a high-energy environment generated by unidirectional currents. A shallow marine strait allowing Pacific waters to travel eastward would account for the faunas with Pacific affinities found along the outcrop (Collins et al., 1996).

The Toro Member underlies the Piña Sandstone towards the east of the outcrop, but it can be seen that overall the three members of the Chagres Formation are in contact with the underlying Gatun Formation, indicating a lateral facies change of its members. The transition of the Toro Member coquinas into the monotonous sandstones of the Piña Member could indicate a decrease of energy in the environment towards the top of the section and laterally as the distance from the dune field increases. The results of this study suggest the Rio Indio as the deepest of the three members, followed by the Piña Sandstone - the Toro Member being the shallowest. It is proposed that the Toro Member is deposited under the influence of a unidirectional current; the Piña Sandstone and the Rio Indio members deposited as distal facies moving away from this current.

The morphology of the Chagres Formation yields for a second hypothesis. The Gatun Formation has been proposed in previous studies as a shallow water embayment (Coates & Obando, 1996; Hendy, 2013) existing during a time of active transoceanic interchange of marine faunas (e.g. Collins et al., 1996; Pimiento et al., 2013). The location and outcrop pattern of the Chagres Formation suggests that this formation as well could have been an embayment area (Fig. 1). Paleobiological studies indicate that the Toro and Rio Indio members are the shallowest, the Piña Sandstone Member being the deepest (Hendy et al., in press; Aguilera & Aguilera, 1999; Carrillo-Briceño et al., 2015). If the Chagres Formation was deposited in a shallow marine embayment, the sedimentological and ichnological data show that there could have been a unidirectional current flowing in from the location of the Toro Member, energy decreasing from this member in the direction of Rio Indio.

The Chagres Formation has been proposed as the location where the last deep water connection existed between the Caribbean and the Pacific as late as six million years ago, based on the results obtained from the census of benthic foraminifera (Collins et al., 1996; Coates and Stallard, 2013). Coates and Stallard (2013) proposed that the Chagres sediments represent a deep, narrow strait that would be largely undetectable in geological reconstructions of tectonic blocks, and would still pose an effective barrier between vertebrate biogeographical provinces. The results obtained in this study indicate that the Chagres Formation was deposited in shallow marine environments, disagreeing with this hypothesis.

Ichnofossils have the intrinsic value of forming *in-situ*, intimately related with the depositional processes and never being reworked, unlike microfossils (Collins et al., 1996) or macrofossils (De Gracia et al., 2012) which could have been transported and redeposited. This gives them an added value as a paleoenvironmental proxy. It is then suggested that if indeed a deep water connection was still possible between the Caribbean and the Pacific by the Miocene-Pliocene, the Chagres Formation is not the geographical location of this passage.

7. Conclusions

-The Chagres Formation was deposited in either a wave or tide dominated platform, subjected to periodic storm action

- The Toro Limestone Member can be classified as inner shelf: less than 50m depth, deposited under a high energy regime.
- The Piña Sandstone Member can be classified as middle to lower shoreface of a shallow marine shoreline, with moderate energy.
- The Rio Indio Siltstone can be classified as lower shoreface – upper offshore transition, with low energy.
- The Toro Limestone Member represents a subtidal dune migration field, product of the action of a unidirectional current.
- The location and outcrop pattern of the Chagres Fm. suggests that it could have been an embayment area.
- The Chagres Formation could have not been the last deep water connection between the Pacific Ocean and the Caribbean Sea.

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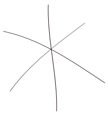
Supporting files

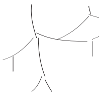
Panoramic view of Toro Point.

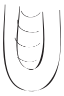
Icnofossils

 Asterosoma

 Aulichnites

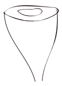
 Bergaueria

 Chondrites

 Diplocratherion

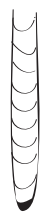
 Ophiomorpha

 Paleophycus

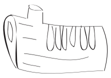
 Rosselia

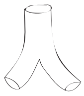
 Scolicia

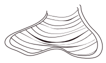
 Skolithos

 Teichichnus

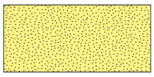
 Schaubcylindrichnus

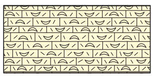
 Teredolites

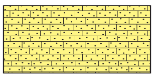
 Thalassinoides

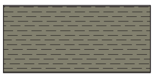
 Zoophycos

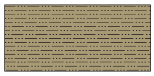
Lithology

 Sandstone

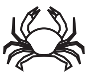
 Barnacle & Echinoid coquina

 Alternating sandstone and coquina

 Mudstone

 Siltstone

Fossils

 Crustacean

 Echinoderms

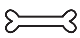
 Fish

 Gastropods

 Inv. skeletal fragments

 Mollusks

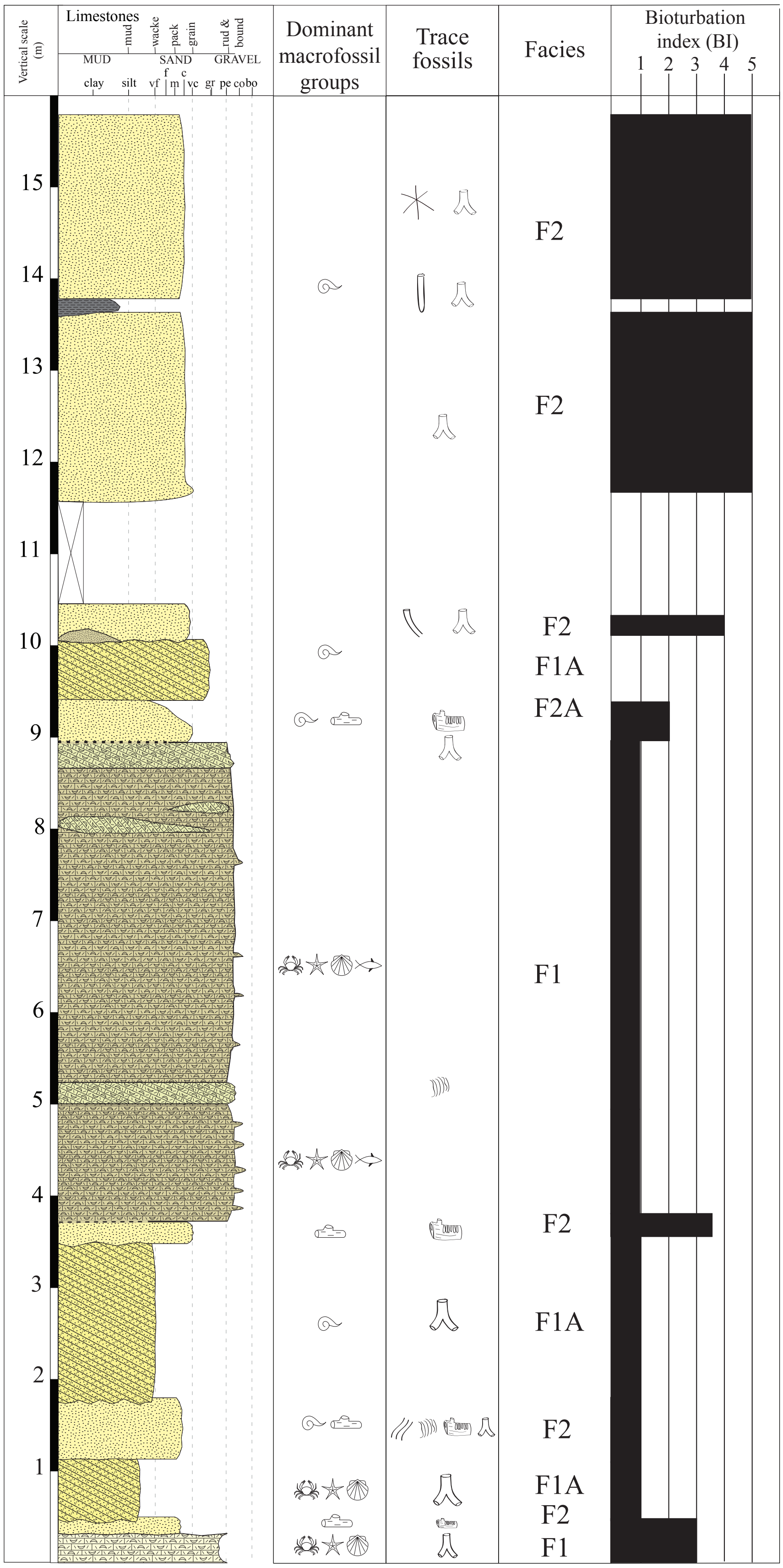
 Seeds

 Vertebrates

 Wood

Chagres Fm.
Toro Point

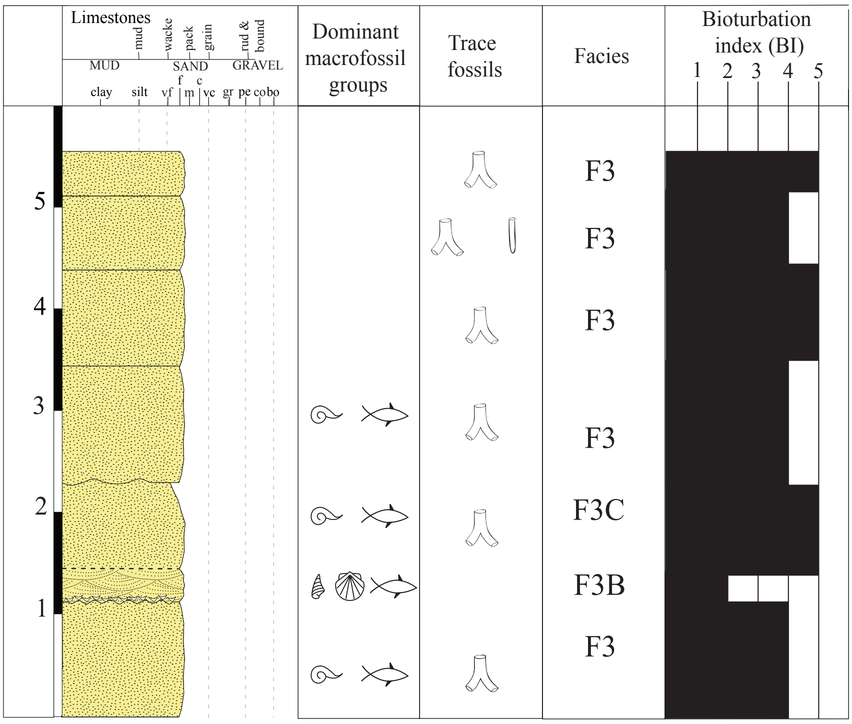
Base of section: 9°22’17,4’’N, 79° 57’ 14,4’’W
Top of section: 09°22'13.4"N, 79° 57' 22.8960" W



Chagres Fm.

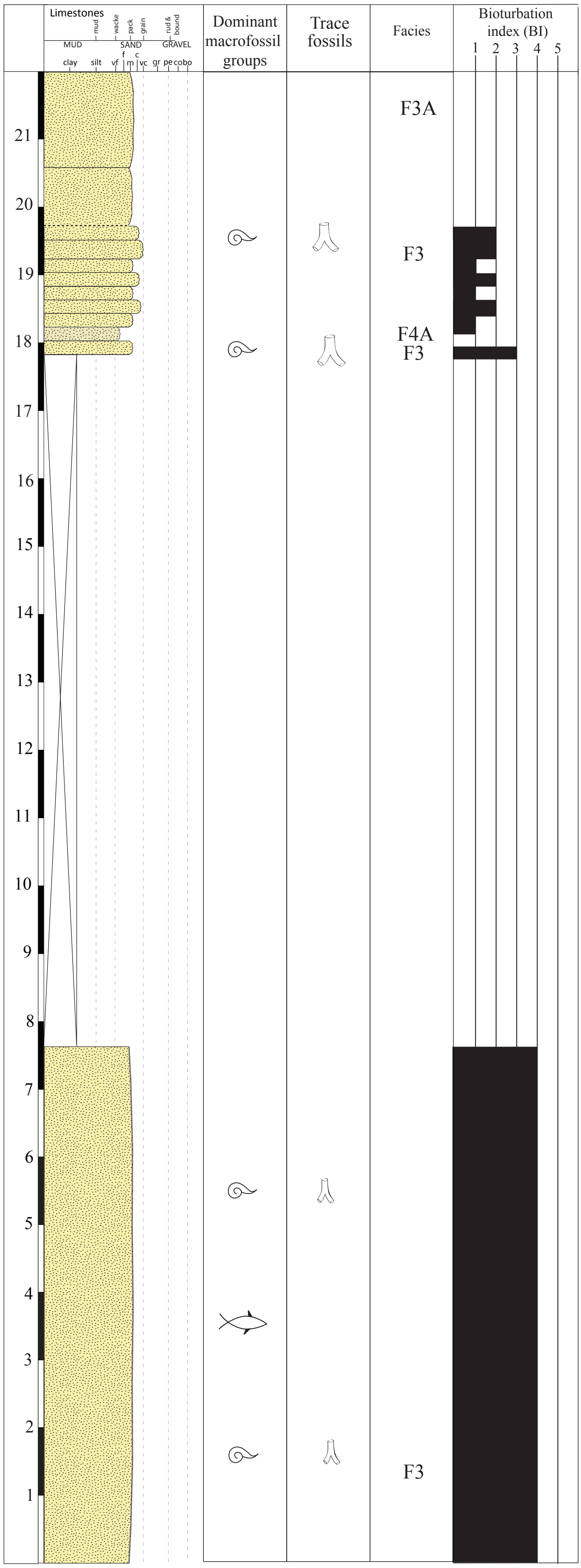
Playa Tortuguillas

Base of section: 9° 19' 36.1200" N, 80° 0' 13.6080" W



Chagres Fm.
San Lorenzo

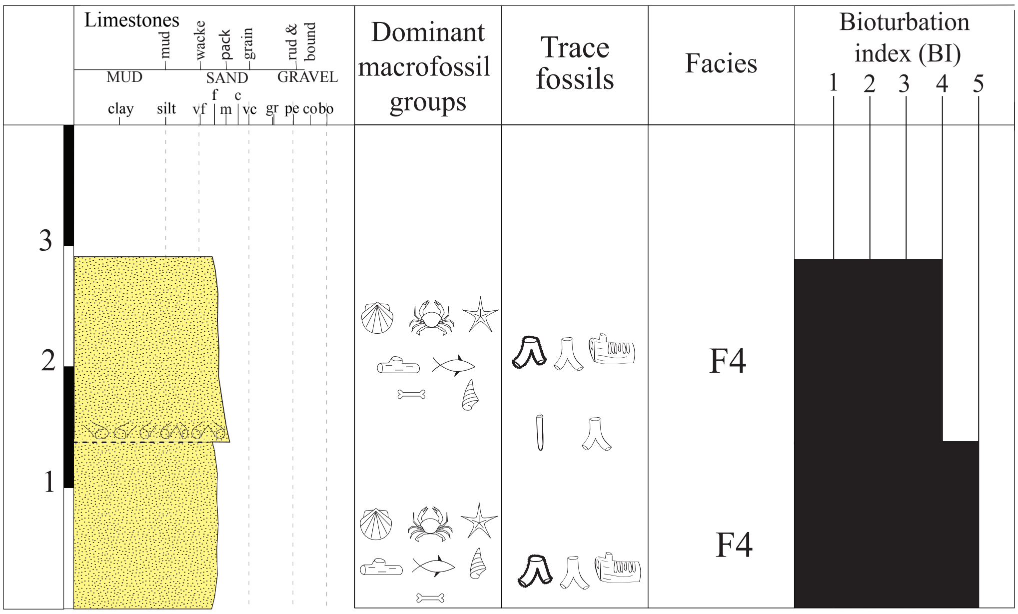
Section: 9° 19' 21.4680" N, 80° 0' 13.0320" W



Chagres Fm.

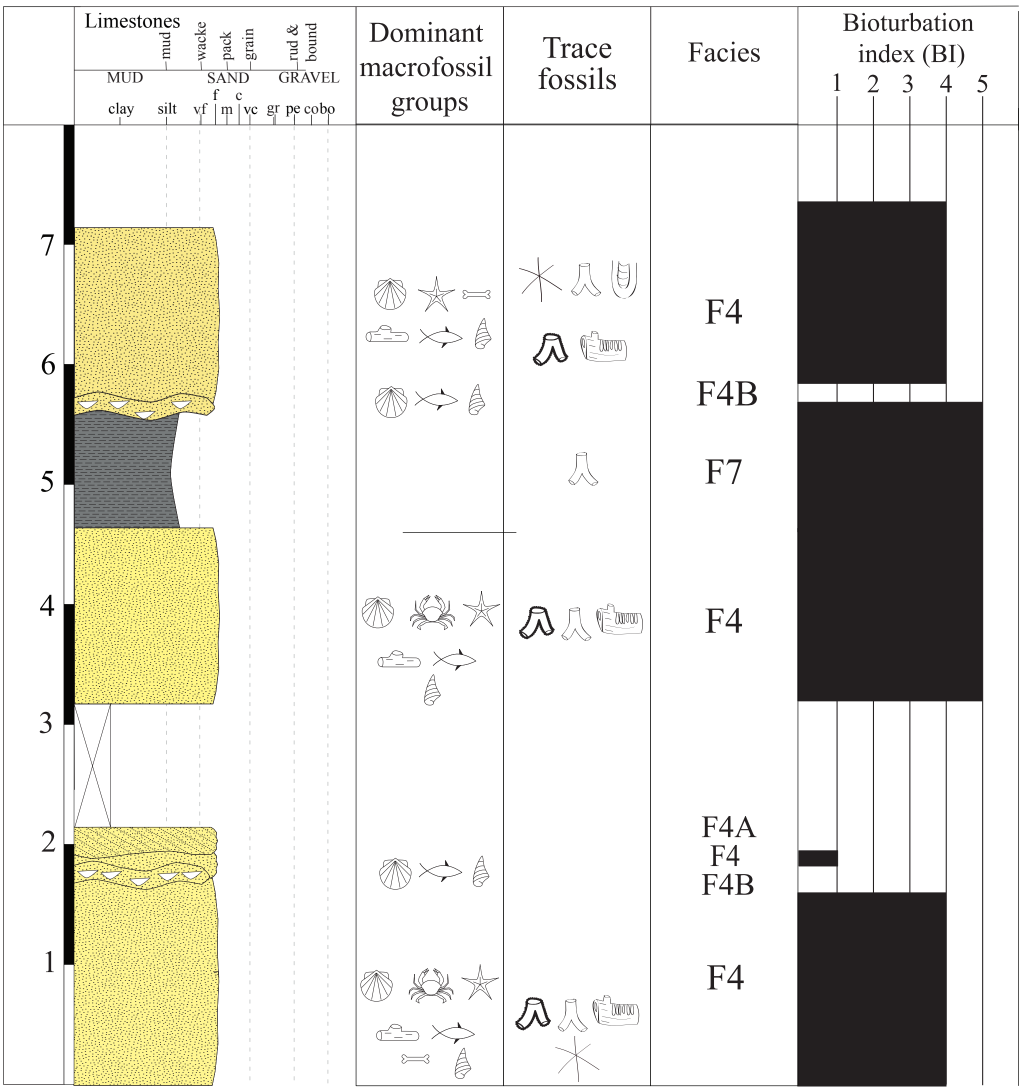
Piña Norte 1

Base of section: 9° 17' 36.1320" N, 80° 2' 16.0080" W



Piña Norte 2

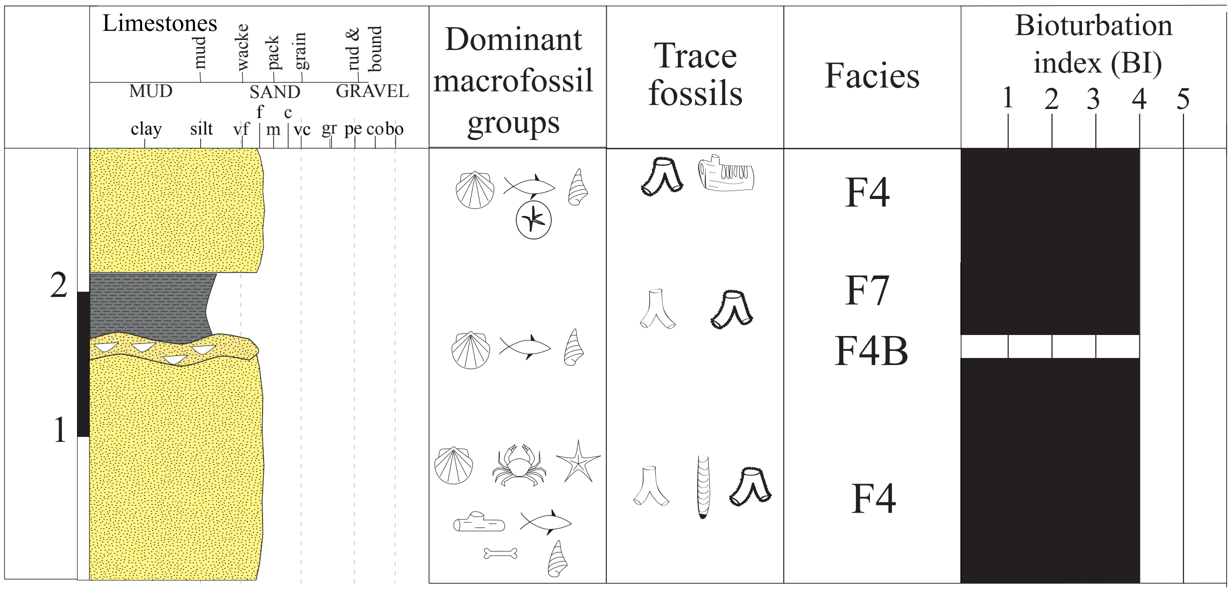
Base of section: 9°17’27’’N, 080°02’23’’W



Chagres Fm.

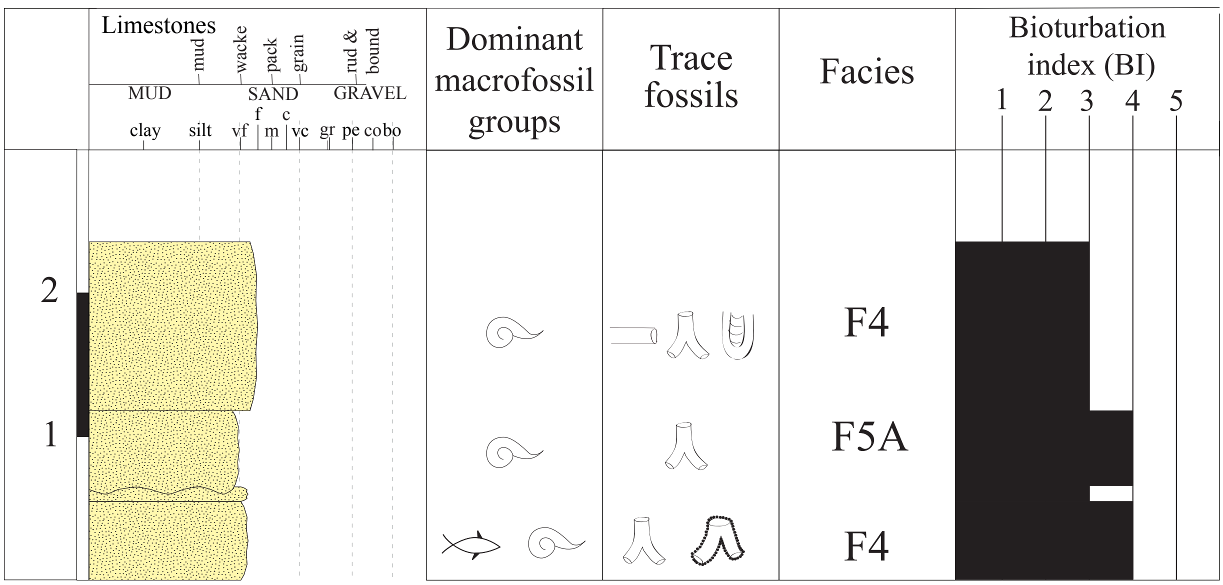
Piña Sur

Base of section: 9°16’27’’N, 080°03’11’’W



Balneario Tommy

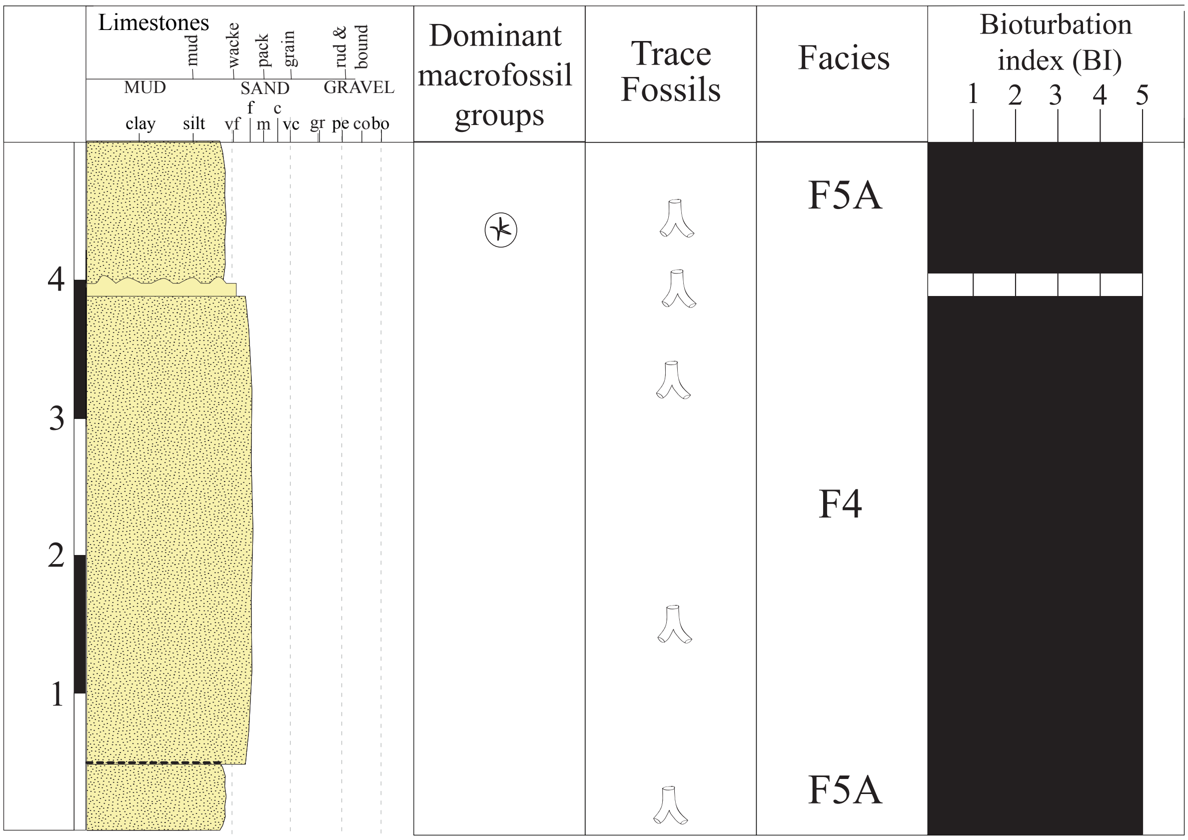
Base of section: 9° 15' 19.9440" N, 80° 4' 13.1880" W



Chagres Fm.

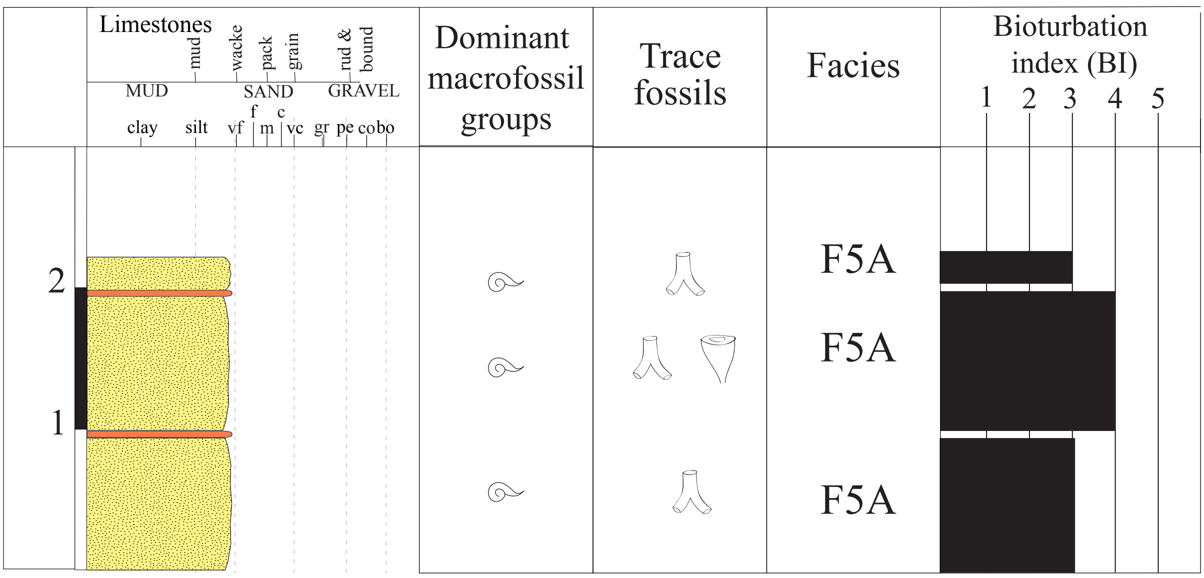
Monasterio Palmas Bellas

Base of section: 9°14'8.52"N, 80° 5'13.78"W



Palmas Bellas

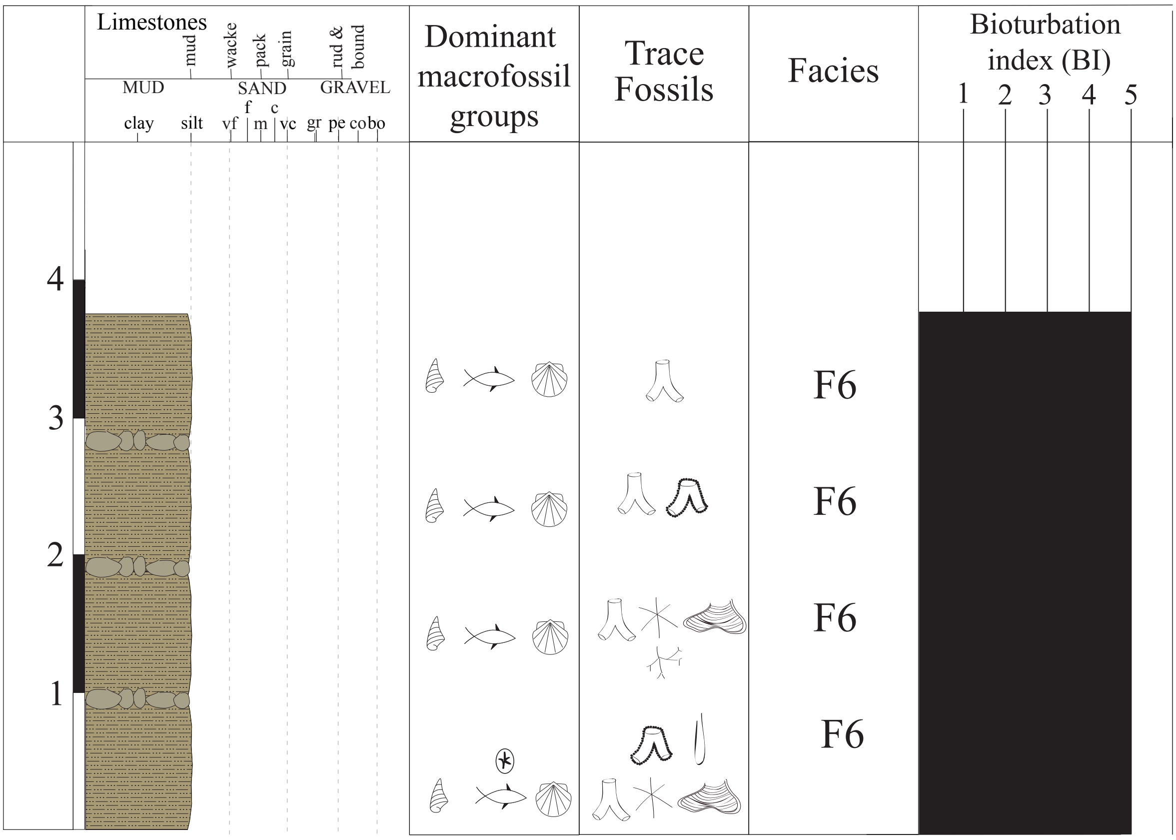
Base of section: 9°, 13' 13.6200" N, 80° 6'33.41"W



Chagres Fm.

Rio Indio

Base of section: 9° 9' 25.4880" N 80° 17' 34.5120" W

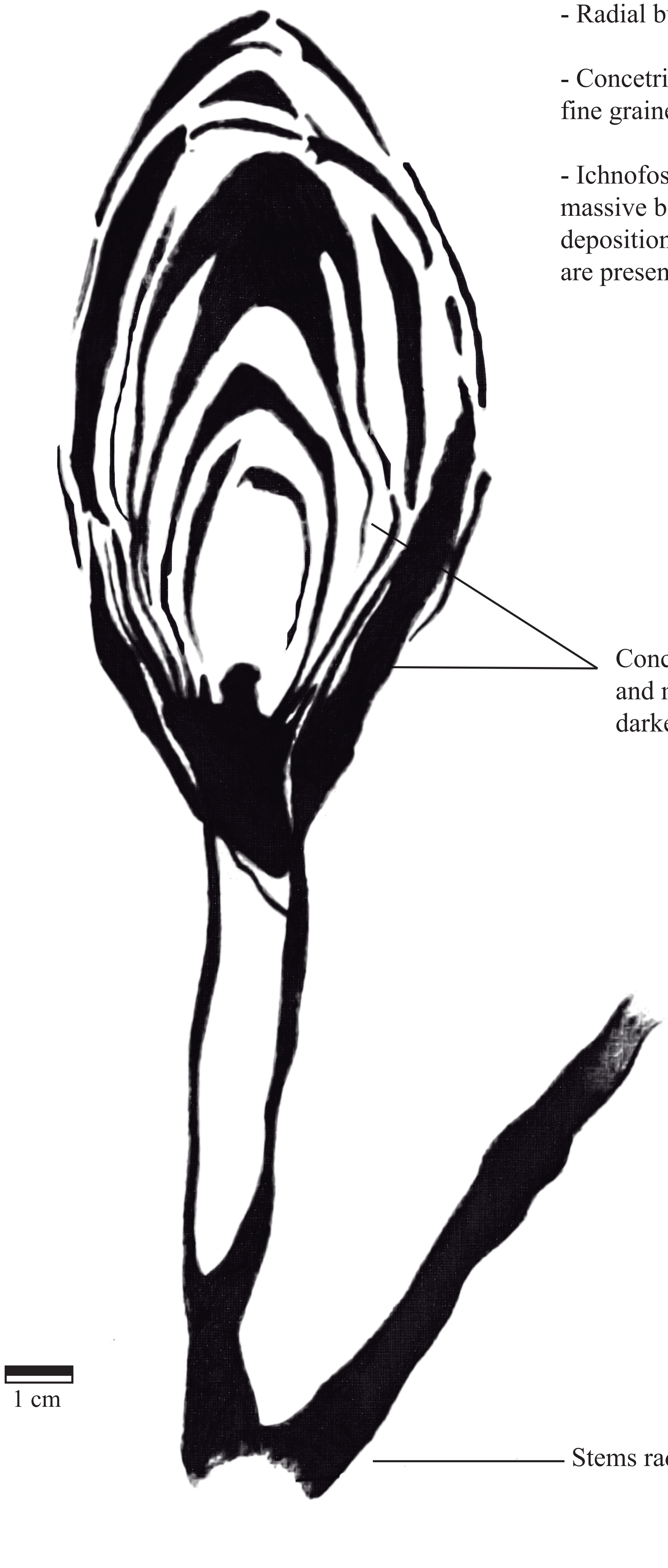


Asterosoma

- Radial bulbs stem from a center

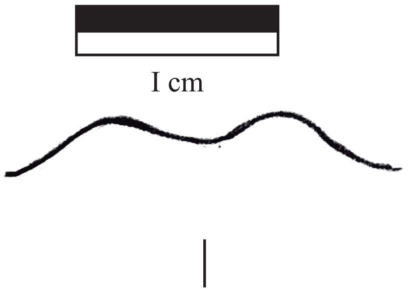
- Concetric laminations of mud or fine grained material and sand

- Ichnofossil is generally seen in massive bodies of sand where no depositional sedimentary structures are present.

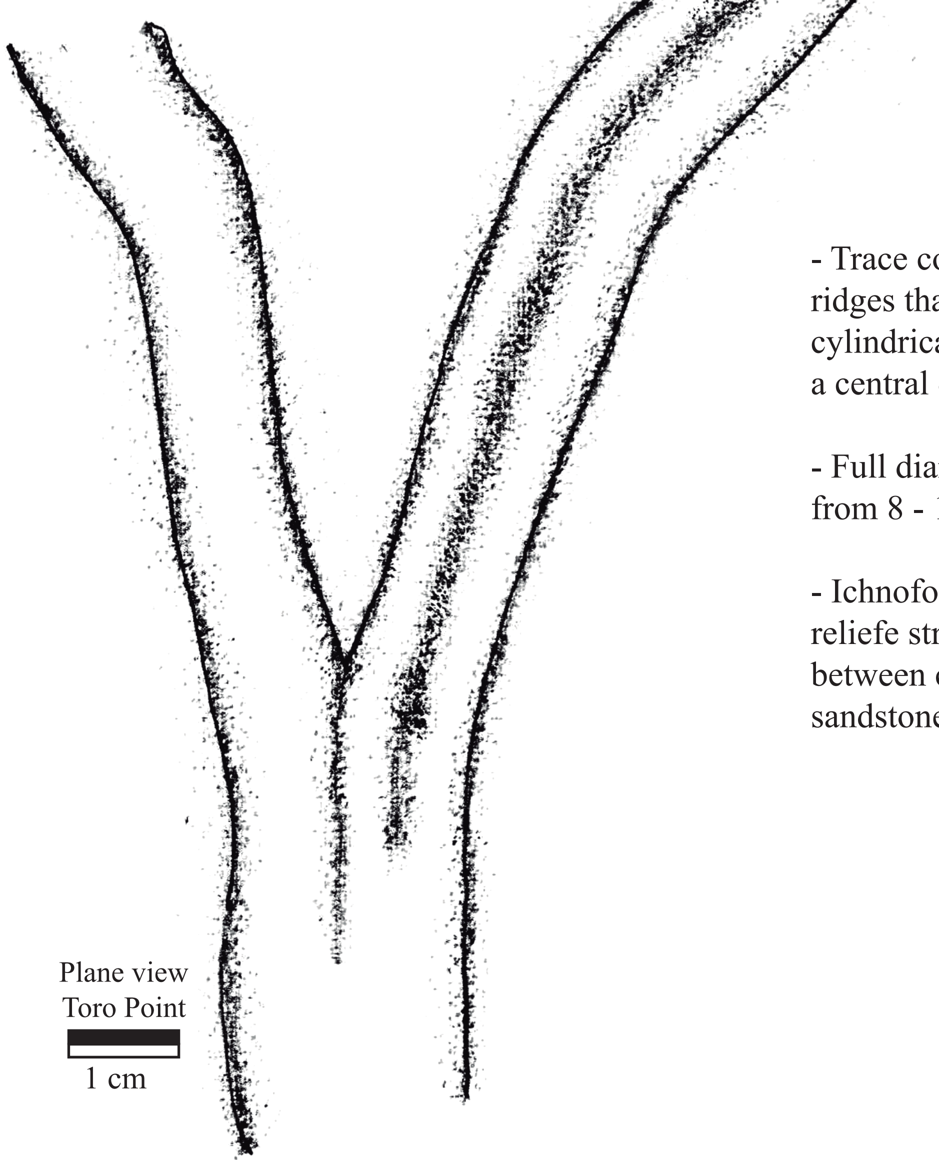



5 CM
1:1000 METRIC
10 SCALE

Aulichnites



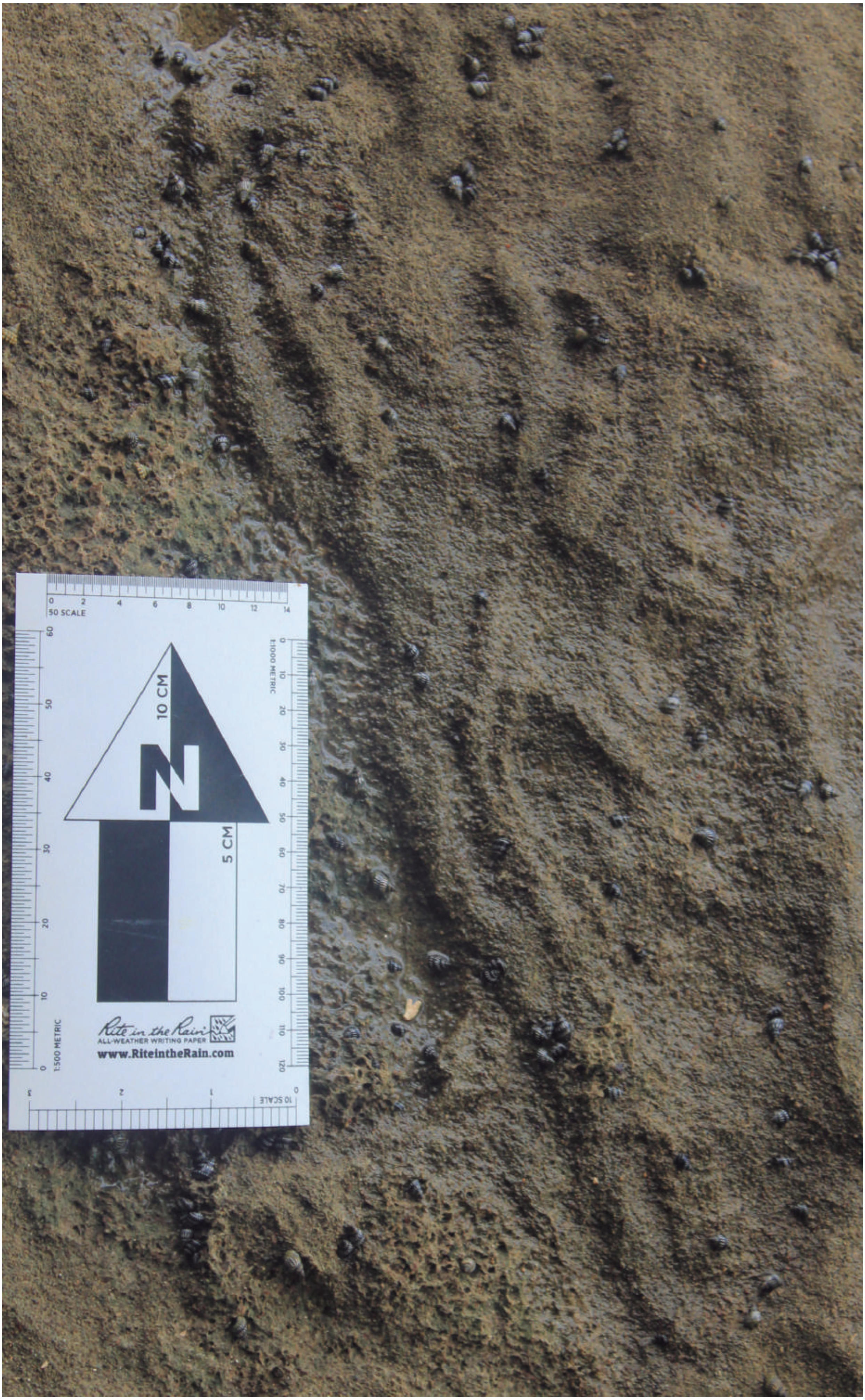
Central furrow separates two convex rigdes



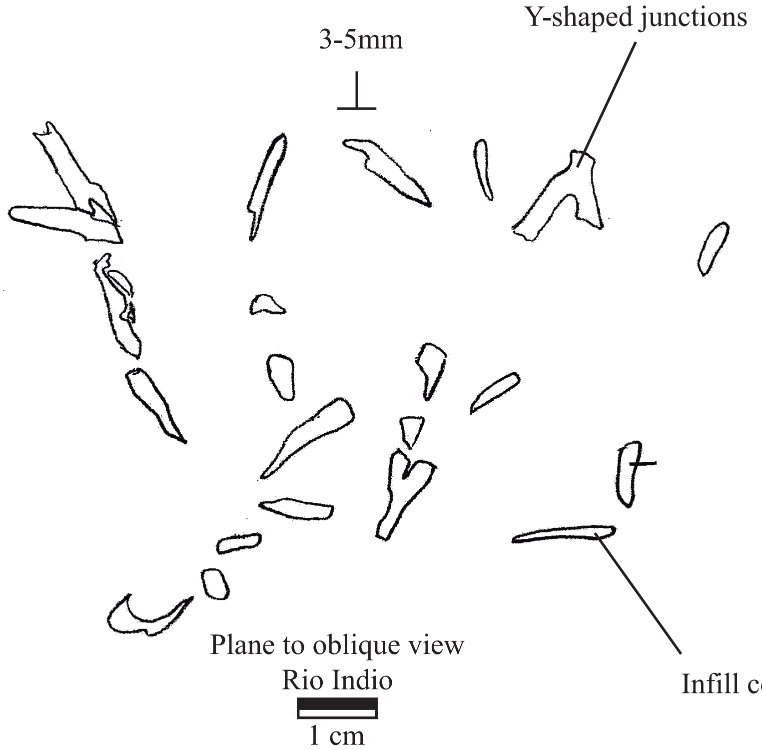
- Trace consists of two convex ridges that appear to be almost cylindrical in shape, separated by a central dent

- Full diameter of trace may range from 8 - 10 mm

- Ichnofossil is found as a positive reliefe strucutre on boundaries between cross bedding and massive sandstone layers


50 SCALE
10 CM
N
5 CM
1:1000 METRIC
1:500 METRIC
Rite in the Rain
ALL-WEATHER WRITING PAPER
www.RiteintheRain.com
10 SCALE

Chondrites

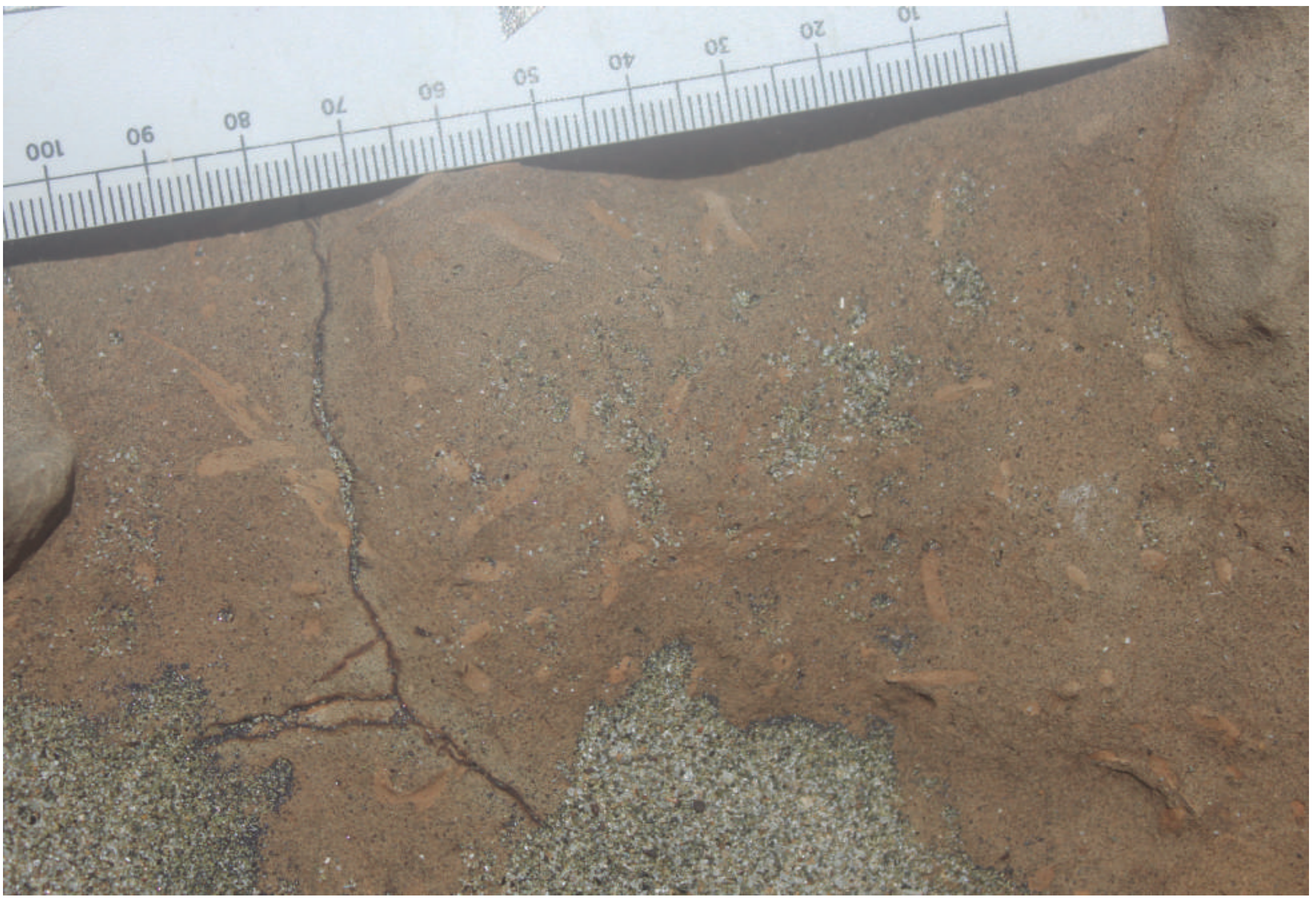


- Trace appears to be a branching system of small diameter burrows

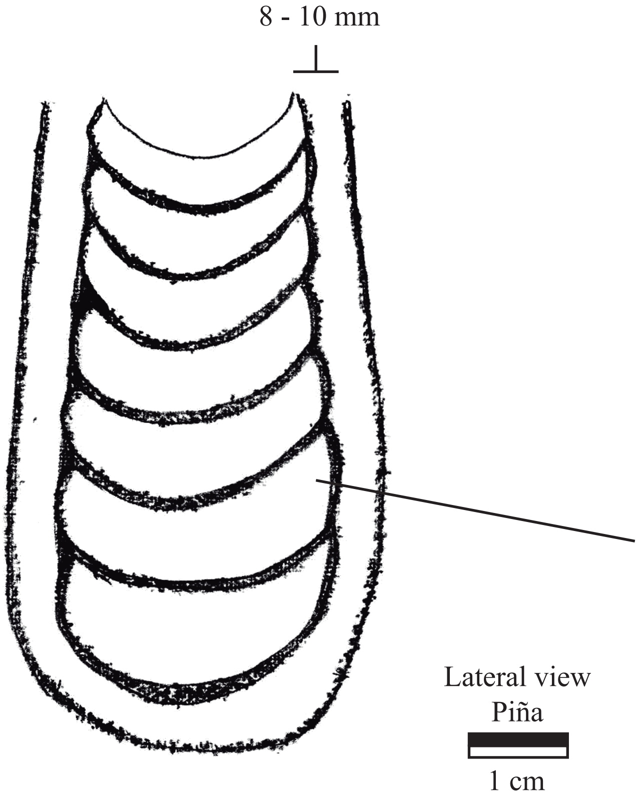
- Diameter of each individual branch ranges from 3 - 5mm

- Infill contrasts with surrounding sediment; it appears to be finer grained than surrounding matrix.

- Y-shaped junctions mark branching pattern



Diplocratherion

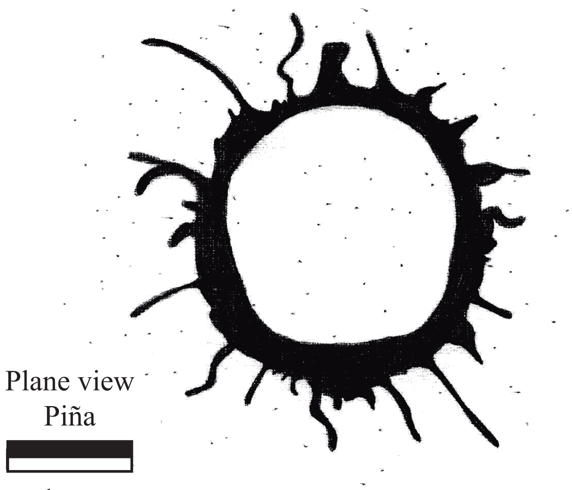


- Vertical U-shaped burrow with protrusive spreite between entrance tubes

- No wall lining

- Diameter of entrance tubes may be 8 - 10mm in size.

Ophiomorpha irregulaire

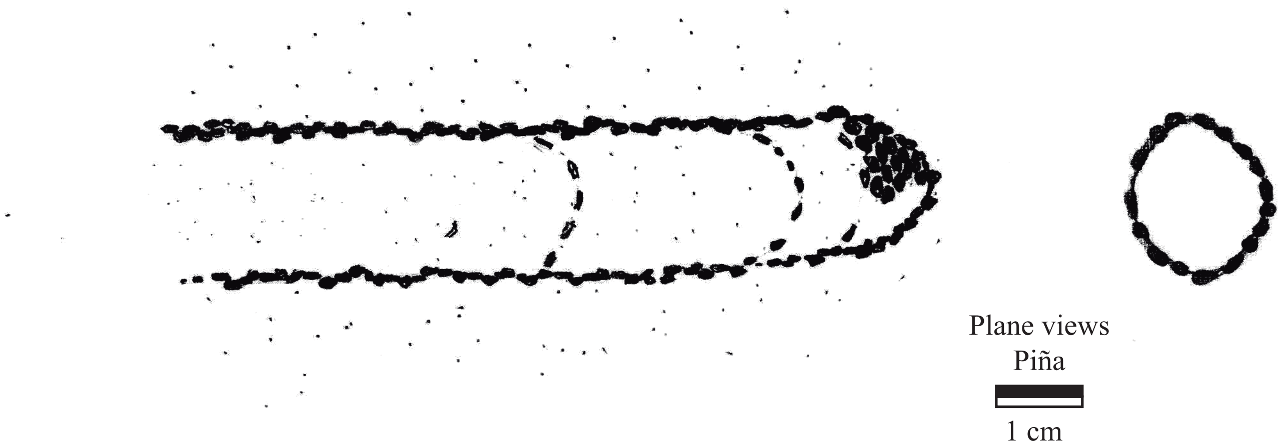


- Trace is observed as a circular aperture thickly lined with organic matter or fine grained material arranged in lateral projections irregularly distributed

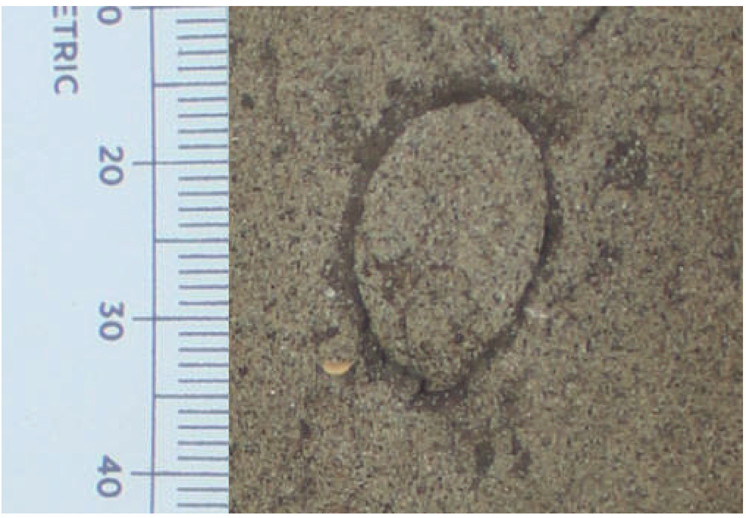
- Diameter ranges from 18 - 20 mm

- No horizontal burrows could be observed in the oucrops scouted.

Ophiomorpha nodosa

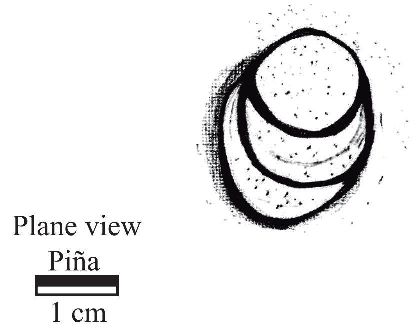


- May be vertical to horizontal cylindrical burrows
- Apertures are circular and may range from 15 - 20 mm in diameter
- Burrows are lined with small cylinder shaped pellets up to 1mm in diameter, densely packed.
- Burrows may be branched or single
- Bifurcations are Y-shaped



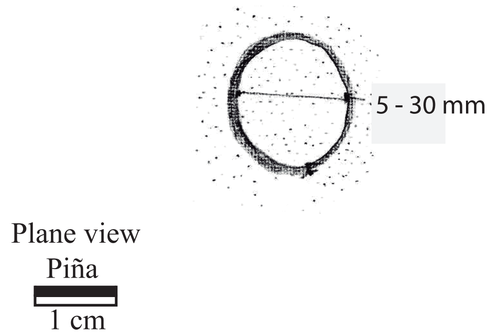
Ophiomorpha isp.

A



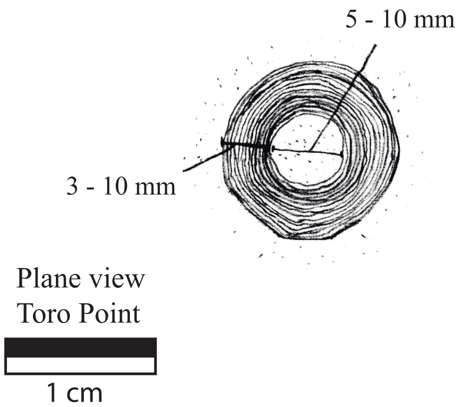
- Circular aperture appears to be surrounded by a series of concentrical ring structures consisting of intercalations of mud or organic matter and the sand od the surrounding matrix
- Aperture diameter ranges from 10 - 25 mm
- Lining thickness varies from 1 - 2 mm
- ;May represent lateral readjustment of burrow made by organism
- Similar exposures may be seen in both vertical and horizontal rock exposures

B



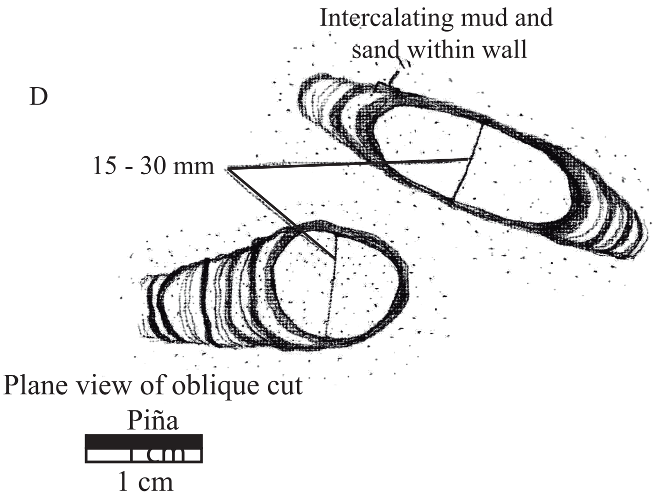
- Apertures are circular, lined with mud or organic matter
- Infill of burrow appears to be the same grain size as surrouding sediments
- Diameter may range from 5 - 3 mm
- Wall lining thickness ranges from a little less than 1 mm up to 2 mm
- May be observed both in vertical and horizontal exposures

C



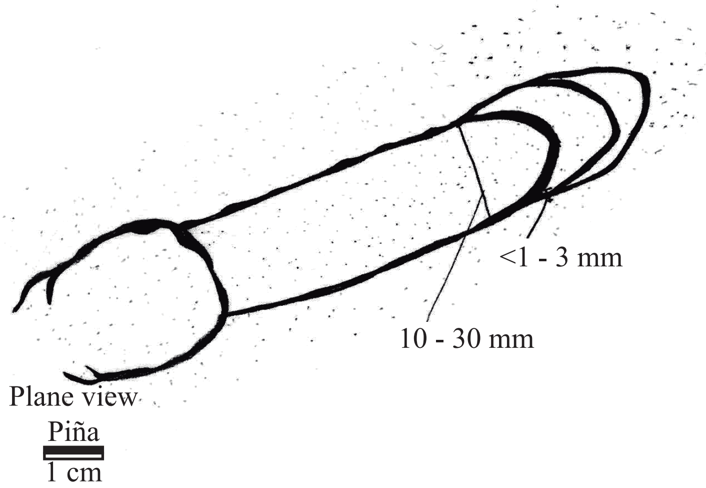
- Circular aperture, wall lis lined by a series of very thin concentrical rings oforganic matter or mud
- Infill matches the surrounding sediment
- Diameter of aperture ranges from 5 - 10 mm
- Thickness of wall lining may range from 3 - 10 mm
- May be observed in both horizontal and vertical exposures of the bedding.

D



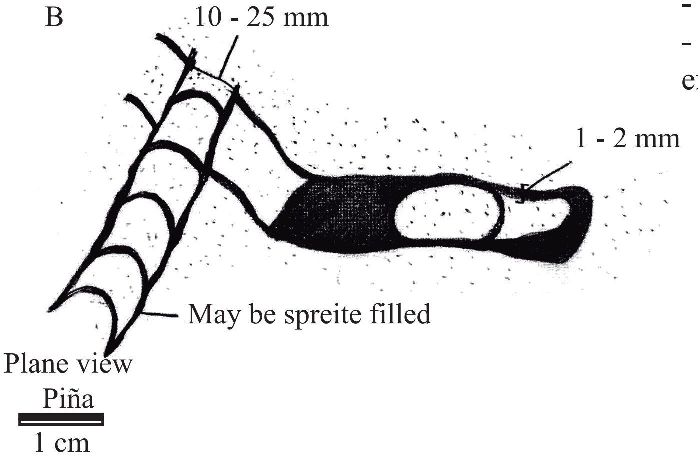
- Oblique cut of cylinder shaped burrow, which may be vertical or horizontal
- Wall lining is clearly seen along the cut
- Intercalating mud and sandstone rings can be seen along the cut
- Intercalations can be seen mainly in oblique cuts

A

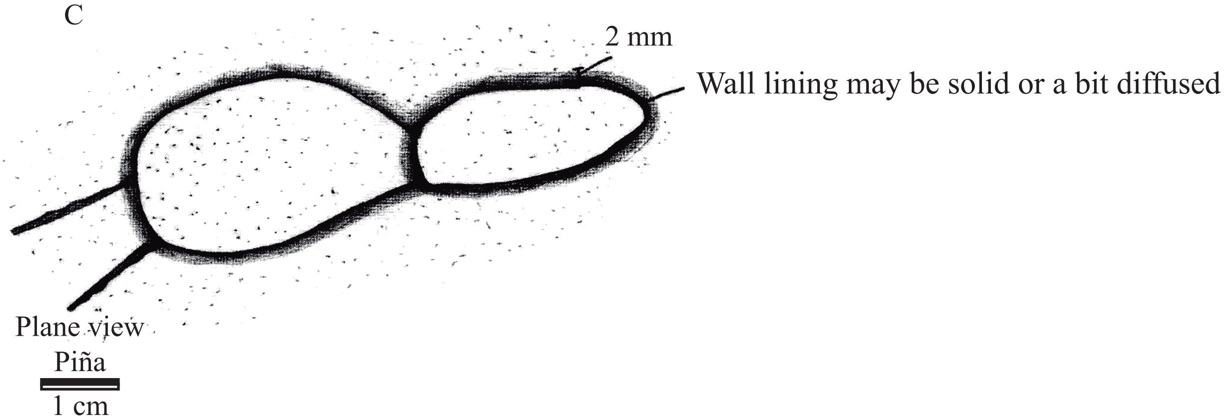


- Trace may be straight to sinuous
- Wall is lined with mud or organic matter
- Sediment infill may be the same grain size as surrounding matrix
- Infill may consist oc spreite intercalating mud and sand
- The bulges it may present, could represent the lateral or vertical migration of the burrow in oblique view
- Wall lining may be slightly irregular around the edges
- Diameter ranges from 10 - 30 mm
- Wall lining thickness ranges from 1 - 3 mm
- Cuts along the wall may give the appearance of a thicker wall lining
- Traces may not branch out for significant lenghts
- No relief is observed
- May be vertical or horizontal
- Can be observed in both horizontal and vertical exposures of bedding

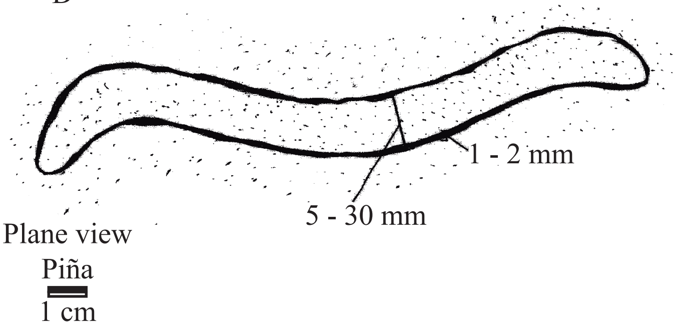
B



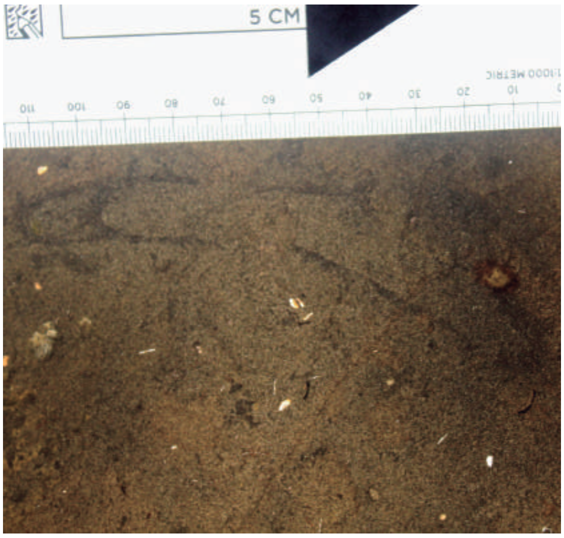
C



D



A


5 CM

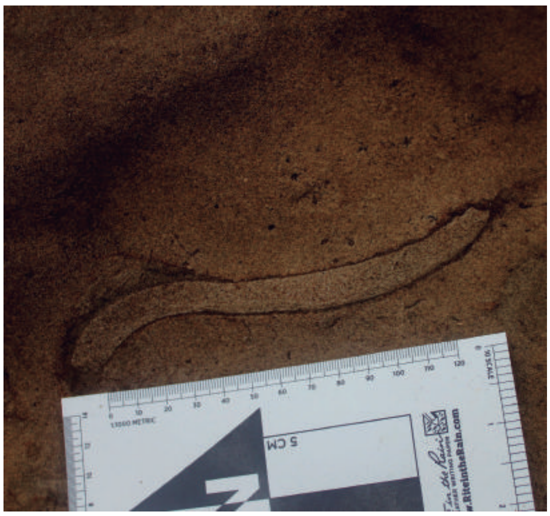
B


40 50 60 70 80 90 100 110 120

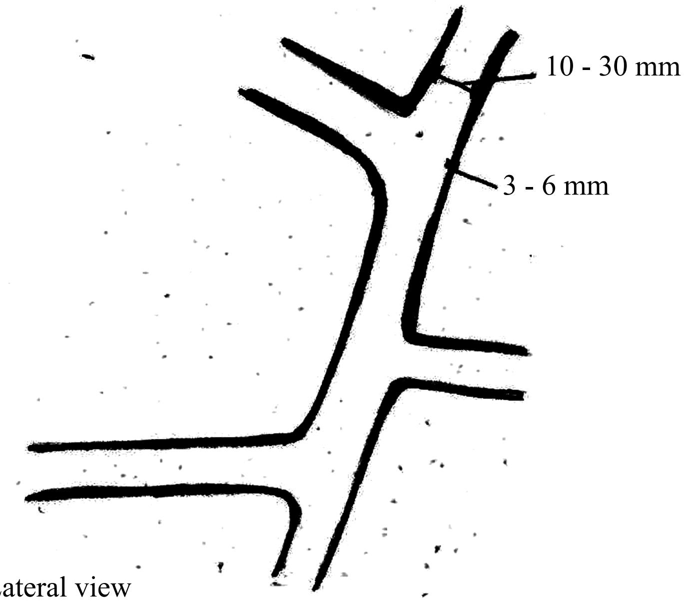
C


0 10 20 30 40 50 60 70 80 90 100
1:1000 METRIC

D


5 CM

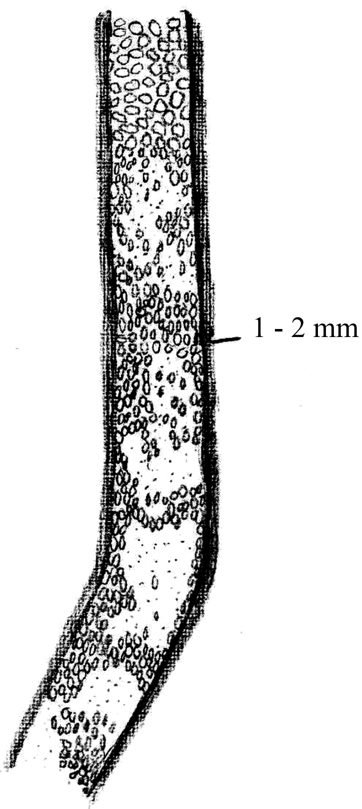
A



- Trace is straight
- Wall is lined with a single set of lining
- Trace infill has the same grain size as surrounding sediment matrix, or may be filled with spreite consisting of intercalations of sand and mud
- Wall lining may be slightly irregular
- Diameter ranges from 10 - 25 mm
- Wall lining thickness ranges from 1 - 2 mm
- Trace branches out in Y-shaped or nearly straight angle junctions
- May be vertical or horizontal

Lateral view
Piña
1 cm

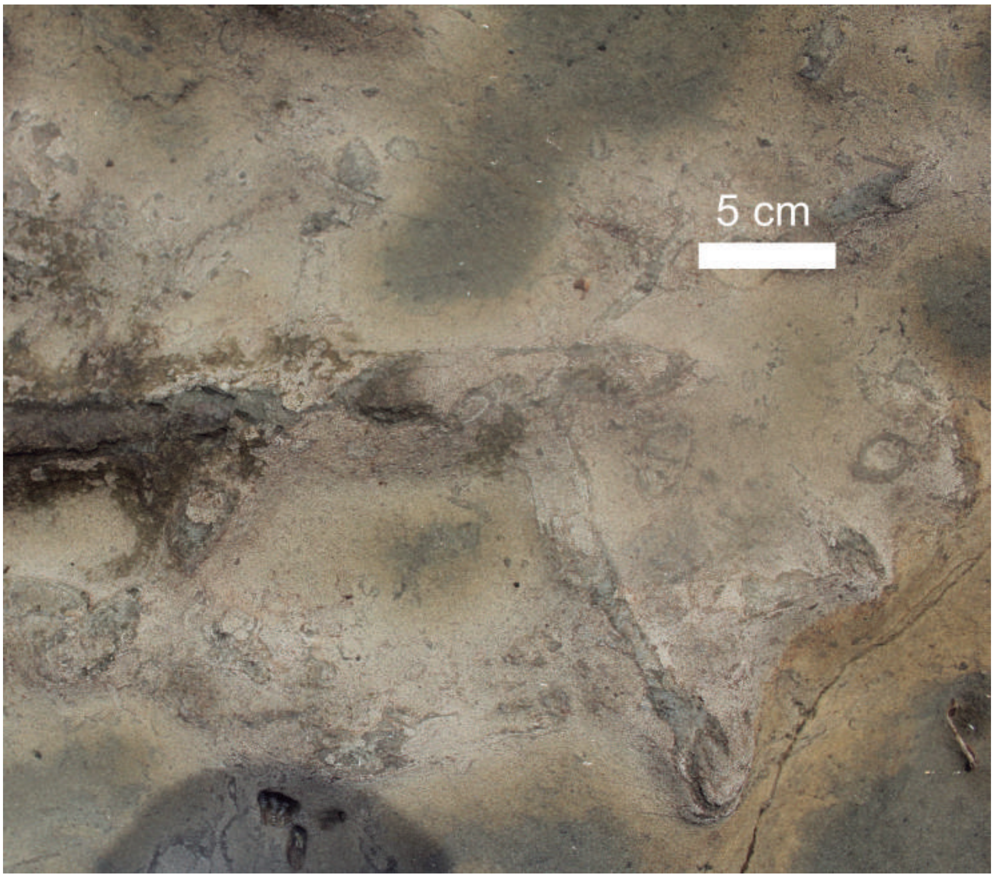
B



- Trace may be straight or slightly curved
- Wall is lined with organic matter
- Trance infill is consistent with surrounding sediment matrix, and additionally it contains an abnormal concentration of foraminifera relative to surrounding sediment
- Wall lining is irregular
- Diameter ranges from 8 - 11 mm
- Wall lining thickness varies from 1 - 2 mm
- Trace shows no branching
- May be vertical or horizontal

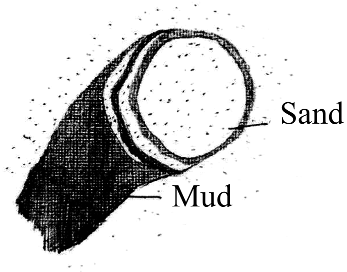
Lateral view
Piña
1 cm

A



B

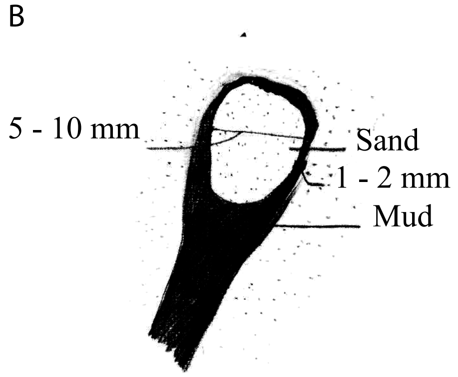
A



- Aperture may be circular to oval shaped.
- Wall is lined with mud or organic matter and can be observed along the trace
- This oblique view may be observed mostly along vertical to sub horizontal exposures of bedding

Lateral view
Toro Point
1 cm

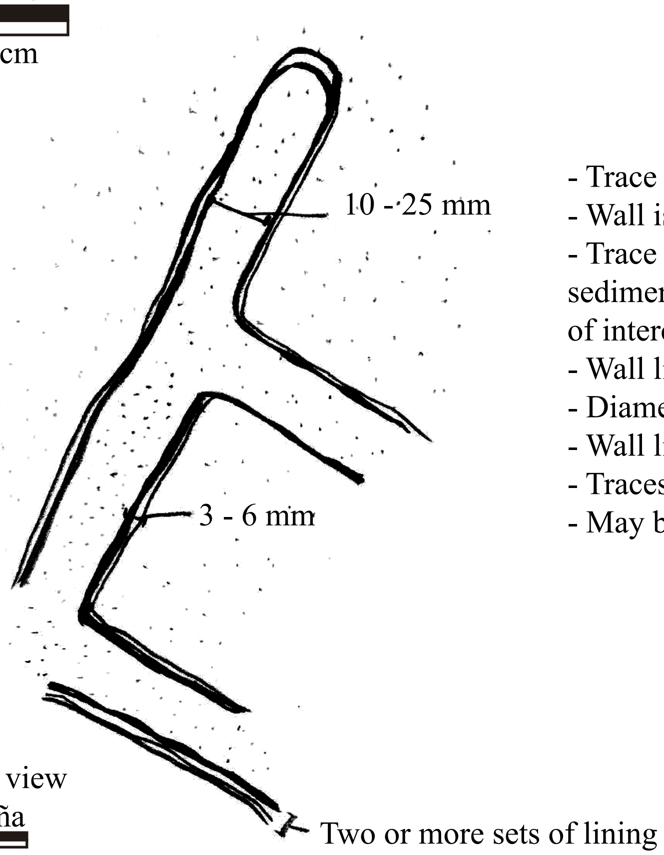
B



- Aperture may be circular to sub circular, varying with orientation of the cut
- Wall lining has irregular edges, revealing an irregular wall structure
- Wall lining consists of mud or organic matter
- Diameter of trace ranges from 5 - 10 mm
- Lining thickness may range from 1 - 2 mm

Lateral view
Toro Point
1 cm

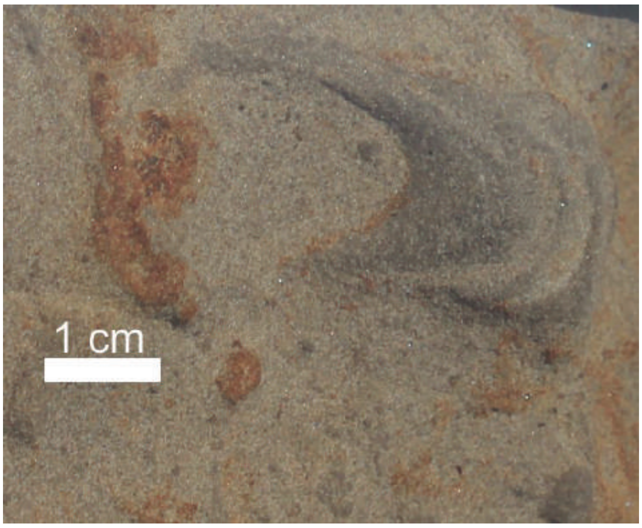
C



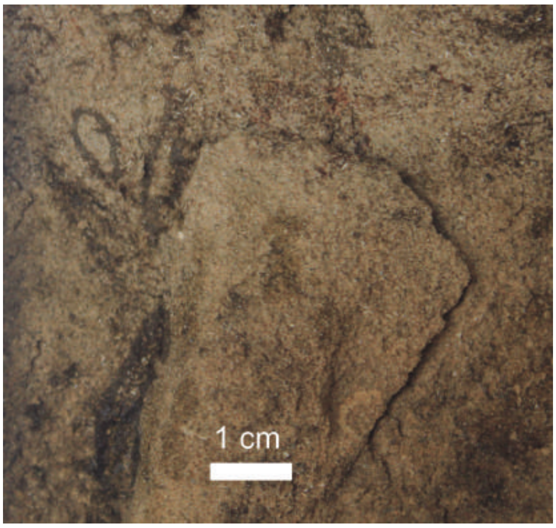
- Trace is predominatly straight
- Wall is lined with two or more sets of lining
- Trace infill has the same grain size as surrounding sediment, or may be filled with spreite consisting of intercalations of sand and mud
- Wall lining may be irregular
- Diameter ranges from 10 - 25 mm
- Wall lining thickness ranges from 3 - 6 mm
- Traces branch in nearly straight angles
- May be vertical or horizontal

Plane view
Piña
1 cm

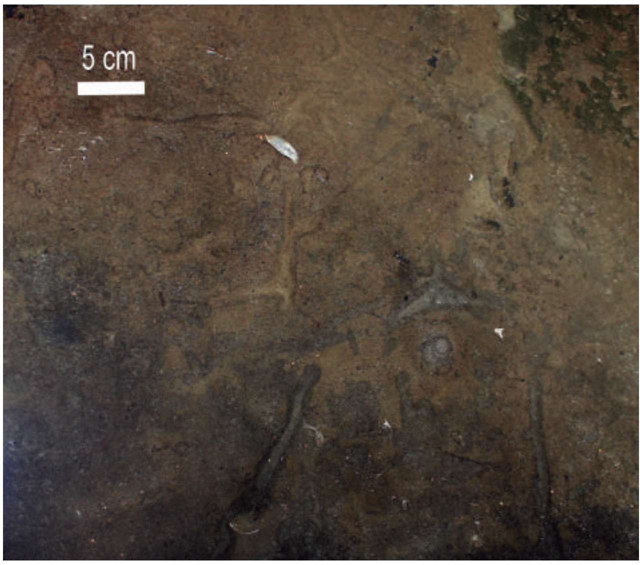
A



B

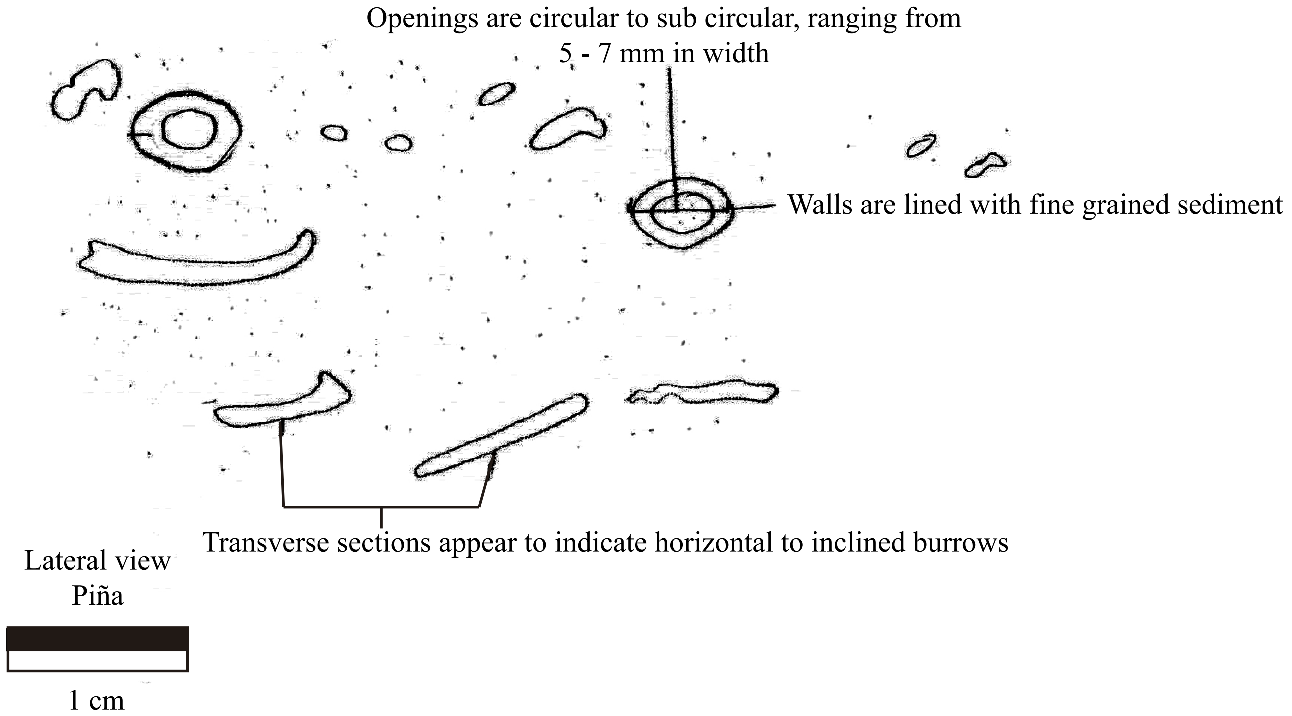


C



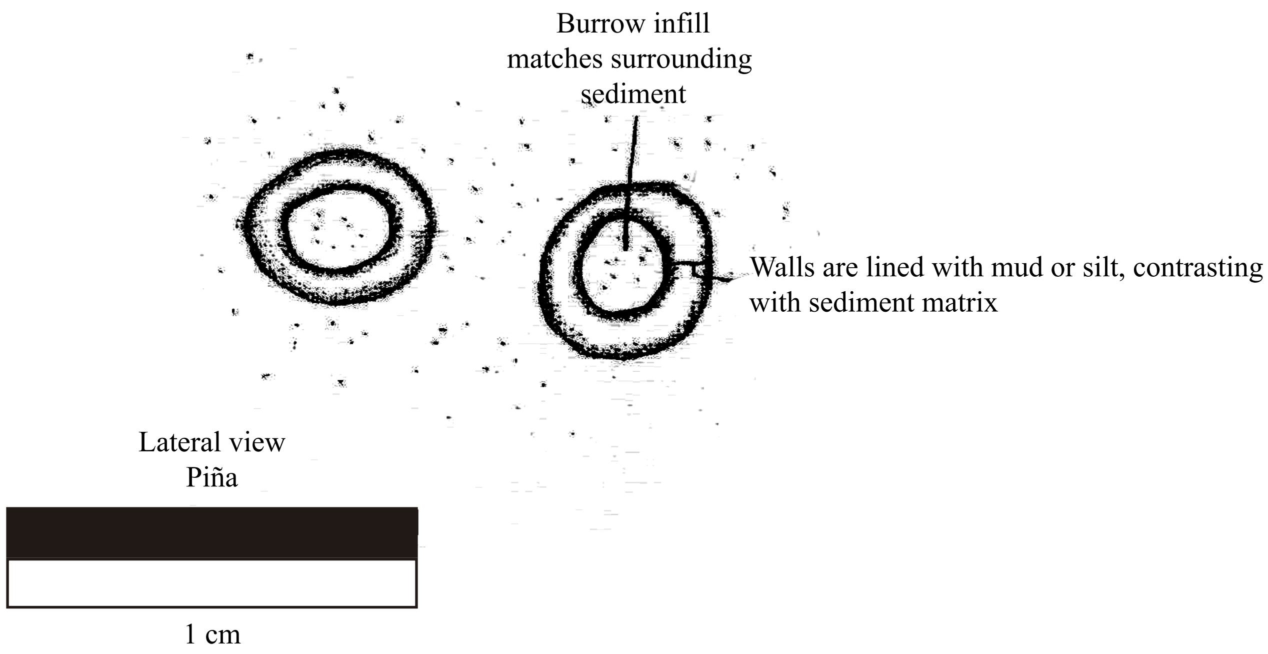
Palaeophycus

A

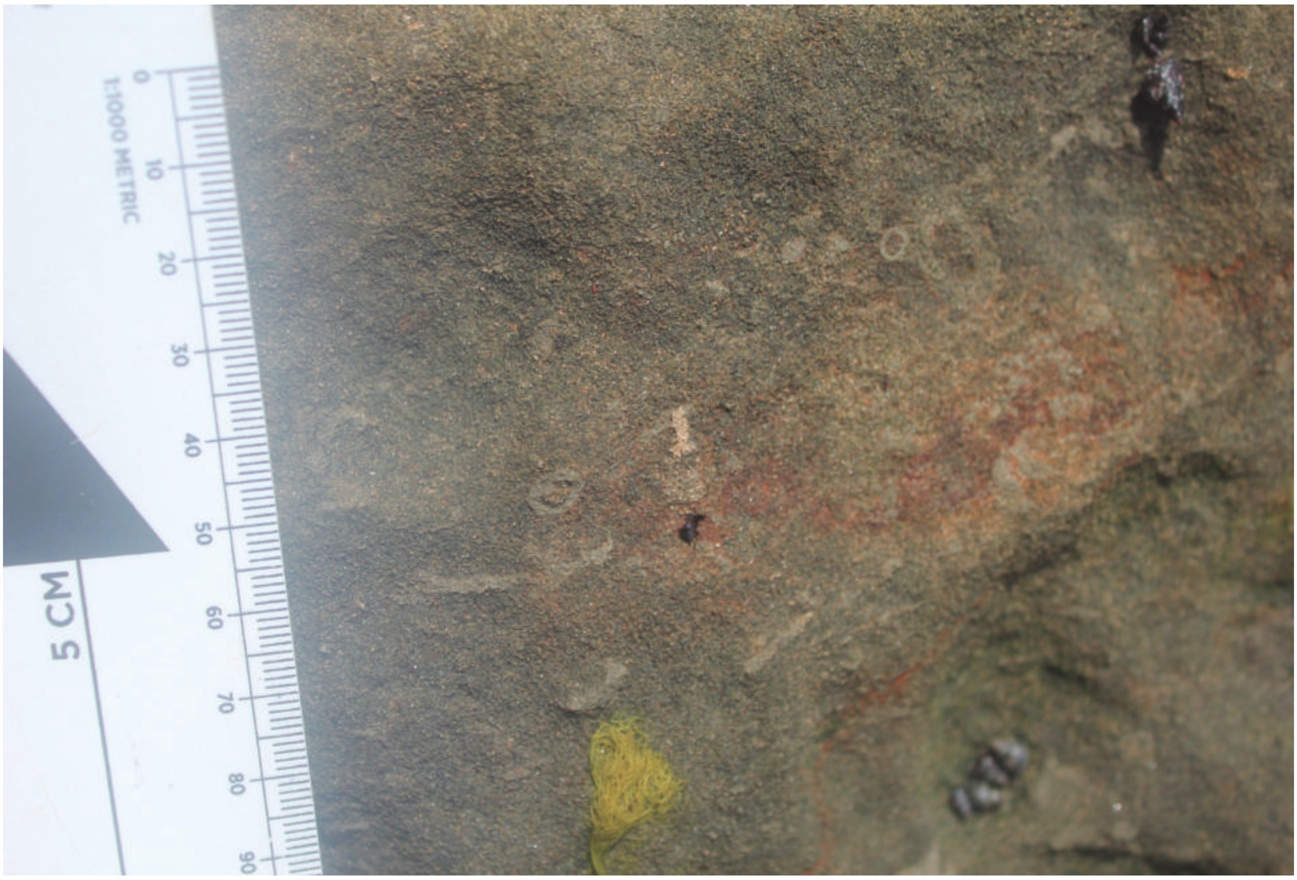


- Small cylindrical horizontal to sub horizontal burrows
- Wall is lined with distinct mud - silt layer, contrasting with surrounding sediment
- Sediment infill matches surrounding sediment matrix
- Wall linings appear to be smooth based on observations of lateral cuts observed in outcrop

B

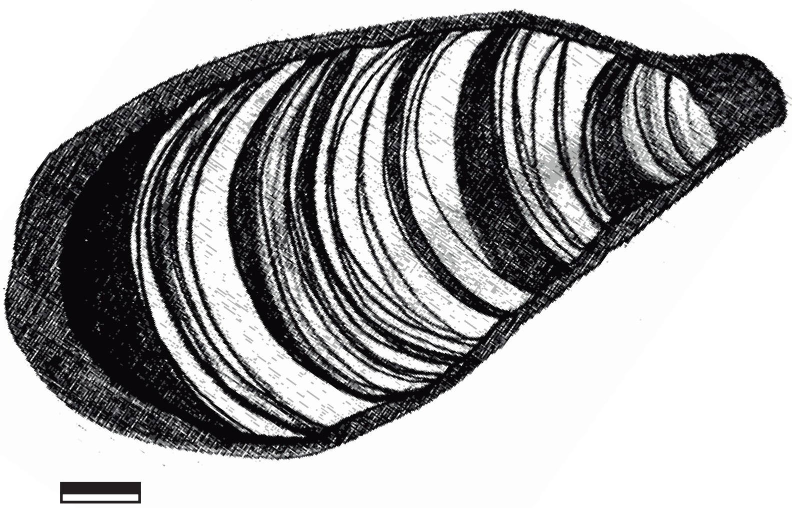


A



B

Rhizocorallium



1 cm

Plane to oblique view
Rio Indio

- ~ 1cm thick U-shaped tube filled with U-shaped spreite.

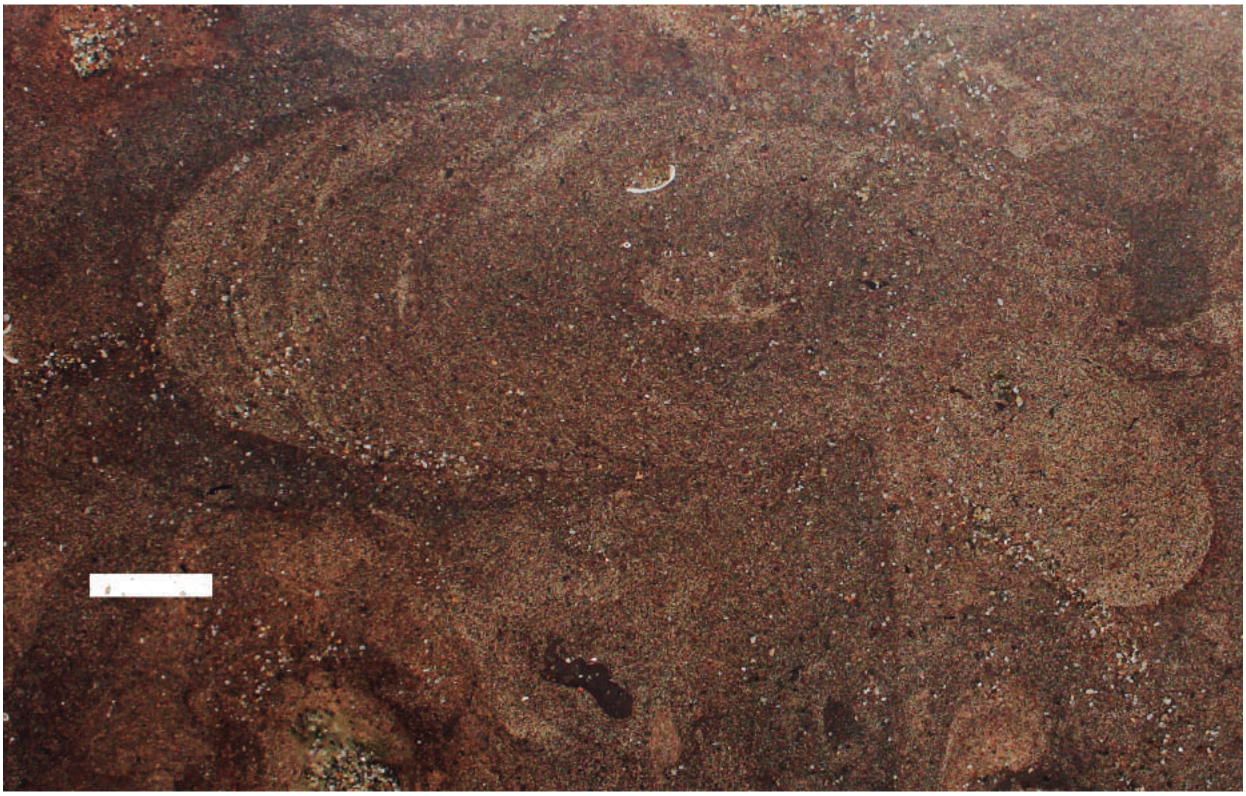
- Horizontal to oblique to bedding plane

- Spreite is protrusive

- Infill of silty and muddy laminae

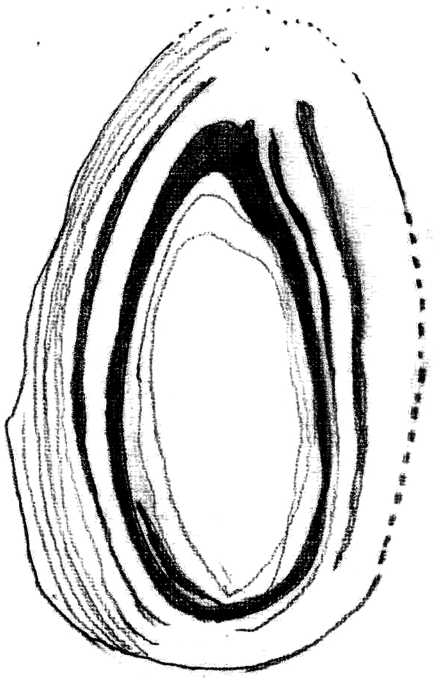
- Laminae usually thinner than tube wall thickness

- Spreite parallel to inside tube margins



Rosselia

A

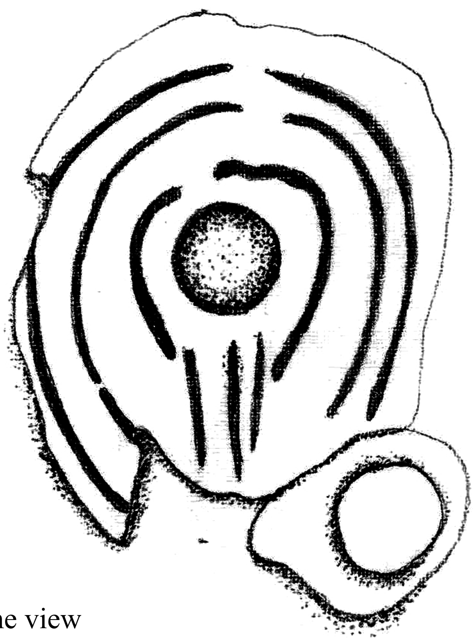


- Vertical, bulb shaped burrow displaying poorly developed concentrical layering
- Layering consists of fine grained sediment and organic rich fine grained sediments
- In lateral cuts, bulb appears to have and oval shape

Lateral view
Rio Indio

1 cm

B



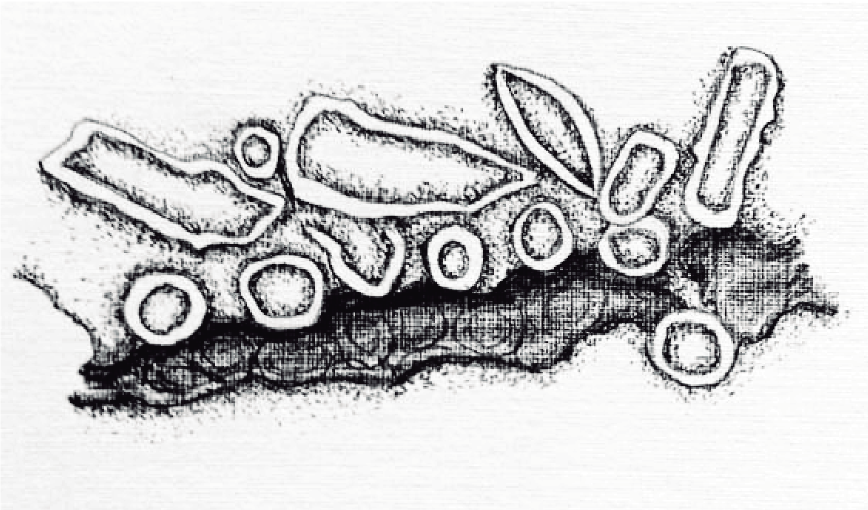
- Circular opening surrounded by faint concentric layers with varying amounts of organic content

Plane view
Rio Indio

1 cm

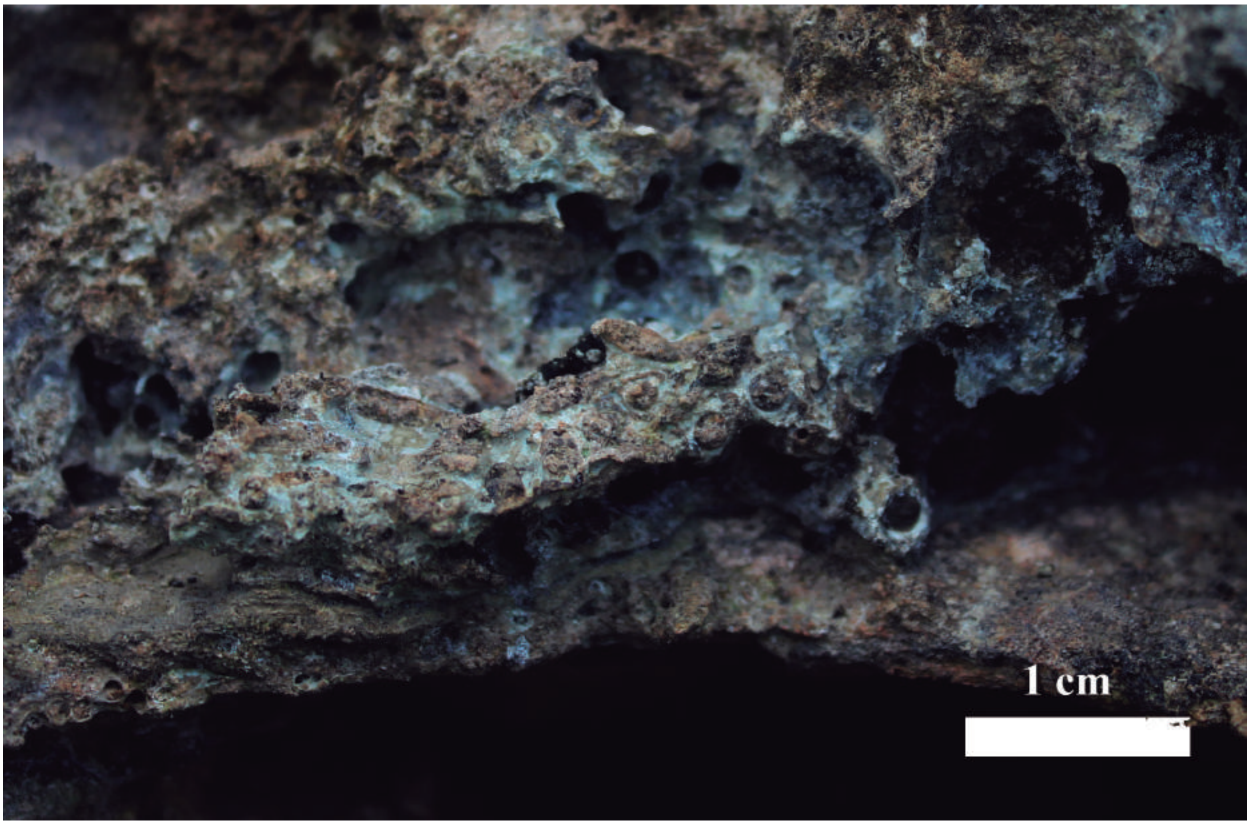

60
70
80
90
100
110
120

Schaubcylindrichnus



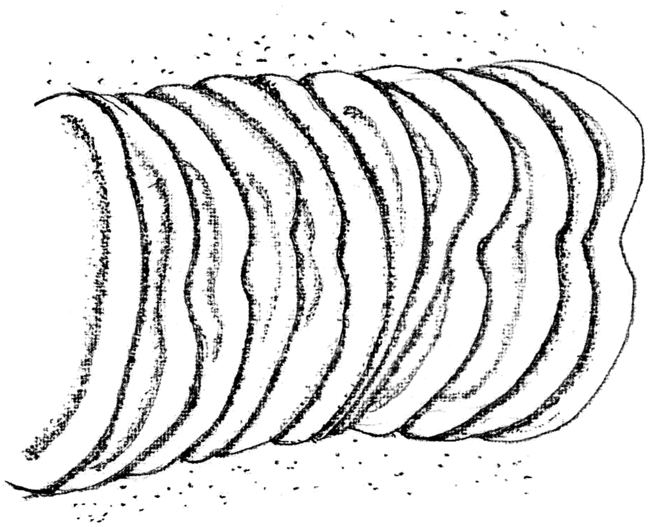
Side to oblique view
Toro Point
1 cm

- Plural curving tubes, gently arcuate with upper ends being vertical
- Lower ends nearly horizontal
- Tubes do not branch or interconnect
- Tubes are well lined
- Both interior and exterior surfaces of tubes are smooth and unornamented



Scolicia

- Horizontal trail representing migration
- Bilobed, symmetrical sediment wedges
- Ribbed medial axis
- Narrow ridge seems to outline each individual wedge
- Distance between wedges ranges from 10 - 15 mm
- Is also found in the coquinas



Plane view
Toro Point
1 cm

Siphonichnus

- Unlined vertical tube

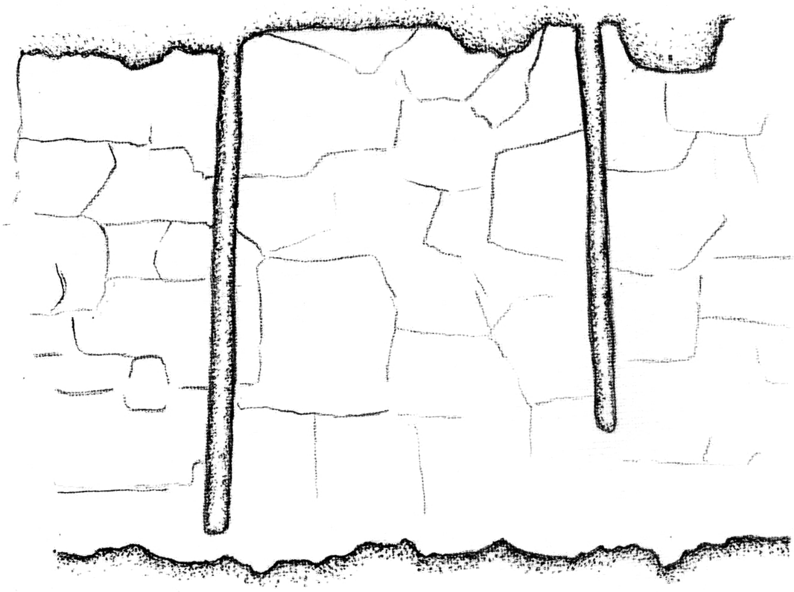
- Concave upward laminae are penetrated by a single central shaft

Side view
Rio Indio

1 cm


1 cm

Skolithos



- Single entrance to straight, vertical, crylindrical shaped tubes

- No wall lining

- Trace is found within a discrete mud lens, infill matches that of upper layer of sediment

- individual burrows are parallel

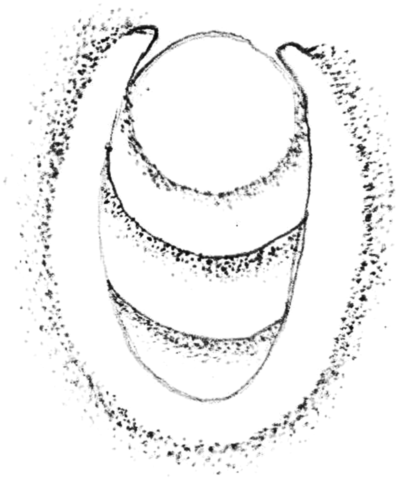
- May be slightly inclined

- Is commonly found in bedding planes

Lateral view
Toro Point

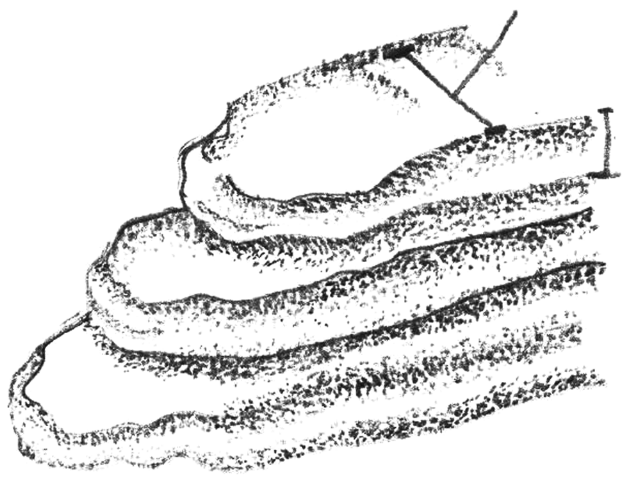
1 cm

Teichichnus



- Trace appears to reveal the vertical migration of a central cylinder shaped tube
- There appears to be no wall lining, but there is a solid halo surrounding the structure probably originated during diagenesis
- Sediment infill coincides with sediment matrix
- It only seems to represent vertical migration no horizontal analogues were observed

Lateral view
Piña
1 cm

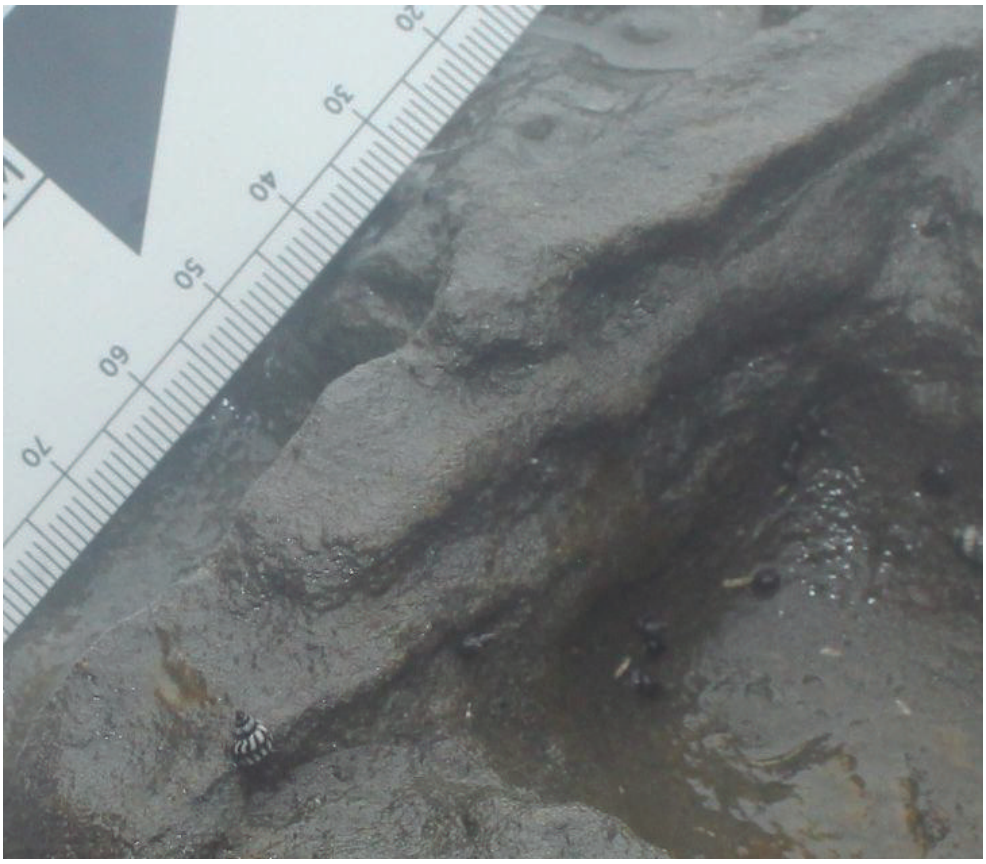


- When observed from an oblique cut, the trace seems to resemble a stack of horizontal burrows
- There is probably a thin layer of mud between each horizontal layer

Lateral view
Piña
1 cm

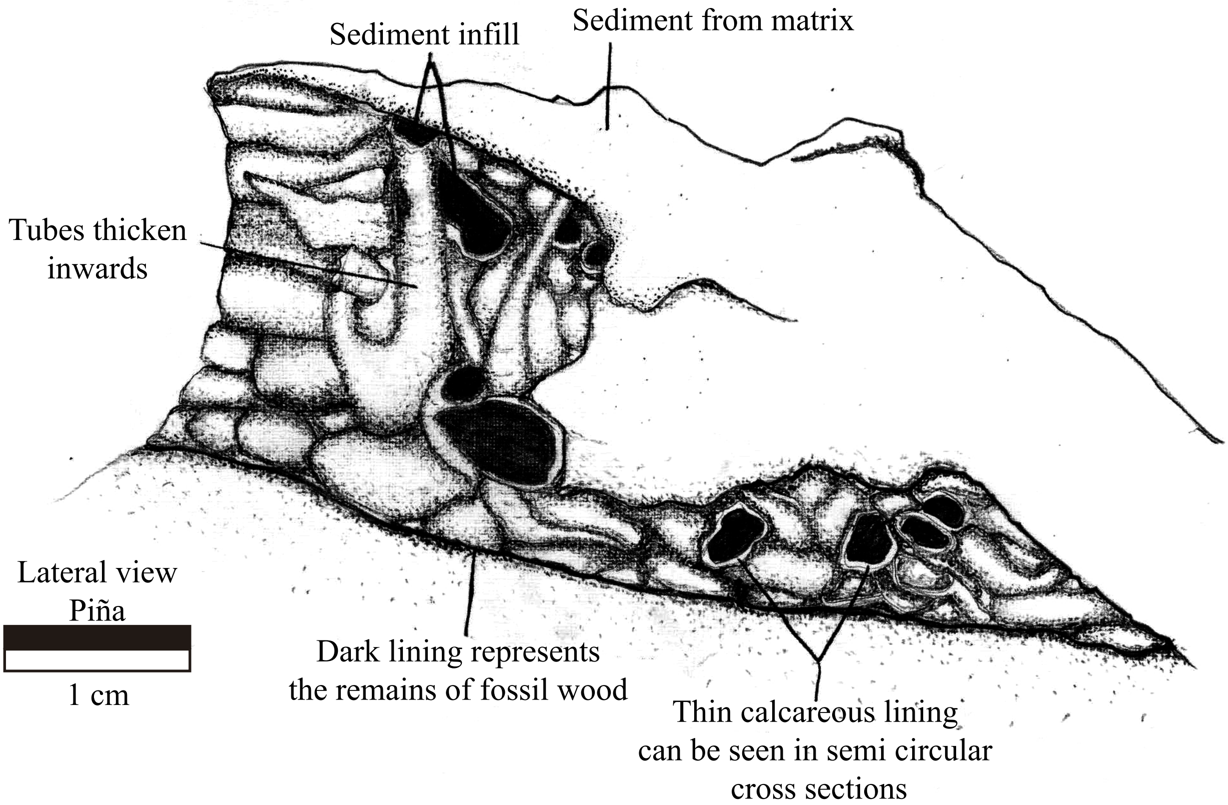
A

B



Teredolites

A

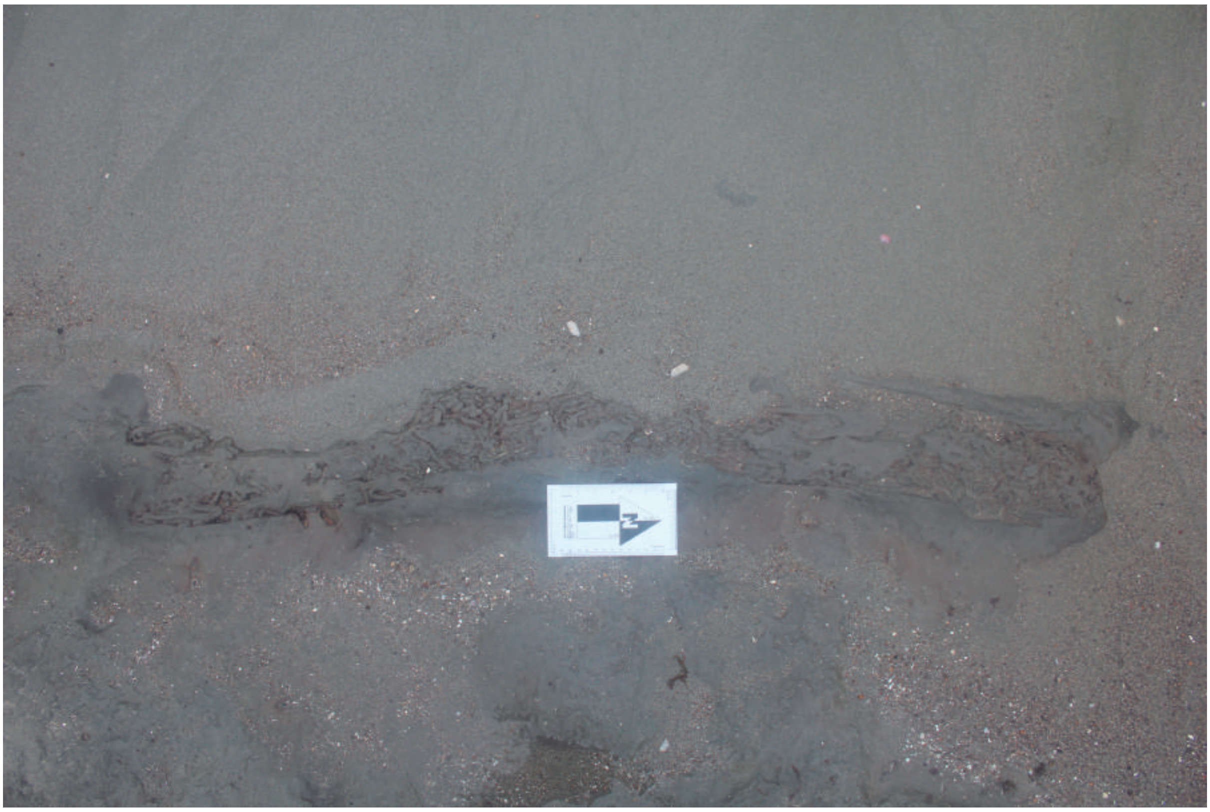


- Cluster of elongate pear shaped tubes, bored into fossilized wood
- Each tube has a thin calcareous lining
- Each tube opening is found in the interface between the fossil log and the sediment matrix that contains it
- Tubes are filled with the sediment from the surrounding matrix
- Large logs of up to 2 m can be found along the coastal exposures

B

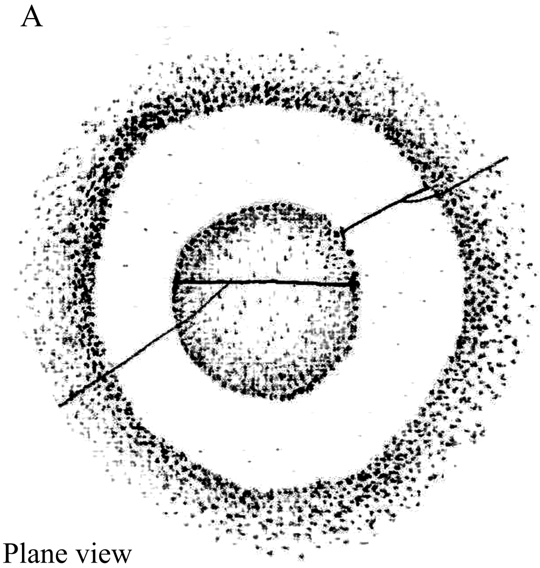
A

B



Thalassinoides

A

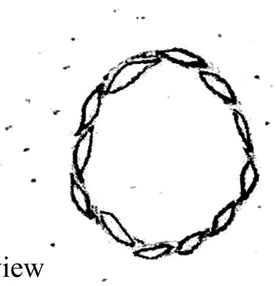


Plane view
Piña

1 cm

- Circular aperture, no wall lining
- Sediment surrounding aperture has been solidified, probably by diagenetic processes
- Aperture diameter ranges from 15 - 30 mm
- Solid sediment halo thickness ranges from 5 - 20 mm
- Burrow infill is generally absent, resulting in hollow tubes
- May be observed in both the vertical or horizontal exposures of bedding

B

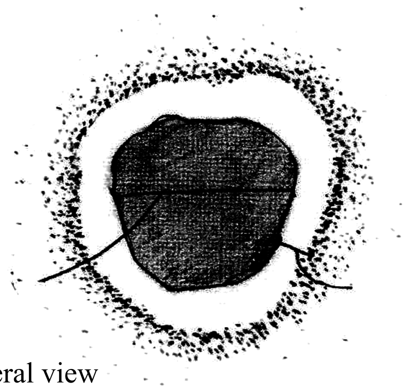


Plane view
Toro Point

1 cm

- Circular aperture
- Wall is ornamented with barnacle plates and shell fragments from the surrounding sediment
- Shell fragments are organized in the lining with a particular orientation, indicating deliberate use by organisms to ornament walls
- Aperture diameter ranges from 6 - 10 mm
- Wall lining is 1 - 1.5 mm thick

C



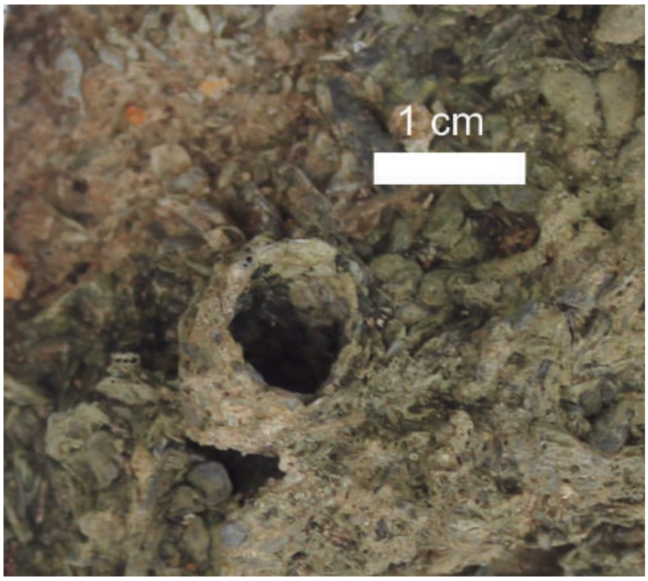
Lateral view
Piña

1 cm

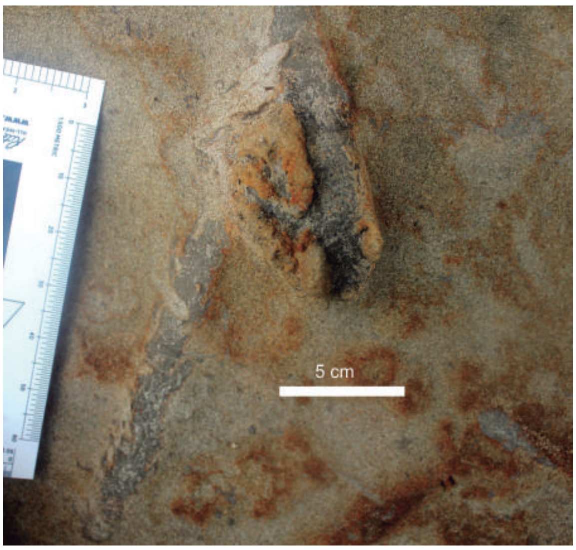
- Semicircular aperture with irregular edges, probably due to the fact that the burrow is infilled with finer grained sediment
- Wall is unlined, but a solid sediment halo surrounds the aperture probably due to diagenetic processes
- Infill is mudsized sediment
- Diameter ranges from 15 - 20 mm
- Solid halo surrounding aperture is 5 - 6 mm thick
- May be seen both in vertical and horizontal bedding exposures

A

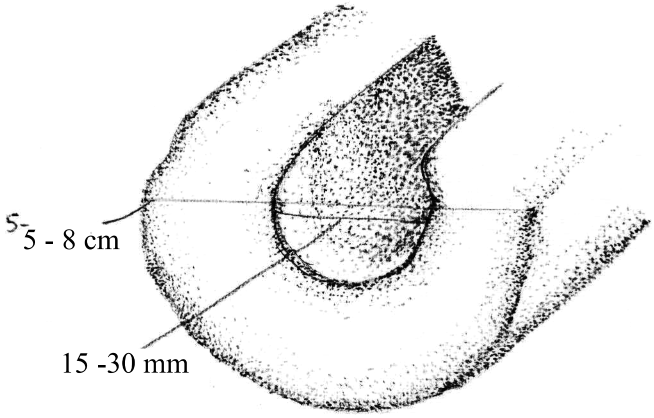
B



C



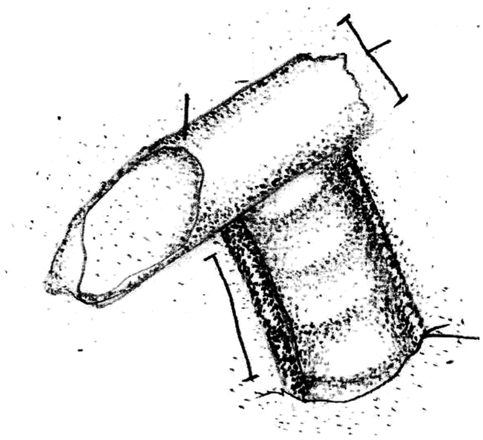
A



Lateral view
Piña
1 cm

- Solid halo is preserved around hollow circular apertures, resulting in hollow tubes
- Their total diameter can range from 50 - 80 mm, which makes them look like relatively large burrows when compared to other traces in the formation, but the true diameter of the trace is the diameter of the hollow inner tube
- Inner tube diameter ranges from 15 to 30 mm
- Solid lining ranges from 20 - 30 cm in width

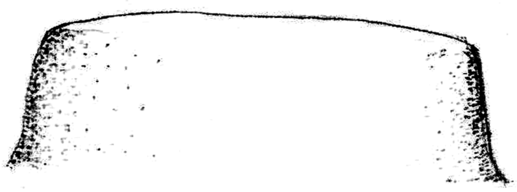
B



Plane view
Piña
1 cm

- Circular aperture lined with a solid sediment wall lining, may not always be preserved
- In traces where lining is dissolved, internal structures are revealed: spreite consisting of intercalations of sand and finer grained sediment
- When wall is preserved, it is smooth and may consist of finer grained sediment
- Diameter ranges from 15 - 20 mm
- wall lining is 1 - 2 mm thick

C



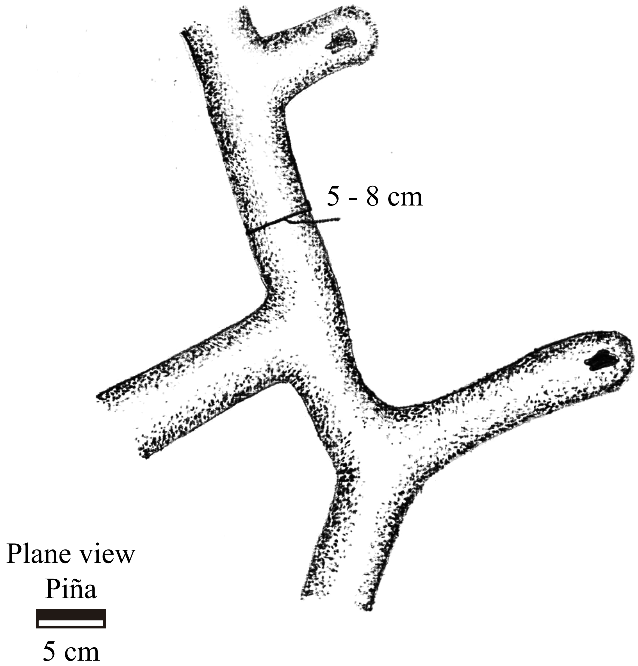
Lateral view
Piña
1 cm

A

B

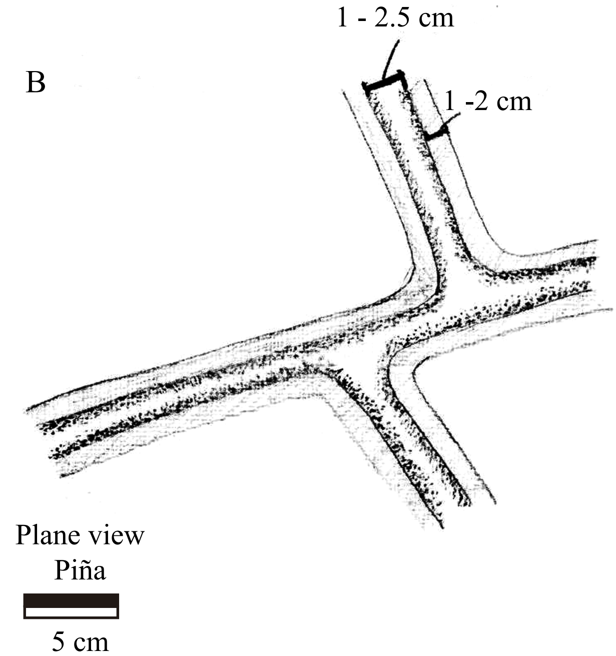
C

A



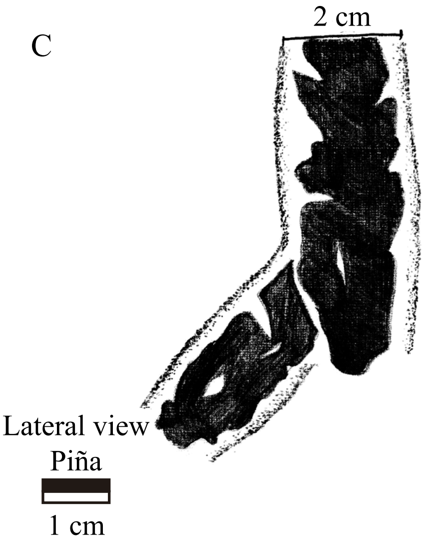
- Trace is invariably straight , very regular
- Solid halo surrounding circular inner tube is the bulk of the trace, making it appear large
- Infill is usually dissolved, resulting in hollow tubes
- Diameter including solid halo ranges from 5 - 8 cm
- Diameter of the inner tube ranges from 1.5 - 3 cm
- Solid lining may range from 2 - 3 cm in width
- Solid lining is inferred as a product of diagenetic processes
- Trace branches out in Y- shaped or straight angle shaped junctions

B



- Trace is invariably straight , very regular
- Inner tube is lined with a thick layer of mud to silt sized grains
- Lining has been dissolved leaving only inner tubes in most cases
- Infill may or may not have spreite structure
- Diameter including wall lining ranges from 5 - 6 cm
- Inner tube diameter ranges from 10 - 25 mm
- Mud lining thickness ranges from 10 - 20 mm
- Trace branches out in nearly straight angles or Y - shaped junctions

C



- Trace is straight
- Wall shows no lining, but a solid halo surrounds the inner tube which is infilled with fine grained sediment
- Wall is irregular, may show signs of posterior bioturbation
- Diameter ranges from 15 to 20 mm
- Trace branches out in Y- shaped junctions or nearly strainght angles
- May be vertical or horizontal

A

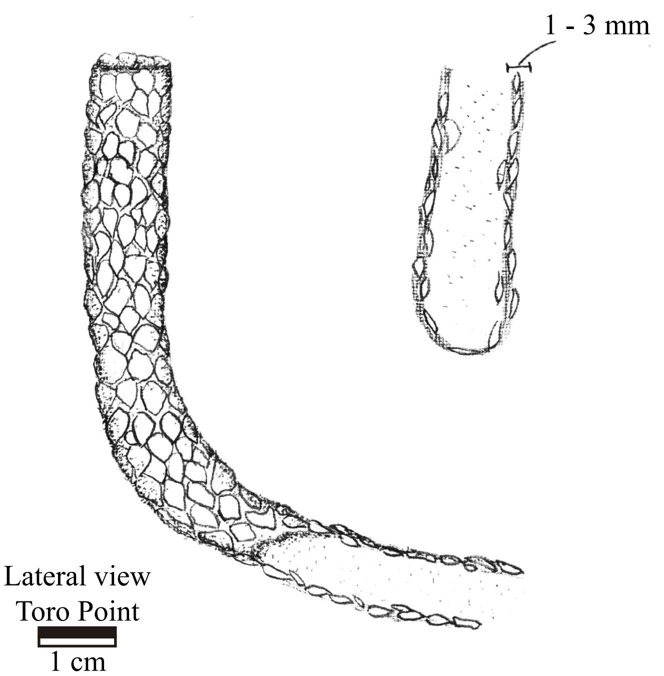
B

C

A

- Trace is straight, vertical
- Wall is lined with a thin layer of mud sized grains
- Trace is filled with great abundance of mollusks amd shell fragments along with sediment from the surrounding matrix
- Wall lining is regular
- Diameter is large compared to other traces in the formation, ranging from 2 - 4 cm
- Wall lining thickness ranges from 1 -2 mm
- Trace shows some branching in almost straight angles

B

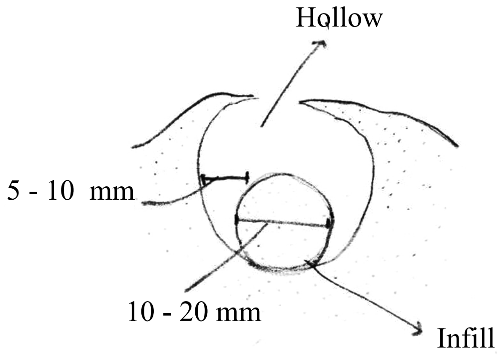


- Trace is curved
- Wall is lined with a mixture of barnacle and mollusk fragments with mud
- Orientation of fragments suggests that the organisms deliberately placed the fragments to ornament the burrow walls
-Trace infill has smaller grain size than the surrounding sediment matrix
- Wall lining is regular, and inner wall is very smooth
- Diameter is usually less than 10 mm
- Lining thickness varies from 1 - 3 mm
- Trace does not present branching
- May be vertical or horizontal

A

B

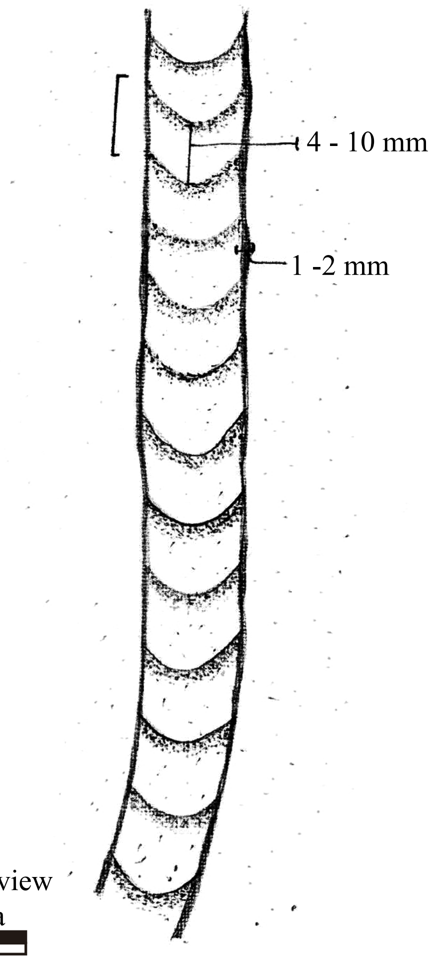
A



Lateral view
Piña
1 cm

- Circular aperture, wall lining is dissolved leaving a hollow halo surrounding the preserved infill
- Infill has same gran size as surrounding sediment matrix
- Diameter ranges from 10 - 20 mm
- Hollow wall surrounding inner tube has a thickness of 5 - 10 mm
- May be vertical o horizontal

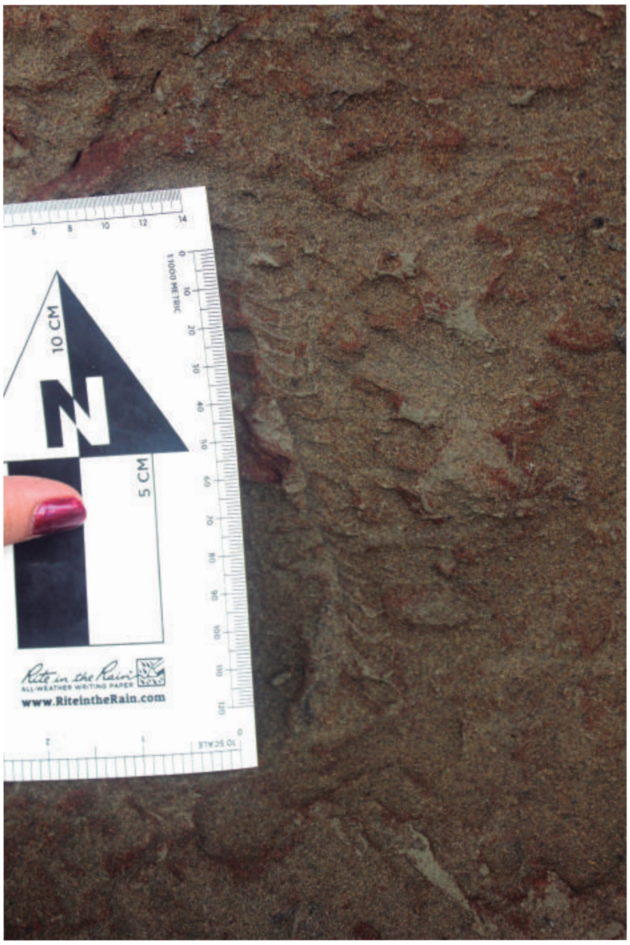
B



Lateral view
Piña
1 cm

- Trace may be straight of slightly curved
- Wall appears to be lined with mud or silt
- Trace infill may have the same grain size as the surrounding sediment matrix, or it may be filled with spreite consisting of mud and sand intercalations, mud laminae are thinner
- Wall lining is regular
- Diameter ranges from 10 - 15 mm
- Lining thickness ranges from 1 - 2 mm
- Traces may exhibit branching at Y-shaped junctions
- May be vertical or horizontal

A



B