

# Deep-sea trace fossils in the West Crocker Formation, Sabah (Malaysia), and their palaeoenvironmental significance

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**Abstract:** In the “flysch” series of the West Crocker Formation (Eocene–Oligocene), Kota Kinabalu, Sabah, trace fossils are fairly common although not ubiquitous. The trace fossils commonly occur as hypichnial semi- or full-reliefs on the sole of thin turbiditic sandstone beds (mainly Bouma Tc division) in the thinly bedded heterolithic sandstone-mudstone facies interpreted as submarine fan lobe deposits. Their presence in mainly the thinly bedded facies of the fan system suggests preferential production and preservation in the fine-grained “distal” parts of the Crocker submarine fan system. Trace fossil assemblages characteristic of the *Nereites* ichnofacies indicate sedimentary environments mainly in bathyal to abyssal water depths (>2000 m). This ichnofacies is dominated by horizontal grazing, farming and feeding traces, ranging from solitary to branching tubular burrows (*Ophiomorpha*, *Palaeophycus* and *Planolites*) to meandering trails and tunnels (*Nereites*, *Cosmorhapha*, *Helminthopsis*), as well as the spiriform burrows *Spirophycus*. Graphoglyptids are the most diagnostic of the *Nereites* ichnofacies, produced by sediment grazers and farmers (agricrnia) and often displaying intricate networks of mainly horizontal tunnels preserved as hypichnial semi-reliefs. They include the delicate spiral traces of *Spirorhapha*, as well as the enigmatic hexagonal network burrow *Paleodictyon*. Other ichnogenera include *Planolites*, *Thalassinoides* and *Ophiomorpha* which are facies-crossing and not environment specific. Detailed observations of the trace fossil assemblages and the degree of bioturbation enabled different sub-ichnofacies of the *Nereites* ichnofacies to be distinguished. *Ophiomorpha* is more common in sandy “proximal” facies and tend to penetrate deeply into pre-existing turbidite beds, its presence suggests a well-oxygenated newly deposited turbidite substrate, probably in the axial region of the fan lobes. Hence, channel axis and proximal fan deposits tend to be dominated by the *Ophiomorpha rudis* sub-ichnofacies. The *Paleodictyon* sub-ichnofacies is more typical of the lower energy lobe/fan fringe subenvironments. Proximal but off-axis areas are characterized by a mixture of the *Ophiomorpha rudis* and *Paleodictyon* sub-ichnofacies.

**Keywords:** Trace fossils, turbidites, ichnofacies, graphoglyptids, paleoenvironment, Sabah

## INTRODUCTION

The deep-sea environment is relatively stable, dominated by pelagic/hemipelagic deposition of clay-rich sediments. This background sedimentation is punctuated by the intermittent terrestrial sediment influx via sediment gravity flows (turbidity and debris flows). The resulting “event beds” are of interest to sedimentologists for their academic and economic value. The fine-grained muddy intervals also contain a wealth of information but are paid less attention. During the quiet “non-event” periods, burrows, tracks and trails are produced by organisms on the deep sea floor but the occurrence of trace fossils is usually mentioned only in passing. Careful study of the traces and the host sediment would shed light into the organism-sediment interactions and the palaeoenvironmental conditions during the non-turbiditic “background” intervals, which are equally as important as those of the event beds themselves.

In deep-sea turbiditic sequences of the West Crocker Formation, West Sabah, trace fossils are fairly common, especially in the thinly bedded sandstone-mudstone sequences. Although the sedimentology and structure of the Crocker Formation have been studied for decades, the

trace fossils within it have not been given much importance. Careful study of the traces and the host sediment would shed light into the biogenic activities during the quiescent periods between turbiditic events, which are essentially “catastrophic” events of relatively short duration when compared to the “background” hemipelagic/pelagic sedimentation. Organism-sediment interactions may give insightful information into the depositional environment during those “quiet” intervening periods.

This paper describes some of the trace fossils found in the outcrops of the West Crocker Formation around the city of Kota Kinabalu, Sabah, and briefly discusses their palaeoenvironmental significance in relation to the deep-sea depositional processes in the Eocene–Oligocene NW Borneo margin. Some trace fossils from the West Crocker Formation have been mentioned by previous workers but their detailed description and significance to palaeoenvironmental studies have not been given enough attention. It is hoped that this paper will stimulate further interest in the study of trace fossils as an important tool for palaeoenvironmental analysis, not just in the West Crocker Formation but in other geological settings.

## GEOLOGICAL SETTING

The study area around Kota Kinabalu is situated in the Cenozoic NW Borneo Basin, which underlies Sarawak, Brunei and Sabah at the southern margin of the South China Sea (Figure 1). The Crocker Formation, which forms the entire coastal zone and foothills of Western Sabah, is considered by many workers as a part of an uplifted Upper Cretaceous to Lower Miocene accretionary prism that resulted from the subduction of a proto-South China Sea oceanic crust underneath Sabah (Tan & Lamy, 1990; Hazebroek & Tan, 1993; Hall, 2002) (Figure 2). The uplifted accretionary prism forms an oroclinal fold-and-thrust belt made up of flysch-like deposits that spans the entire island of Borneo, from west Kalimantan to Sabah (Moss *et al.*, 1998; Hutchison, 1996, 2010). In West Sabah, particularly in the Kota Kinabalu area, these flysch-like rocks have been mapped as the West Crocker Formation. The eroded fold-and-thrust belt essentially forms the basement to the NW Sabah basin. Continuous shelf-slope progradation since the Middle Miocene resulted in the accumulation of sediment more than 12 km thick under the shelf off western Sabah.

### Stratigraphy and sedimentology

The age of the West Crocker Formation is still uncertain. It had been dated on the basis of foraminifera as Oligocene to Lower Miocene by Wilson (1964), although in the Stratigraphic Lexicon of Malaysia (Lee *et al.*, 2004), an age ranging from Paleocene to Miocene is quoted based on works by different authors. Late Eocene planktonic foraminifera were reported from red mudstones of the West Crocker Formation in the Pun Batu area, in the interior of south-west Sabah (Basir *et al.*, 1991). Later paleontological studies using foraminifera have also found that the West Crocker Formation could be Upper Eocene to Oligocene in age (Lambiase *et al.*, 2008; Cullen, 2010; Cullen *et al.*, 2012), slightly older than previously thought. This new age seems to support the presence of a “Top-Crocker Unconformity” that marks the Oligocene-Miocene boundary event in Sabah (Lunt & Madon, 2017).

Onshore, the imbricate thrusting that affected the Crocker Formation, with individual thrust slices (200–600 m thick) generally younging from west to east, had resulted in steeply dipping beds (Tongkul, 1989, 1999). The stratigraphy may be repeated over relatively short distances, but the poor exposure make regional correlation difficult. The steep dips, in places vertical or overturned, however, enable easy logging. High rates of weathering meant that the outcrops deteriorate rapidly.

The West Crocker Formation has an estimated total thickness of >6000 m (Lee *et al.*, 2004), comprising predominantly unmetamorphosed deep-sea deposits, which have been described invariably as “flysch”, “turbidite”, “submarine fan”, and/or “mass-flow” deposits (e.g. Stauffer, 1967; Tongkul, 1989; Crevello, 1998; Hutchison, 2005; Crevello *et al.*, 2007a). Five decades ago, Stauffer (1967)

described the Crocker Formation in detail as Paleocene to Early Miocene deformed submarine fan system consisting of “*flysch-type sequences, laminites, red and green mudstone, massive sandstone, and zones of primary slump deformation*”. This description formed the basis for future work that was to follow in the subsequent decades. But for a long time, not much happened since Stauffer’s publication, until around the mid-eighties.

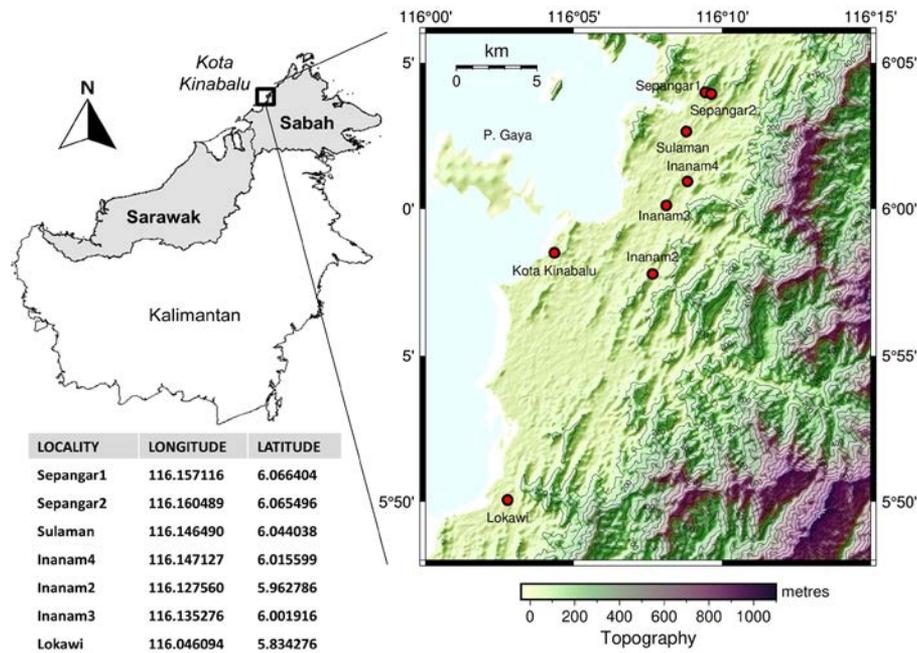
Tongkul (1989) observed that the Crocker Formation consists of a lower shaly unit and an upper sandy unit deposited by a large northward-prograding submarine fan system. A 500 m-thick sequence was interpreted as a stacked channel-levee-fan lobe complex, draped over by about 100 m of basin-plain deposits. At least 20 major channel-sand sequences (5–70 m thick) were identified. These channel sand sequences extend laterally for several kilometres. Later workers have slightly different interpretations of the West Crocker Formation, which include an unconfined basin-floor fan with mixed braided- and leveed-channel systems (Crevello *et al.*, 2007c), a complex system of small progradational lobes in a slope apron environment (William *et al.*, 2003; Lambiase *et al.*, 2008), and a large submarine fan (Jackson *et al.*, 2009; Zakaria *et al.*, 2013).

### DESCRIPTION OF THE HOST SEDIMENTS

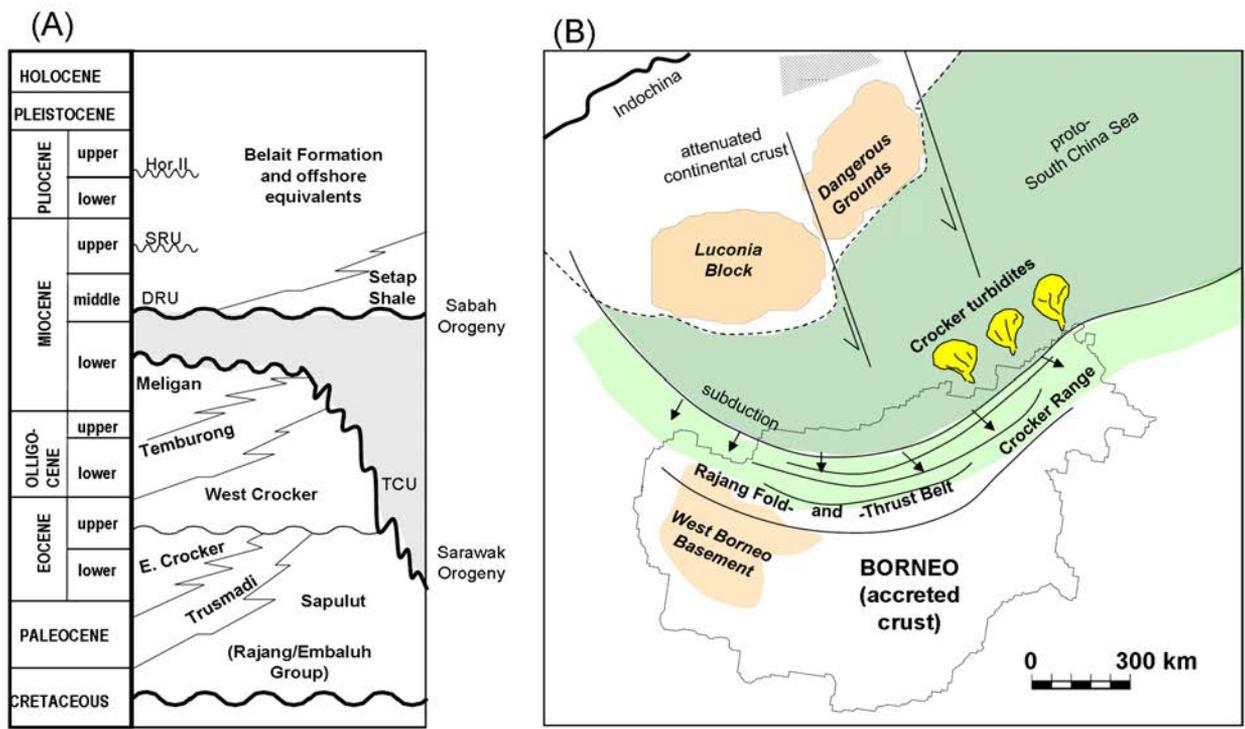
The trace fossils described in this paper were found in a number of outcrop localities around Kota Kinabalu area (Figure 1 with their coordinates). Most of them were from six localities, which are referred to herein as Inanam 2, Inanam 3, Sulaman 2, Sepangar, Sepangar 2, and Inanam 4. Figure 3 shows some field photographs of the outcrops. The outcrops were logged for sedimentological facies analysis while trace fossil occurrences were documented for identification and further analysis.

Figure 4 shows some examples of the sedimentary logs from two selected outcrops where most of the trace fossils were found. Both outcrops show a sand-rich succession characterized by mostly fine-grained, very thick- to medium-bedded sandstones (Figure 5A). Some of them are pebbly sandstones interbedded with mudstone and mud-rich slump intervals. Rip-up clasts often found “floating” within the top of sandstone beds indicate the erosive nature of the depositing turbidity flows. Some of the thicker amalgamated sandstone beds may exceed 30 m in thickness. Many of them are massive and exhibit erosive bases and faint parallel lamination, often with dewatering features such as dish and pipe structures, usually in Bouma Ta/Tb divisions (Figures 5B, 5C). Thinly bedded turbidites (<1 m) show graded bedding with common Bouma Ta-Tb-Tc-Td divisions easily recognized (Figures 5D, 5E). Many sandstone beds have well-developed sole marks, which include flute casts, current lineation, as well as load and flame structures (Figures 5F, 5G).

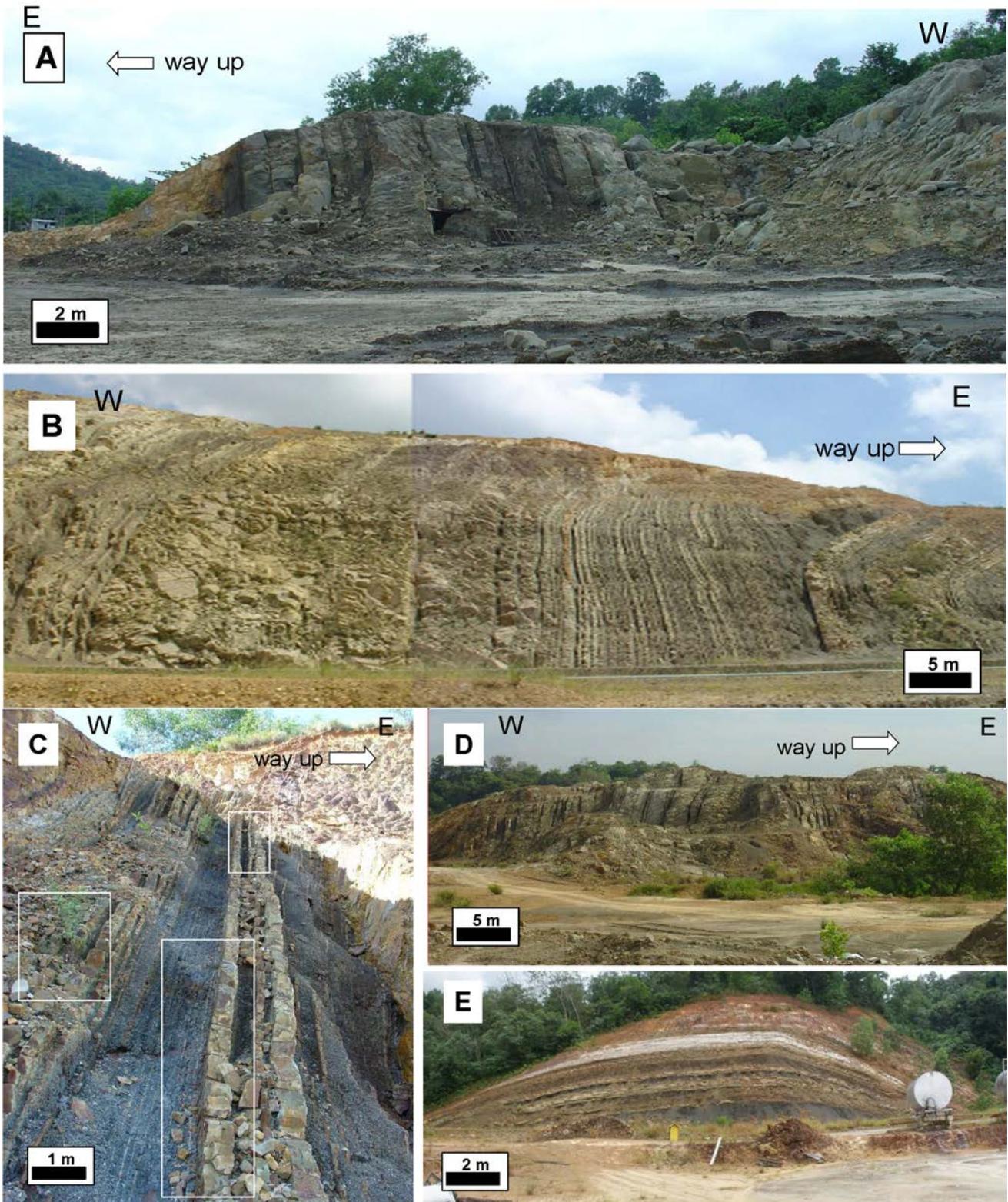
The West Crocker Formation around Kota Kinabalu area are interpreted mainly as basin-floor fan deposits, based



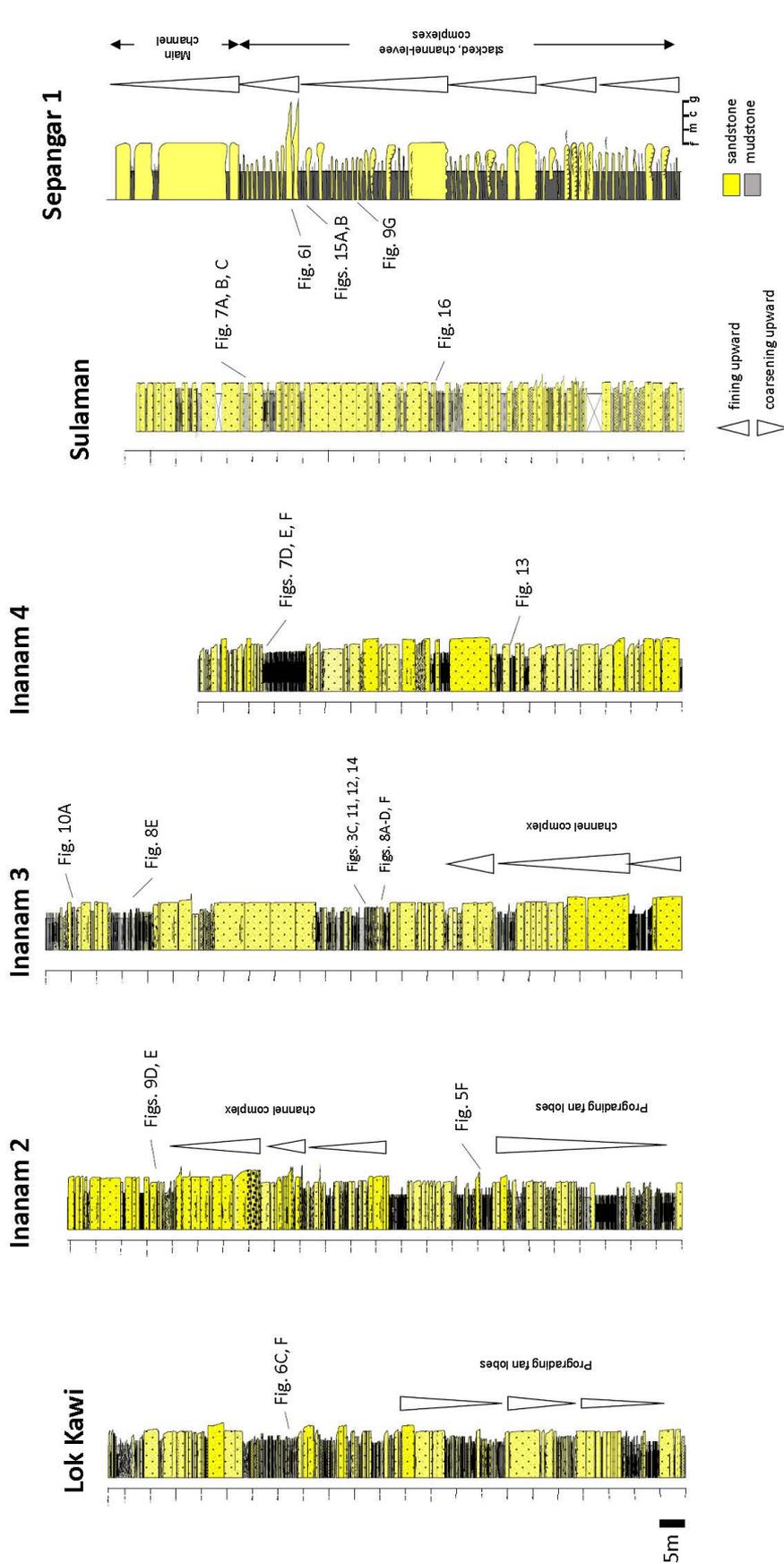
**Figure 1:** Map of study area in Kota Kinabalu, Sabah, in northern Borneo, showing the main outcrop localities mentioned in the text. Topographic map is based on SRTM v4.1 ( <https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/> ).



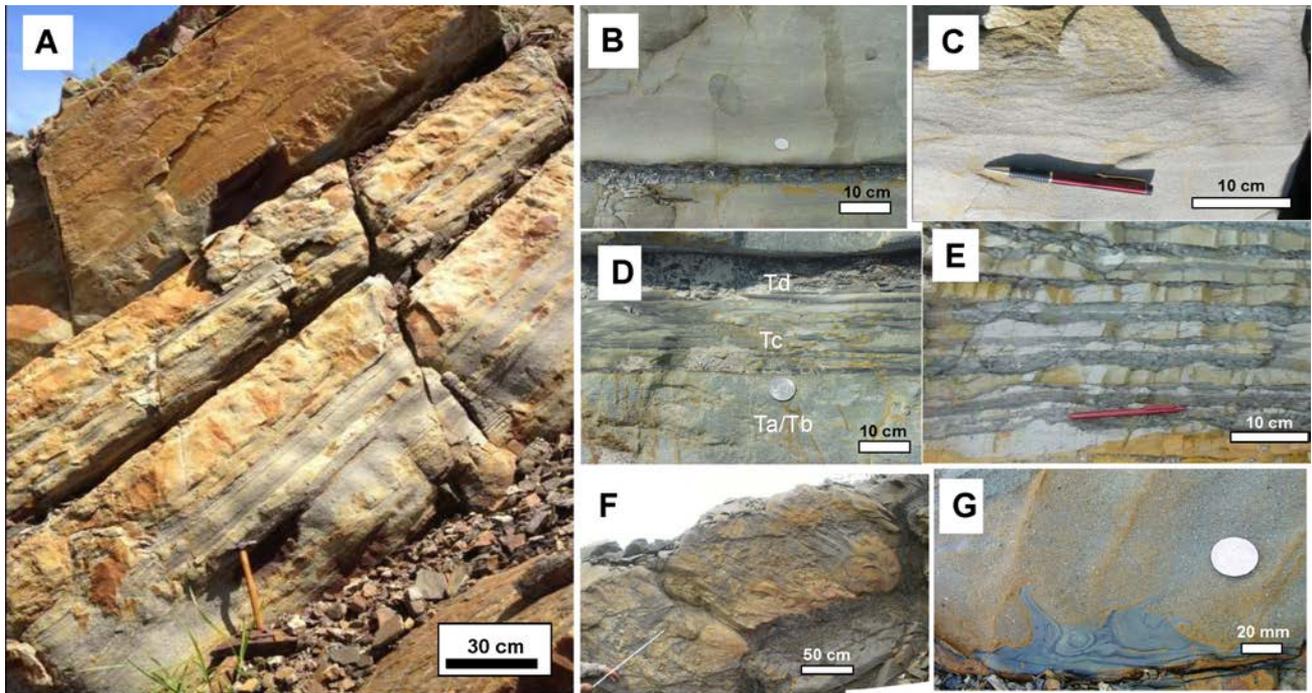
**Figure 2:** Regional geological and tectonic framework of the study area. (a) Stratigraphic summary of the Western Sabah region, based on various sources, including van Borren *et al.* (1996), Cullen *et al.* (2012), Leong (1999), Hutchison (1996), Hall *et al.* (2008), and Lunt & Madon (2017). The Top-Crocker Unconformity (TCU) was introduced by Hall *et al.* (2008) as the regional base-Miocene angular unconformity that marks the peneplanation of uplifted Crocker accretionary prism, hence the name. The Deep Regional Unconformity (DRU), of Middle Miocene age, is the regional angular unconformity at the base of shallow marine sequences in the offshore NW Sabah but has been shown to merge with the TCU landwards (Levell, 1987; Cullen, 2010). The DRU and TCU are therefore shown here as a composite unconformity. (b) Schematic paleogeography of the NW Sabah basin during the deposition of the West Crocker Formation (~Late Eocene). Present-day outline of Borneo is shown for reference.



**Figure 3:** Field photos of some of the outcrops where trace fossils were found and described in this paper. Outcrop locations are shown in Figure 1. (A) Inanam 2. (B) Sepangar. (C) Inanam 3; white rectangles indicate places where abundant trace fossils were discovered. (D) Sulaman 2. (E) Inanam 4. White arrows in (A) to (D) show way-up (younging) direction, approximately to the east. In (E) the view is eastwards.



**Figure 4:** Sedimentary logs from the trace fossil localities described in this study (see Figure 1) showing the bedding style and facies patterns (yellow- sandstone, grey – mudstone). Some coarsening-upward and fining-upward parasequences are apparent in places, which may represent stacked channels (e.g., fining-up parasequences at Inanam 2 and Sepangar 1) or prograding fan lobes (e.g., coarsening-upward parasequences at Lokawi and Inanam 2). Labels refer to the respective Figure numbers in which the trace fossils are described and photographed.



**Figure 5:** Sedimentary features in turbidites of the West Crocker Formation. (A) medium-bedded turbidites in which specimens of *Spirorhaphe* were found (see Figure 15 later). Location: Sepangar 2. (B) Sharp basal surface of thick sandstone (Ta/Tb division), overlying another sand with thin mudstone parting. Note the faint parallel lamination and normal grading. The lowermost few cm are slightly lighter coloured, representing the basal “traction carpet” of the turbidity flow which sometimes exhibit reverse grading. (C) water-escape dish structures in massive turbidite sandstone (Bouma Ta division) at Sulaman 2 outcrop. (D) close-up of top of sandstone with recognizable Bouma divisions Ta/Tb – Tc – Td, overlain erosively by overlying sandstone. (E) well-developed ripple laminated sandstones (Bouma Tc division) at Inanam 3. (F) sole marks in turbidites at Inanam 2. (G) load and flame structures at base of turbidite bed, Lokawi.

on the bedding characteristics: flat bases and tops, lack of major erosional scours and generally high sand-shale ratios (estimated net-to-gross ratio > 70-80%, Madon *et al.*, 2010). The sandstones appear to have sheet-like geometry and, therefore, probably are laterally continuous, at least at the scale of the outcrop. The turbidite sequences show repetitive coarsening-upward packages of beds of about 15–25 m thick (Figure 4), which are indicative of progradational submarine fan lobes, probably in the middle to lower fan region. Fining-upward units, with very thick massive sandstone at the base, may be interpreted as channel-fill deposits in the upper fan or slope region, resulting from the basin-ward advance of the depositional lobes over the submarine fan complex. Trace fossils are often easily found in the thicker shale intervals, which could represent the inter lobe or overbank areas, or basin plain mudstones off fan aprons (Figure 6).

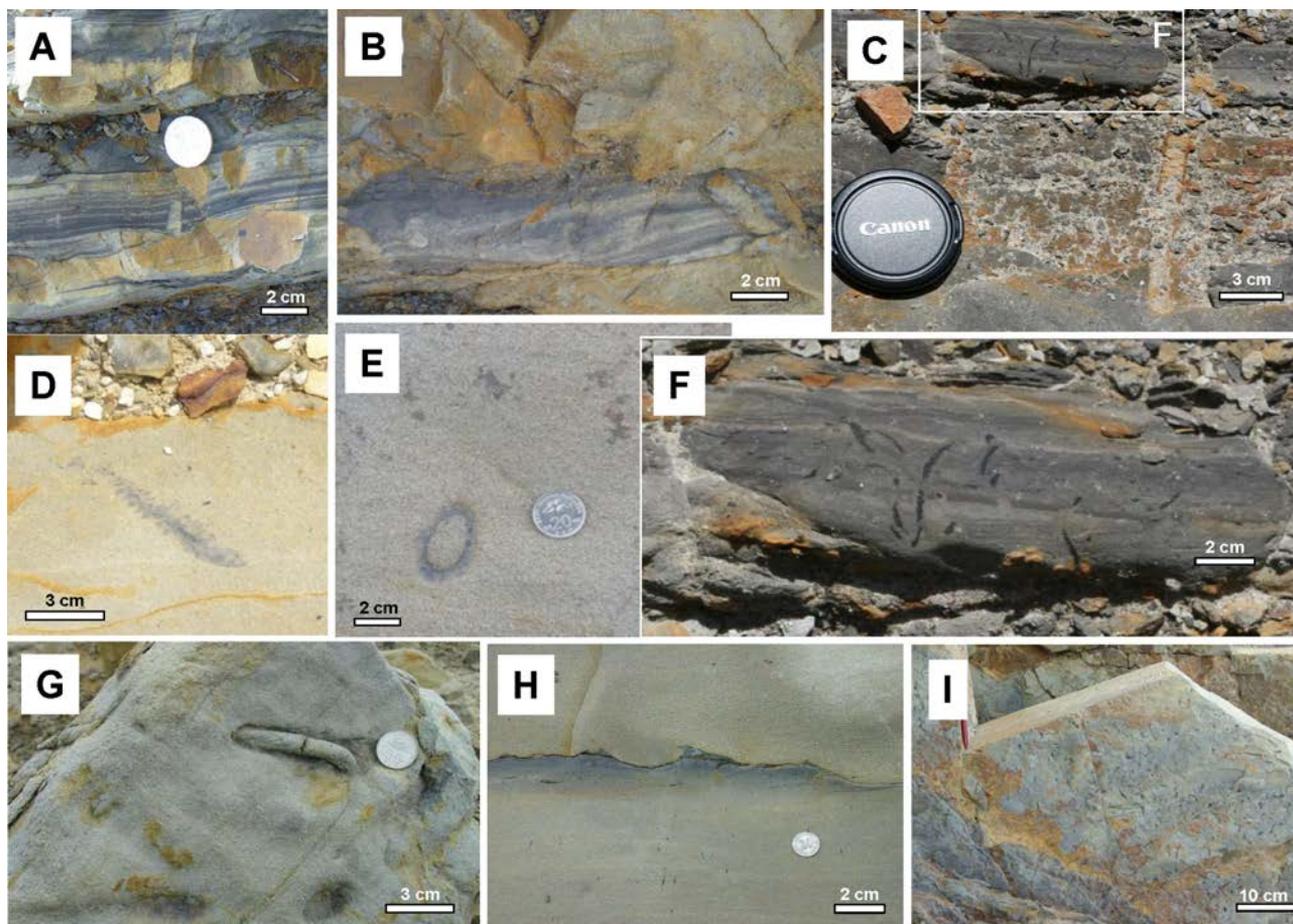
### DESCRIPTION OF THE TRACE FOSSILS

Trace fossils are most abundant in the thick shaly intervals within the turbiditic sequences. They are found mainly on the sole (underside) of thin sandstone beds (mainly Tc divisions) as hypichnial (meaning at the basal bed boundary) semi- or full reliefs. In a particular example, at Inanam 3 (Figure 3C), a thick shaly interval includes thin distal turbidite beds characterized by ripple cross-laminated

sandstone (Tc division) which contain abundant trace fossils. The trace fossils were photographed and described in the field but unfortunately due to logistics and storage constraints no samples were collected. Some of the outcrops described here may have disappeared due to rapid development around Kota Kinabalu.

Trace fossils can be classified as either pre- or post-turbidite, in respect of the timing of the event bed hosting the trace fossils. Similarly “post-depositional” traces are those that form after deposition of the hosting bed, whereas pre-depositional traces are those that form before deposition. Thus post-depositional traces may be found at the top of an event bed and often penetrate deep into it, and therefore tend to be subvertical. Pre-depositional or pre-turbidite trace fossils are commonly found at the sole of the overlying bed and tends to be horizontal.

Fuchs (1895) coined the term “graphoglyptids” for some forms of pre-depositional traces that exhibit delicate “artful” patterns, probably produced by invertebrate deposit feeders and farmers (Seilacher, 1977b). Many of the trace fossils found in the West Crocker Formation are pre-depositional structures preserved in hypichnial semi-relief, and can be assigned to graphoglyptids. In this study, the trace fossil forms are identified mostly at the ichnogenus level. Only when the morphology is clear the ichnospecies is identifiable.



**Figure 6:** Examples of post-depositional trace fossils. (A, B) – *Planolites* isp. (C, D, E, G) *Ophiomorpha* isp. (D, E) – *Ophiomorpha nodosa*. (F) – mudstone on top of burrowed turbidite sandstone outlined by white rectangle in (C), burrowed by *Chondrites*. (G) – *Ophiomorpha rudis*. (H-I) *Chondrites* at the top of turbidite bed (Tc-Td divisions). Location: A, B, D, E, H – Sulaman; C, F – Lokawi; G – Inanam 2; I – Sepangar 1.

### *Planolites* Nicholson, 1873

#### *Planolites* isp.

**Description:** Simple, solitary, unlined burrows commonly found in thinly-bedded ripple laminated turbiditic sandstone-mudstone beds (Bouma Tc division) (Figures 6A, 6B). The burrows are small (< 30 mm in length, <10 mm in diameter) and generally sub-vertical, cutting across the lamination and locally show a backfill structure. These are identified as endichnial, cylindrical sand-filled burrows in thin (distal) turbidite sandstone beds with parallel lamination, which are common in heterolithic sand-mud facies.

**Remarks:** The sand-fill burrows in mud-rich host sediment are typical of *Planolites* isp. which is a common post-depositional trace fossil in turbidites. They are undoubtedly post-depositional, as it cuts through bedding surfaces, and also appear to have been affected by compaction of the muddy sediments, producing the “wriggly” or “wrinkled” appearance. The burrows are relatively short and do not penetrate deep into the laminated sandstone-mudstone bed, probably due to lack of nutrients, as the organisms only preferred to feed on the muddy substrate.

*Planolites* is interpreted by most authors as a pascichnion (grazing trace) (e.g. Pemberton & Frey, 1982; Keighley & Pickerill, 1995).

### *Chondrites* Sternberg, 1833

#### *Chondrites* isp.

**Description:** These are tiny mm-scale, subhorizontal to subvertical, clay-filled cylindrical burrows in mudstones or very fine grained silty sandstone at the top of turbidite beds (Bouma Td division), wherein the burrows are easily identified by the colour contrast with the host sediment (Figure 6F). Depending on the way the surface of the outcrop is cut, they may appear as simple (Figure 6H) or branching 3-D structures with slightly incline burrows (<15°) (Figures 6F, 6I).

**Remarks:** These clay-filled burrows in muddy turbiditic deposit represent deposit-feeders after deposition of the host bed. The inclined tubes and branching pattern resemble *Chondrites* isp. In the literature, *Chondrites* is normally characterized by clay-filled, plant-like branching burrows having the same lithology as the host sediment (Seilacher,

1977a). They appear to be probing and/or feeding bifurcating burrows of an animal starting at the top and spreading out into many branches downwards into the muddy substrate to form dendritic or radial patterns. *Chondrites* burrows seem to be normally associated with oxygenated mudstones (Uchman & Wetzel, 2012), as evident from the West Crocker, they occur in dark laminated mudstones or very fine silty sandstone at the top of turbidite beds (Figures 6F, H, I). Uchman *et al.* (2012) reviewed the taxonomy of *Chondrites* species and found discrete fields of burrow width/burrow system width of different ichnospecies. Based on the burrow widths (<1-2mm) and inferred width of burrow system (<30cm), the West Crocker specimens are most likely *C. intricatus* or *C. targionii*.

### ***Ophiomorpha* Lundgren, 1891**

**Description:** Subhorizontal to subvertical, simple or branched, mostly straight, locally curved cylindrical tubes in sandstone, 10–12 mm in diameter, filled with the same material as host sediment, with or without clay linings. Some clay linings have distinctive granulate or nodular irregularities (Figure 6C, 6G). The simple burrows occur in the thicker (>30 cm) sandstone beds but these are not common. In another instance, the clay lining of the burrow has been totally weathered out, leaving a cast of the inner sand-filled tube (Figure 6G).

**Remarks:** Their occurrence in the middle of sandstone bed suggests that these burrows are post-depositional tubes built by sand-dwellers. The clay lining with irregular outer surface appear to be the characteristic granulate or nodular pattern of *Ophiomorpha nodosa* (identified as such in Figures 6D, 6E), which is a common trace fossil in shallow marine sandstones deposited in shoreface to lower foreshore zone. The nodular clay linings could be fecal pellets used by the organism to build the wall of the burrows. *Ophiomorpha rudis* in deep sea deposits has similar features as *O. nodosa* (Uchman, 2009). *Ophiomorpha* is commonly abundant in shallow marine (coastal and shelf) sediments, belonging to the *Skolithos* ichnofacies, but are not uncommon in deep-marine turbidites (e.g. Uchman & Wetzel, 2012). They are generally interpreted to be the dwelling burrows of the decapod crustacean (shrimp) *Callianassa* (now *Callichirus*) *major* (Pryor, 1975; Bromley, 1990).

Besides *O. nodosa*, several ichnospecies of *Ophiomorpha* are recognized in the outcrops studied. Their morphological differences are described in Uchman *et al.* (2004). *Ophiomorpha nodosa* is easily recognized by subvertical burrow and granulate wall linings (Figures 6D, 6E). The commonly smooth-walled ichnospecies, *O. annulata* and *O. rudis*, were found in several beds at Sulaman 2. These are typically longer than *O. nodosa*, horizontal, and occur as a network of branching tunnels (Figures 7A, 7C, 7D). *Ophiomorpha annulata* occurs both as smooth and granulate forms, and their burrows penetrate from top deeply into sand and spread laterally at the base of the bed. *Ophiomorpha*

*rudis* has similar morphology to *O. annulata* but its deep penetrating tunnels may cross several turbidite beds (Uchman, 2009; Uchman *et al.*, 2004). In terms of burrow diameter, although not diagnostic of the species and may be region-specific, *O. annulata* tends to be smallest (2–7mm) than the others (>10 mm). *O. nodosa*, however, tends to be much bigger than the other varieties (35–45 mm).

*Ophiomorpha* was generally believed to be facies-crossing ichnofossil in that it is found both in shallow and deep marine facies and therefore are not environmentally diagnostic (e.g., Monaco *et al.*, 2007). Subsequent revisions of the ichnotaxon (Uchman, 2009) however found that ichnospecies of *Ophiomorpha* could be used to discriminate between different parts of deep-sea turbidite systems. While *O. nodosa* is typical of shoreface to lower foreshore environment, *O. rudis* is typical of sandy parts of deep-sea turbiditic systems (Uchman & Wetzel, 2012).

### ***Thalassinoides* Ehrenberg, 1944**

#### ***Thalassinoides* isp.**

**Description:** Hypichnial, long, smooth, cylindrical and mainly horizontal burrows. They show Y-shape branches, or rarely trilete form, but without a distinct regular branching pattern. Individual burrows normally are less than 10 mm in diameter, but some are larger (a few cm), e.g. at Sulaman 2 (Figure 7B). They also tend to occur in patches, forming massive networks of burrows, as observed at Inanam 4 (Figures 7E, 7F). Figures 9A to 9C shows more examples of *Thalassinoides* at Sepangar 2.

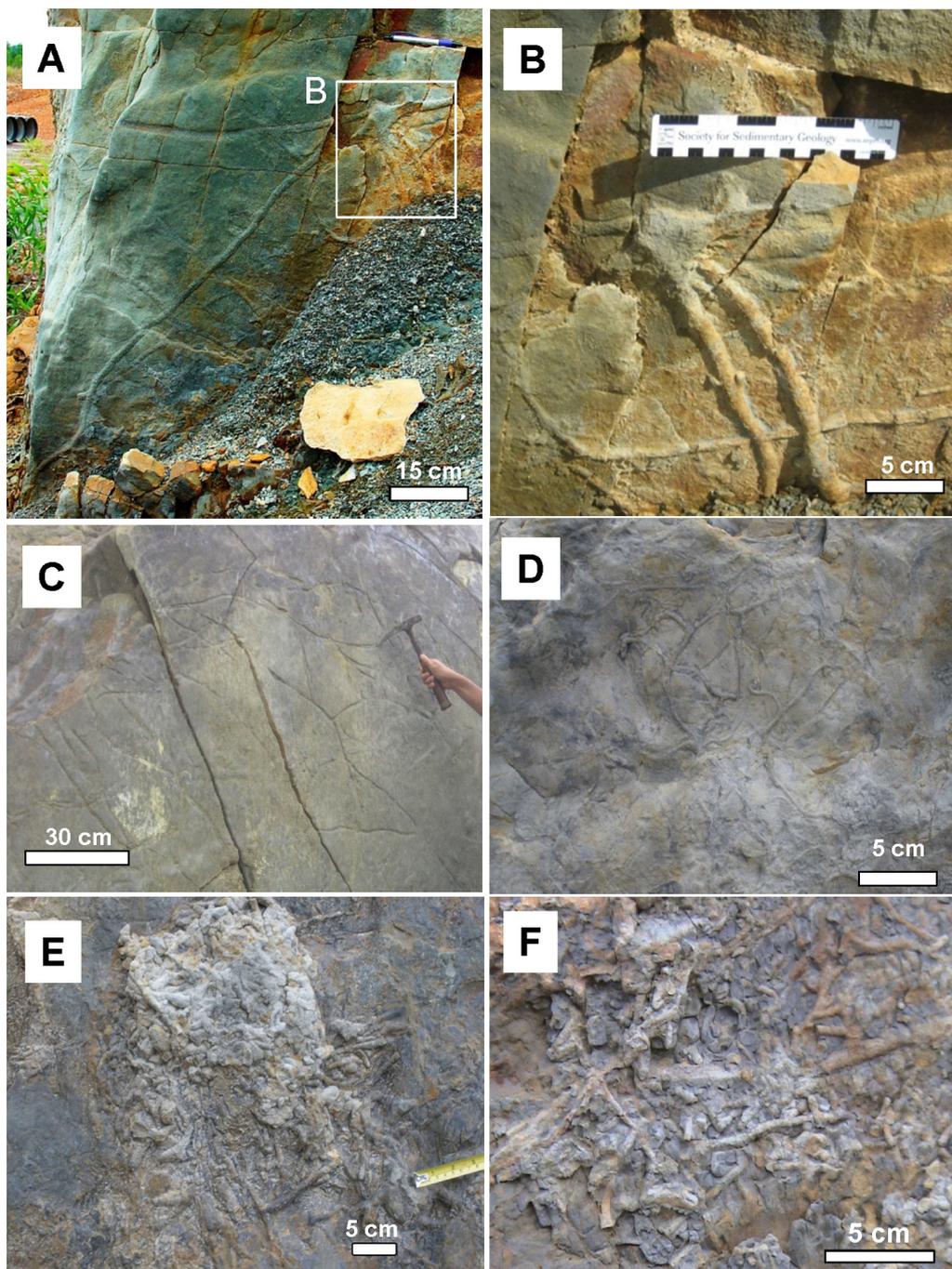
**Remarks:** A distinguishing feature of *Thalassinoides*, as opposed to *Ophiomorpha annulata*, is that the tubes tend widen slightly or swell to three times its size at the branching points (see Figure 7B, also Uchman *et al.*, 2004). *Thalassinoides* is a facies-crossing trace fossil commonly found in shallow-marine environments, although not uncommon in deep-sea settings. It is thought to be produced mainly by crustaceans (e.g., Frey *et al.*, 1984; Ekdale, 1992; Monaco *et al.*, 2007). According to Föllmi & Grimm (1990), crustaceans producing *Thalassinoides* may survive in turbidity currents and produce burrows under anoxic conditions.

### ***Palaeophycus* Hall, 1847**

#### ***Palaeophycus* isp.**

**Description:** *Palaeophycus* burrows are mainly simple, horizontal or slightly oblique cylindrical tubes, commonly straight, gently curved or slightly twisted. The tubes are of various lengths (>5 cm) and diameters (up to few cm) (Figures 8A–E). No burrow lining is apparent from the hypichnial traces, but the smooth exteriors of the specimens (Figure 8) suggest the presence of linings, which is a characteristic feature of *Palaeophycus* (Pemberton & Frey, 1982). The burrow fill is of the same material as the host rock. Burrows may show overcrossing.

**Remarks:** These burrows are found in abundance in the West Crocker Formation, particularly at Inanam 3, where



**Figure 7:** Straight, simple and branching burrows. A, B, C – *Ophiomorpha annulata*, Location: Sulaman 2. (D) Underside of turbidite bed with network of branching horizontal burrows displaying the typical ‘*Palaeophycus* ichnofabric’, – mainly horizontal burrows (viewed from underside of sandstone bed) including *Thalassinoides* (branching burrows), and *Palaeophycus* (straight burrows). Location: Inanam 4. (E) Dense colony of *Thalassinoides* and *Palaeophycus*. Location: Inanam 4. (F) *Ophiomorpha rudis*. Location: Inanam.

they occur in the scree that came off the steeply dipping beds shown in Figure 3C. The burrows occur on the sole of thin turbidite beds with ripple cross-lamination (Bouma Tc division) as full or semi-relief tubes beneath sandstone beds (hypichnial). The interpretation is that these are probably produced by suspension or deposit feeders that thrive during the quiet intervals between turbidity flow events. According

to Pemberton & Frey (1982), *Palaeophycus* can also be produced by carnivores.

As in this study, *Palaeophycus* are commonly found in thin sandstone beds (Tb, Tc divisions), are post-depositional traces formed during quiescent periods when the seabed is probably soft-ground in order for the organisms to tunnel through to produce the delicate burrows (Uchman & Wetzel,

2012). *Palaeophycus* is a facies-crossing trace fossil thought to be produced by polychaete worms (Pemberton & Frey, 1982).

***Helminthopsis* Wetzel & Bromley, 1996**

***Helminthopsis* isp.**

**Description:** This particular example of pre-depositional traces, found at Inanam 3, comprises two elements occurring on the sole of thin turbidite sands (Figure 8F): (a) tiny convex-downward, equidimensional “blobs” measuring not more than 5 mm in diameter. (b) curved or meandering mm-thick trails surrounding the abovementioned “blobs”.

**Remarks:** The blobs appear to be the hypichnial casts of objects that laid on a muddy substrate. A possible trace maker could be gastropod or bivalve; these features being the moulds of their resting place. The curvilinear trails do not seem to have any systematic pattern or preferential alignment and could have been generated by the same organism that produced the resting place. They could be trails of gastropods, as they closely resemble gastropod (snail) trails commonly observed on modern tidal flats. These are feeding trails left by the animal searching for food on the

muddy substrate. The hollow of the trail is filled up with the sand of the incoming turbidity flow and then preserved as hypichnial semi-reliefs.

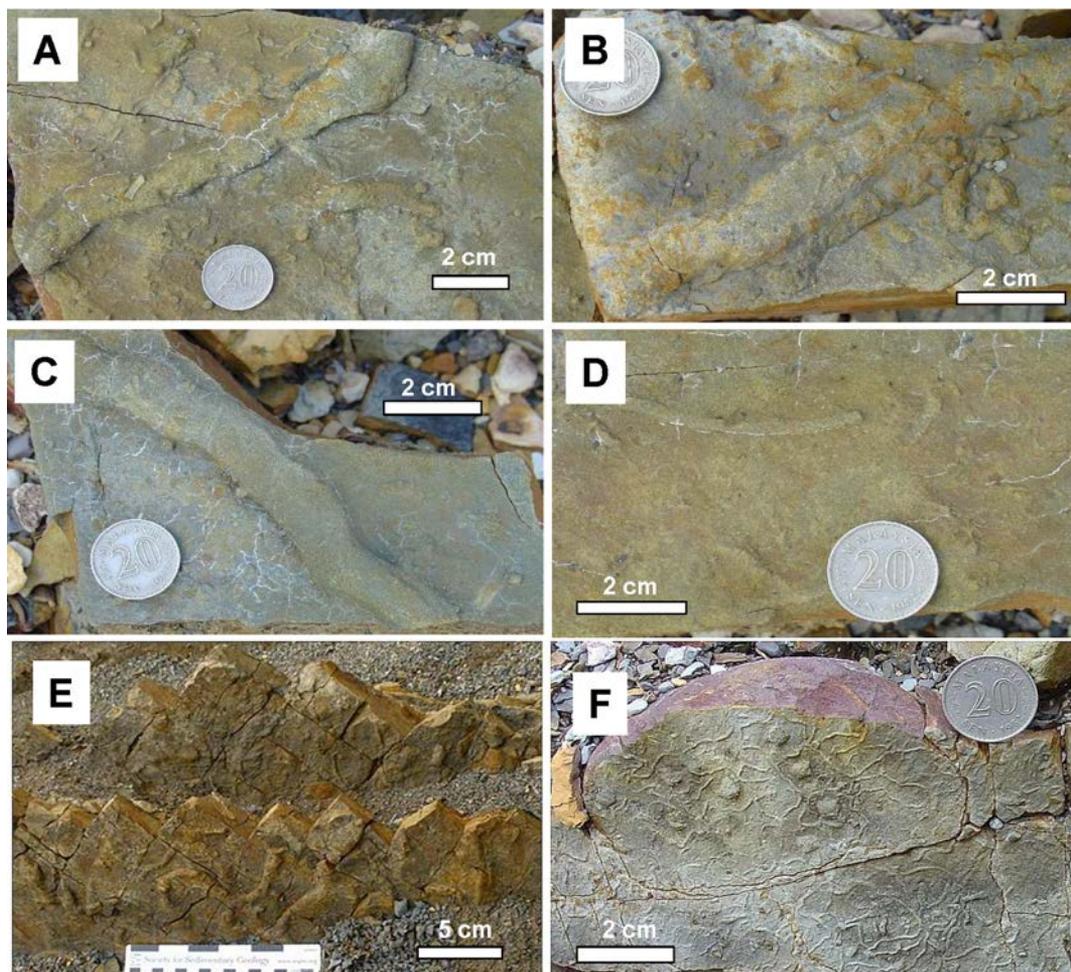
In the ichnology literature, the circular “blobs” resemble the resting trace (domichnia or cubichnia), *Bergaueria* Prantl, 1945, described in Uchman (1998). Uchman *et al.* (2004, his figure 12C) described similar features as “knobs” and “cylinders” which he identified as *Gordia* isp. and *Ophiomorpha rudis*, respectively.

The meandering but random back and forth trails closely resemble the descriptions of the now obsolete ichnogenus *Helminthoida* (Uchman *et al.*, 2004) or *Helminthorhapha* (Fan *et al.*, 2017). They also resemble *Gordia*, believed to be the grazing trail (fodinichnia) of a worm-like creature (e.g. Wang *et al.*, 2009; Zhao *et al.*, 2018), but they tend not to loop or cross over each other (Getty *et al.*, 2017). Moreover, *Gordia* shows loops which are missing in *Helminthopsis*.

***Protovirgularia* McCoy 1850**

***Protovirgularia***

**Description:** These traces (Figures 9D and 9E) are identified as thick (2-3 cm diameter), straight cylindrical

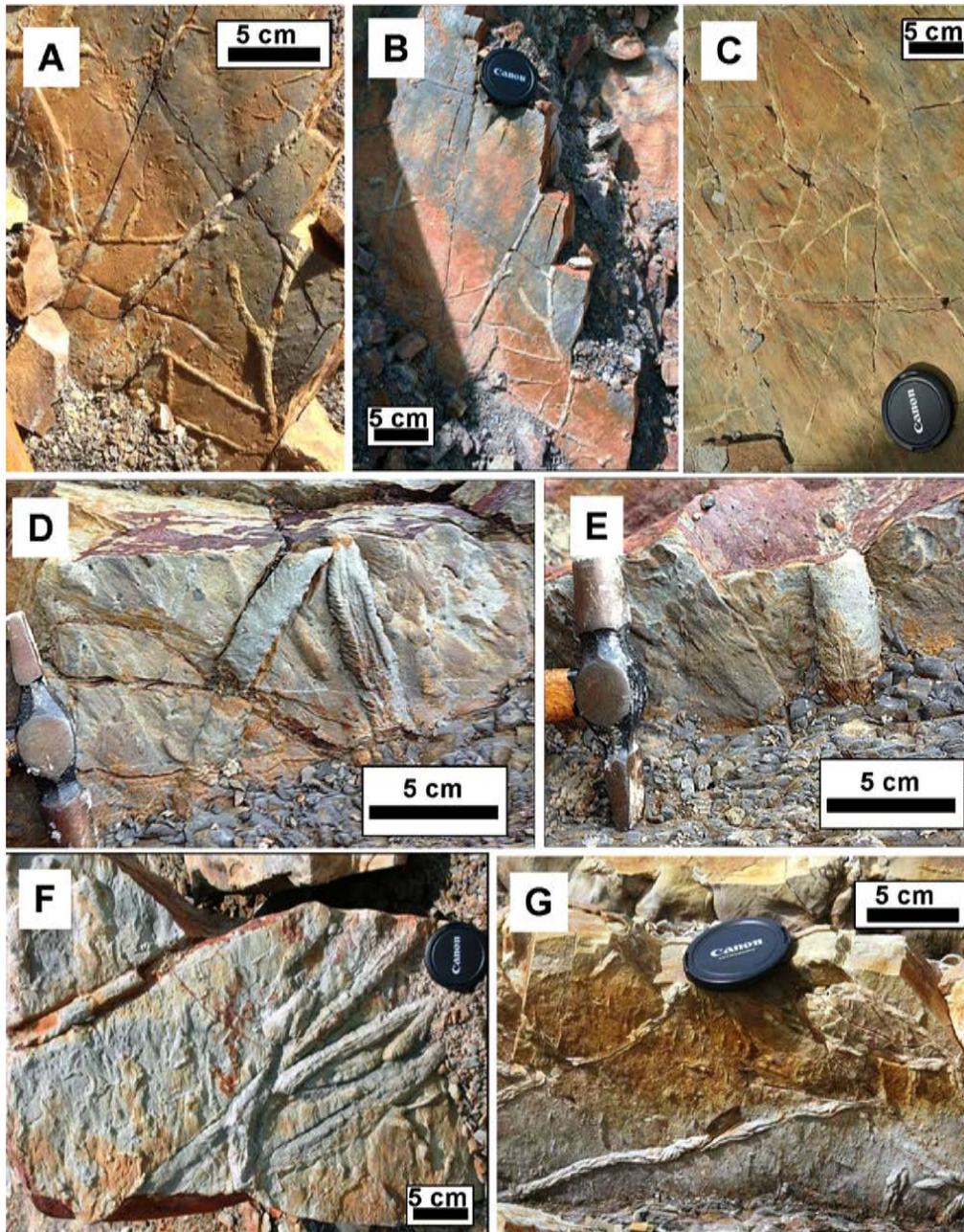


**Figure 8:** (A to E) Various forms of *Palaeophycus* isp. found at Inanam 3 locality. (F) *Helminthopsis*.

burrows that are horizontal to bedding, but with distinctive ornamentations (furrows, striae or ribs) which are transverse as well as along the length of the burrows. The individual burrow appears to have bilateral symmetry, with a large median furrow along their downward side. They tend to occur in groups of several tubes and are preserved as full or semi-relief hypichnial traces on the sole of sandstone beds. From the limited exposure and preserved outcrops specimens, it is uncertain whether they are branched or solitary burrows. Similar forms that have been described from Japanese flysch sequences (Kuwazuru & Nakagawa,

2018) suggest that they tend to be long and sometimes branching burrows.

**Remarks:** *Protovirgularia* is not an uncommon trace fossil in flysch sequences (e.g. Uchman, 1998, Buatois & Mángano, 2011). It is widely described as a typical product of bivalves moving on muddy substrate, which normally produces the transverse, often “chevronate”, ribbed pattern due to the “push-and-pull” locomotion mechanism or, in the case of soft-bodied organisms, peristalsis of the animal (Seilacher & Seilacher, 1994; Buatois & Mángano, 2011; Buatois *et al.*, 2017). The traces shown in Figures 9D



**Figure 9:** A-C – *Thalassinoides*; D, E – *Protovirgularia*; F – *Halopoa imbricata*; G – *Halopoa* isp., Location: A – Sepangar 1, B-G – Sepangar 2.

and 9E closely resemble the specimen of *Protovirgularia* described by Buatois & Mángano (2011, their figure 3A) from Paleogene flysch of the Muroto-Hanto Group, Hane Point, southwestern Japan. Similar forms of *Protovirgularia* isp. were also described from the Shimanto Belt, Japan (Nara & Ikari, 2011; Kuwazuru & Nakagawa, 2018) and in some Miocene turbidites in the Iberian Peninsula, Spain (Gibert & Doménech, 2008).

#### ***Halopoa* Torell 1870**

##### ***Halopoa imbricata* Torell 1870**

**Description:** These are horizontal burrows at the sole of turbidites, occurring as long and slender cylindrical tubes with faint longitudinal furrows or striations as well as transverse ribs. The specimen in Figure 9F suggests that these burrows tend to occur in clusters and cross-over each other. Each individual tube is about 1-2 cm in diameter but may exceed 20 cm in length.

**Remarks:** The specimen in Figure 9F resembles that described in Uchman (1998, his figure 9) and by Tchoumatchenco & Uchman (2001, their figure 4C). They are interpreted to be produced by burrowing organisms with appendages, often attributed to priapulid worms (Książkiewicz, 1977) which created the furrows or striations along the burrows. The striations may also be the effect of collapse of the burrows (Uchman, 1998). They have been compared to *Gyrochorte* although, unlike *Gyrochorte*, these are hypichnial traces, and also show cross-overs and overlaps when in clusters (Figure 9F). Similar traces of *Halopoa imbricata* were described from Ainsa-Jaca basin in Spain (Heard & Pickering, 2008, their figure 18H). Superficially, the *Halopoa* specimen found here resembles the South Asian (Indian) tree fruit of *Moringa oleifera*.

#### ***Halopoa* isp.**

**Description:** This trace fossil (Figure 9G) is identified as a variety of *Halopoa*, which has features distinct from *H. imbricata* described above. These are also horizontal to subhorizontal traces, occurring as cylindrical tubes preserved as hypochnial semi- or full-relief on the sole of thin turbidite beds (Bouma Tc). They are long, straight, and bilobate – with a characteristic median furrow which is not always centred along the axis of the trail but appears to be curved or winding (Figure 9G).

**Remarks:** The specimen found superficially resembles some specimens of *Halopoa* described by Monaco (2014, Plate 2A) as having longitudinal “wrinkles and cracks”. It also closely resembles the drawing of *Fucusopsis* from Paleocene flysch of Poland in Seilacher (2007). Incidentally, *Fucusopsis* is included in *Halopoa* (Uchman, 1998). In addition, Buatois & Mángano (2011, their figure 22A) described similar forms from Eocene flysch in Switzerland.

#### ***Spirocsmorhaphé* Seilacher 1989**

##### ***Spirocsmorhaphé labyrinthica* (Heer, 1877)**

**Description:** Only one instance of this species was found, i.e. at Inanam 3 (Figure 10A). These are tiny burrows preserved as hypichnial semi-relief (0.5-1.5 mm wide) on the sole of thin sandstone beds. They appear to have a regular pattern and shape, but due to poor preservation the complete burrow pattern could not be discerned. The meandering burrows have a distinctive inverted “U” or omega (W) shaped meanders or loops (arrow, Figure 10A).

**Remarks:** Although the specimen is not well preserved due to severe weathering, the presence of small-amplitude meanders suggests that they are second-order meanders in an inferred larger 1<sup>st</sup> order loop (as opposed to only first-order meander in *Cosmorhaphé*). Also a diagnostic feature is the upper-case Omega (W) shape of the second-order meanders (Rodríguez-Tovar *et al.*, 2010). The traces are comparable with *Heminthopsis labyrinthica* Heer (1877, p. 116, pl. 47, fig. 3-5).

#### ***Cosmorhaphé* Fuchs 1895**

##### ***Cosmorhaphé sinuosa* Azpeitia Moros, 1933**

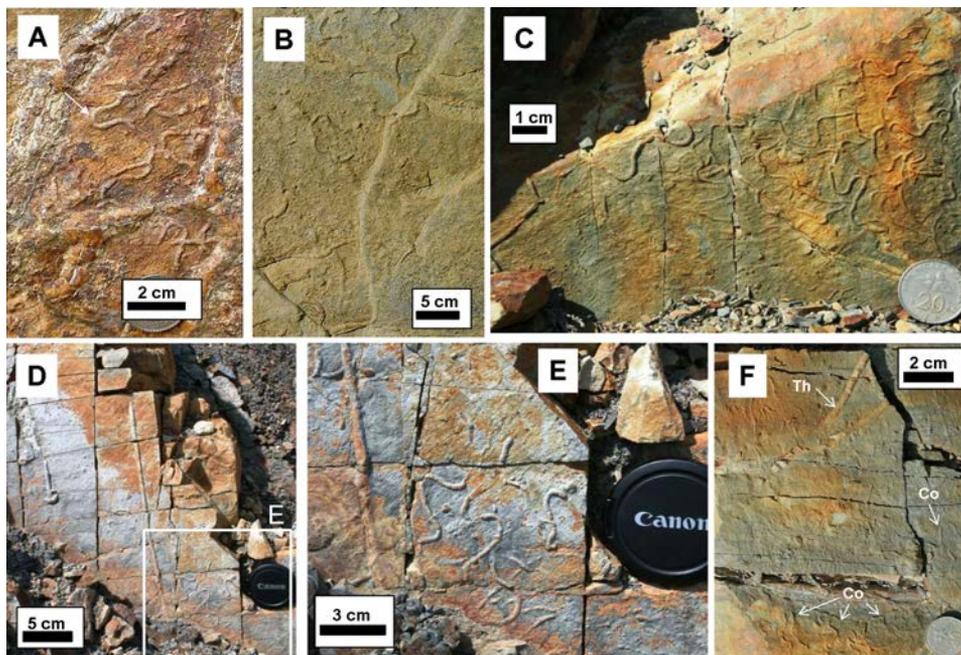
**Description:** These small (~2 mm) hypichnial semi-relief cylindrical burrows are found in abundance on the sole of turbidites at the Sepangar 2 locality (Figure 1). Several forms of these ichnofossil are shown in Figures 10B to 10F. The small meanders seem to be 2<sup>nd</sup> order, but the inferred 1<sup>st</sup> order meanders are not visible due to the poor exposure. The meanders are characterized by random twists and turns, sometimes with sharp angular turns and sometimes crossing over each other, resulting in a complex pattern

**Remarks:** The random meandering patterns suggests that the trace makers were randomly foraging through the substrate for food. *Cosmorhaphé* has also been interpreted as traps for microbes (Seilacher, 1977b). *Cosmorhaphé sinuosa* is a common graphoglyptid in flysch sequences, and is distinguished from *Helminthorhaphé* by having 1<sup>st</sup> and 2<sup>nd</sup> order regular meanders (Uchman & Wetzel, 2012). Complex pattern may result from coalescing burrow networks going in and out of the bedding plane. Unlike *Spirophycus*, some of which could be washed-out casts of backfill burrows, *Cosmorhaphé* is interpreted as open tunnels that are reinforced by a mucus lining (Seilacher, 2007).

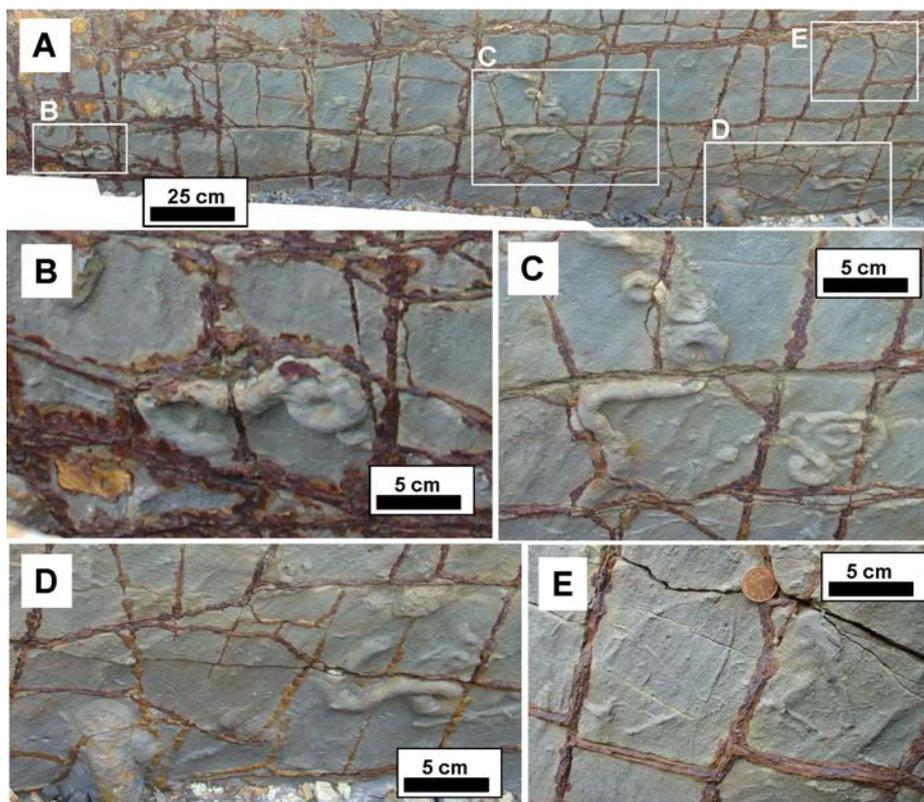
#### ***Spirophycus* Häntschel 1962**

##### ***Spirophycus bicornis* (Heer, 1877)**

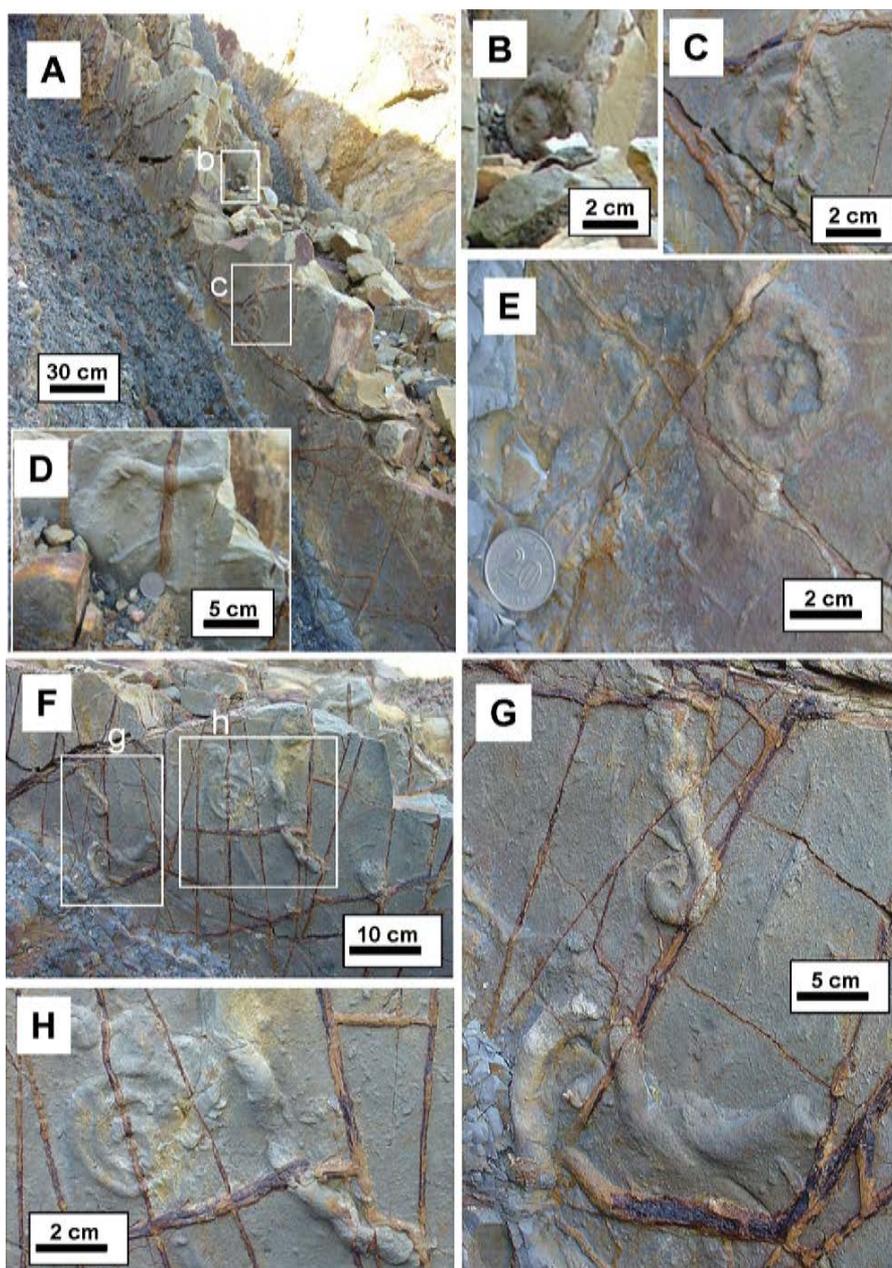
**Description:** *Spirophycus* burrows appear as thick (~1 cm) semi-cylindrical ridges preserved in a spiral or coiled structures 4 to 6 cm in diameter on the sole of thin-bedded turbidites. The wide variety of shape and form of these burrows are shown in Figures 11, 12 and 13, photographed from two main outcrops, Inanam 3 and Inanam 4, which are not far apart (Figure 1 for location). They are hypichnial and convex downward in semi-relief. The individual ridges



**Figure 10:** (A) *Spirocormorhapse labyrinthica* (Heer, 1877) (Inanam 3), with omega-shaped meander (arrow) (B) *Cosmorhapse sinuosa* (C) *Cosmorhapse sinuosa* (Azpeitia Moros), (D) *Ophiomorpha annulata* (long straight burrow) with *Cosmorhapse sinuosa* (within white rectangle), (E) close-up of white rectangle in D, showing *Cosmorhapse sinuosa*, (F) *Thalassinoides* (Th) and *Cosmorhapse sinuosa* (Co) (bottom of picture). Location: A – Inanam 3, B – Sepangar, C-F – Sepangar 2.



**Figure 11:** Various forms of *Spirophycus bicornis* found on a single sole of turbidite sandstone bed at Inanam 3. (A) photo of the entire bed surface, with rectangles represent close-up view of different forms of trace fossils. (B) doubly coiled burrow, joined by a straight tube, (C) spiriform and curved burrow, suggestive of different states of “coiling”. (D) sole of turbidite bed with burrows of *Spirophycus* and unidentified hypichnial cast (probably a resting trace). (E) same surface with linear traces, possible of *Palaeophycus*.

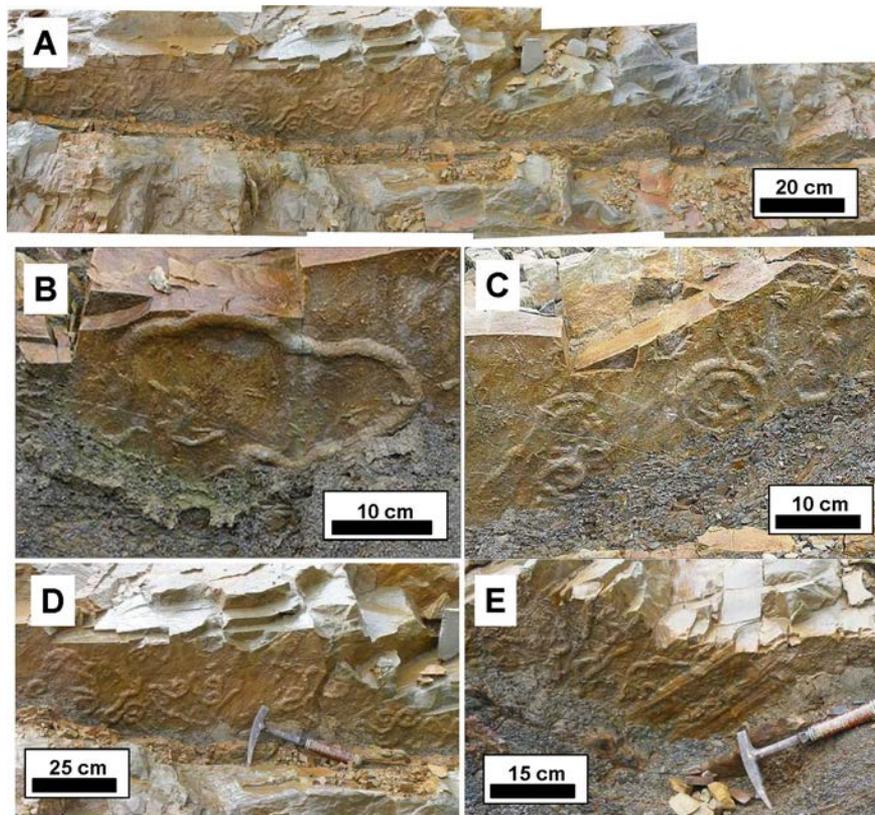


**Figure 12:** *Spirophycus bicornis* at Inanam 3. (A) Bedding surface (sole) with many *Spirophycus*. White rectangles represent close-up in (B) and (C) showing two spiriform (fully coiled) tubes. (D) “uncoiled” tubes. (E) another large spiriform tube. (F) sole of turbidite with several traces of *Spirophycus*. White rectangles represent close-up in G and H with burrows in different states of “coiling”.

or tubes may be smooth, straight or are slightly twisted like donuts or pretzels; some coils are made of one, two, or maximum three, whorls. Some tubes extend laterally from the whorl, giving the appearance of “uncoiled” *Spirophycus* (Figures 11B, 12G). These “uncoiled” traces could well be the result of current action on the soft tubes rolling on the seafloor.

**Remarks:** The species name *Spirophycus bicornis* (according to Seilacher, 2007) specifically refers to the tendency of two spirals at opposite ends meeting one another via a “bridge”, probably representing the meeting

point of two individual trace makers (see Figure 10B). *Spirophycus* is considered as a “non-graphoglyptid” trace fossil (Uchman & Wetzel, 2012). On the soles of turbidite beds, these burrows appear like hieroglyphs, especially at Inanam 4, may have been influenced by current direction, as indicated by the associated sole marks (Figure 13F). The trace fossils observed in this study resemble closely those previously described from other flysch sequences, e.g. *Spirophycus involutissimus* from Tarcau Sandstone, Romania (Buatois & Mángano, 2011, their figure 9.7i) and *Spirophycus bicornis* from Eocene fan deposits in Switzerland (figure



**Figure 13:** Outcrop at Inanam 4, showing underside of thin sandstone bed with hypichnial semi-relief casts of horizontal traces, including spiroform (coiled) *Spirophycus bicornis*. Note that the heiroglyphs appear to have preferred orientation, parallel to the sole marks (groove casts) in (E), indicating the influence of currents on the behavior of the trace maker.

4F of Wetzel & Uchman, 1997) and from the Pagliaro Formation (Paleocene) in Italy (Uchman, 2007a, plate 4 figure 7), and *Spirophycus bicornis* from Eocene flysch of northern Spain (Uchman & Wetzel, 2012, their figure 1G).

*Spirophycus* appears to be spatially and temporally restricted to certain intervals, which may reflect the prevailing bottom conditions conducive for the producing organisms. When they are present, however, they occur in abundance. Some authors (e.g. Wetzel & Uchman, 1997) have suggested that *Spirophycus bicornis* may represent washed-out or cast strings of *Nereites circinalis*.

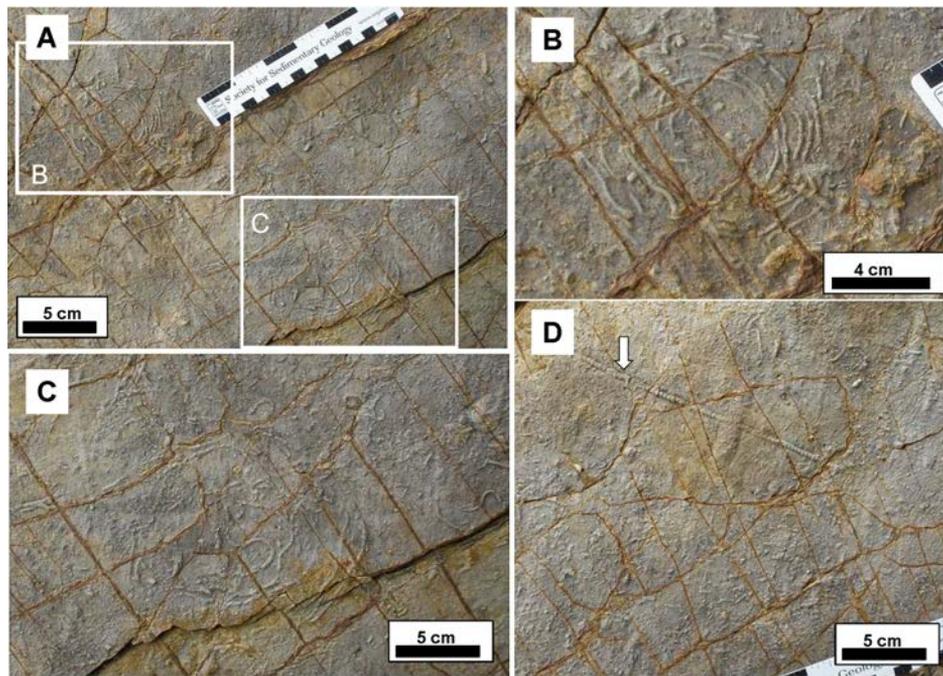
#### ***Spirorhapse* Fuchs, 1895**

##### ***Spirorhapse involuta* de Stefani, 1895**

**Description:** These are thin cylindrical tubes (<0.5 cm) arranged in a tight horizontal spiral or circular patterns. They occur as positive relief or semi-relief on the sole of thin turbidite sandstone beds. Several well-preserved specimens were found at Sepangar 1 and Sepangar 2 localities (Figure 1), and are shown in Figures 14, 15F, 15G, and 15H. Generally, the tubes are spaced close to each other and may be continuous or fragmentary but rarely or never cross each other. Each completely preserved circular pattern may be 15-20 cm in diameter and appears to have been produced by a single organism due to the continuity of the tubes. A

well preserved spiriform specimen could be made up of up to 13 whorls (Figure 15F). Where they are discontinuous, it was probably due to the partial removal or destruction by the incoming turbidity flow event. In the literature (e.g. Wetzel & Uchman, 1997) it is described that the spiral trail coils inwards, loops back, and coils outwards alongside the inward-coiling trail, although this is not easy to establish when the tubes are discontinuous. Apparent discontinuity of the tubes could also be due to the trace maker moving in and out of the bedding plane.

**Remarks:** *Spirorhapse* is a typical graphoglyptid agrichnion, the grazing or farming trails of deposit-feeding invertebrates. The traces are preserved in positive hyporelief on the sole of thin turbidite sandstones. *Spirorhapse* is differentiated from *Spirophycus* by its much thinner (smaller diameter) tubes, (compare Figures 13 and 14) and the more “delicate” and regular construction of spiriform patterns in the former, as well as the presence of a back-loop at the centre of the coil in *Spirorhapse* when well-preserved. The sometimes close resemblance resulted in *Spirophycus* being misidentified as “*Spirorhapse*” by Nizam *et al.* (2008, his figure 2). *Spirorhapse* has been compared to the strikingly similar spiral traces of the modern acorn worms in the deep sea (e.g., Holland *et al.*, 2012; Priede *et al.*, 2012).



**Figure 14:** Sole of turbidites at Sepangar 2, showing the delicate spiral structures of the trace fossil *Spirorhappe involuta*. (A) surface of turbidite sole with two specimens of *Spirorhappe*, marked with white rectangles and blown up in (B) and (C). (d) linear trace with segmented structures or ribbed surface (probably *Protovirgularia* isp.) occurring along with numerous unidentified traces on a fairly bioturbated base of turbidite.

#### ***Glockerichnus* Pickerill, 1982**

##### ***Glockerichnus* isp**

**Description:** These intricate star-like, radial trace fossil (Figure 15A) appears to be a branching network of small tubes or tunnels, radiating outwards from a central area, in a fan-like fashion, thus making a large (20 cm in diameter) stellate (star-like) network on the sole of thin turbidite beds. The tunnels or “strings” has almost uniform diameter, and the fill material is the same as that of the host sediment (see Uchman, 1998). Using the same criteria above, the specimen of Nizam *et al.* (2008, his figure 1), found at the same locality (Sepangar), should be identified as *Glockerichnus* instead of *Chondrites*.

**Remarks:** Uchman (1998) described a number of *Glockerichnus* subspecies, which show similar characteristics as the specimens in the West Crocker Formation, although the specimens he showed are more prominent hypichnial impressions, compared to the more delicate form found at Sepangar. *Glockerichnus* is a well-known ichnofossil in flysch deposits from the Ordovician to the Miocene (Uchman, 1998). Modern analogues were described from the Ontong Java Plateau (Ekdale & Berger, 1978).

##### ***Paleodictyon* Meneghini 1850**

**Description:** This most distinctive and easily recognizable trace fossil is made up of a hexagonal meshes bordered by semi-cylindrical ridges (between 1 and 2 mm thick) forming hypichnial imprints on the soles of turbidite beds (Figures 15B, C, D, 16G). In any particular specimen,

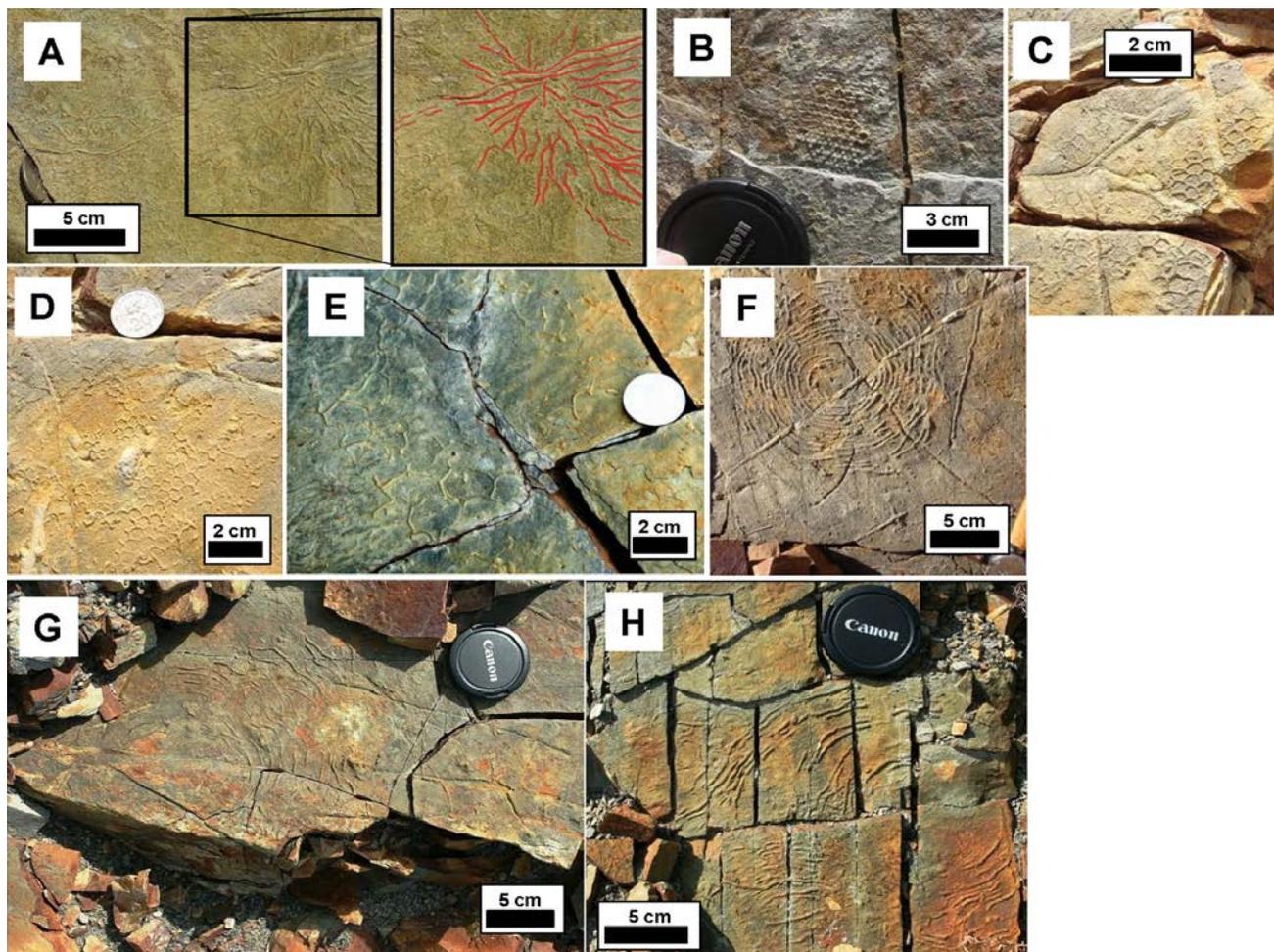
the hexagonal shapes are uniform in size, which may differ from sample to sample (~1 mm to ~5 cm). Based on the shape and size of the hexagonal mesh, several ichnospecies can be identified from the outcrops studied (Figures 15B, C, D, 16G): (a) *Paleodictyon minimum* (b) *Paleodictyon strozzii* Meneghini (c) *Paleodictyon majus* Savi and Meneghini (with large hexagonal net of up to 1 cm diameter).

**Remarks:** The trace maker of *Paleodictyon* is yet to be found, but the supposed modern form, *P. nodosum*, has been observed in deep-sea diving expeditions in the Mid-Atlantic Ridge area in water depths of 3430–3575 m near 26°N, 45°W (Rona *et al.*, 2009) and in the Clarion-Clipperton Fracture Zone in the eastern Pacific Ocean (Durden *et al.*, 2017). Although the resemblance to the fossil *Paleodictyon* is striking, the identity of the animal responsible for the burrows remains unknown. There is still a debate as to whether the hexagonal features are actually burrows or the body parts, vacant residences or the remains of the trace-making animal itself.

##### ***Megagraption* Książkiewicz, 1968**

##### ***Megagraption irregulare* Książkiewicz 1968**

**Description:** These are small cylindrical tubes 1-2 mm diameter in irregular mesh or network, closely resembling the hexagonal pattern of *Paleodictyon* but the pseudo-hexagonal shapes, <20 mm in diameter, are irregular, broken and distorted as shown in this example from Sepangar 2 (e.g., *Megagraption irregulare*, Figure 15E). Furthermore, the burrows are not always straight but curved or incomplete,



**Figure 15:** Various traces found at Sepangar 1 and 2, belonging to the *Nereites* ichnofacies. (A) *Glockerichmus*. A zoom-in view of rectangle to the right shows the trace pattern more clearly in red. (B) *Paleodictyon strozzii* Meneghini (semi relief) or *P. nodosum* (*Ramodictyon*) (C) *Ophiomorpha annulata* and *Paleodictyon*, (D) *Paleodictyon majus* Savi and Meneghini (E) *Megagraption*, (F)-(H). several well-preserved specimens of *Spirorhapse involuta* (de Stefani). (B) and (C) demonstrate the juxtaposition of pre-depositional (*Paleodictyon*) and post-depositional (*Ophiomorpha*) trace fossils at the sole of turbidite beds.

giving the appearance of an “incomplete” or “broken” *Paleodictyon*. The trace is hypichnial in semi-relief.

**Remarks:** *Megagraption* is also common at Sulaman 2 locality, found on the underside of a massive turbidite sandstone bed, and is commonly associated with other trace fossils within a single turbidite bed due to tiering (Figures 16A-C).

#### ***Nereites* Macleay 1839**

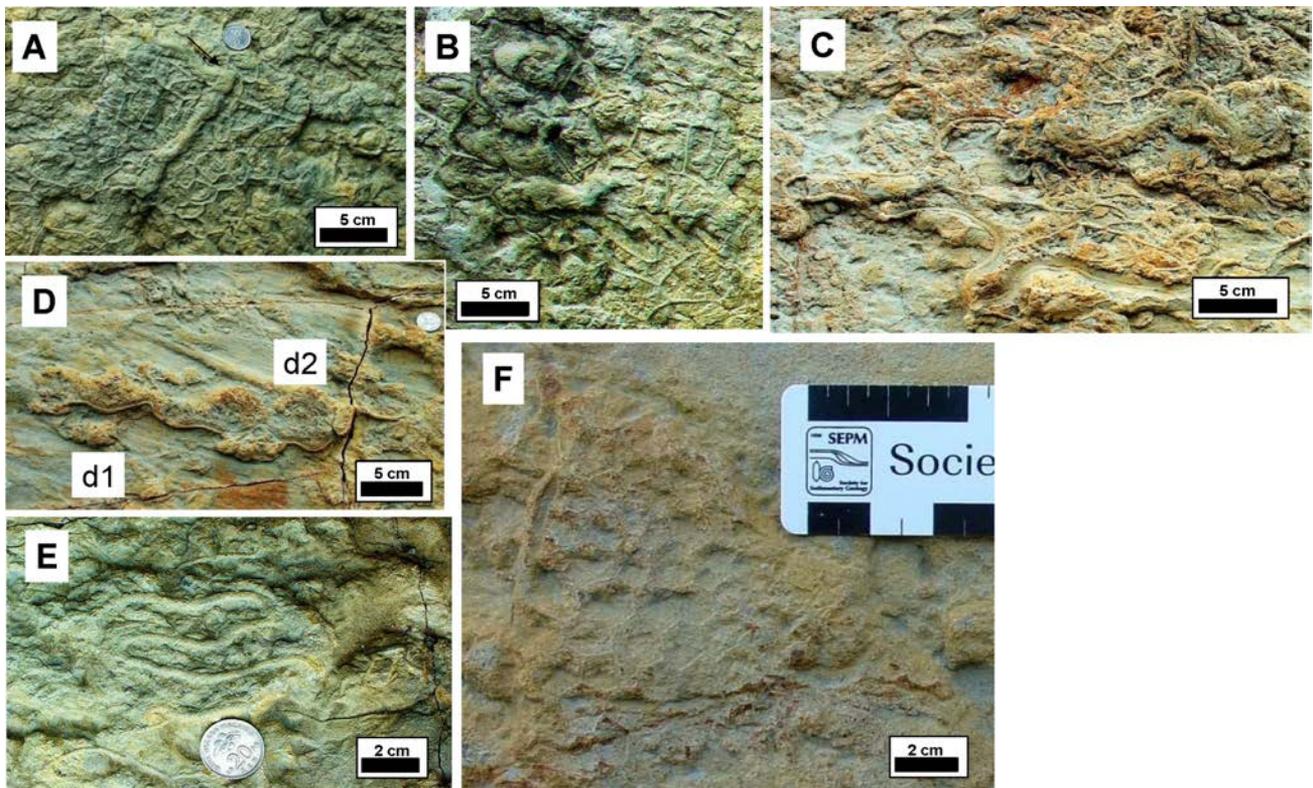
##### ***Nereites* isp.**

**Description:** A single specimen of *Nereites* isp. was found at the Sulaman outcrop (Figure 16E). It is characterised by a long meandering trail with tight meander loops, at least three times going back and forth with very sharp U-turns. The distance between the trails within a meander loop is 3 or 4 times the width of the loop, which is about 3 mm. The median axis of the meanders is curved and seems to be pointing in the

same direction, presumably the direction of “harvesting” by the grazing organism.

**Remarks:** *Nereites* is a hypichnial pascichnion found commonly on the sole of turbidite beds and is the index trace fossil for the *Nereites* ichnofacies (Uchman, 1995, 1999). Seilacher (1977a) referred to it as a “typical” graphoglyptid trace fossil, occurring commonly in flysch and some shallow marine deposits. They are usually post-depositional and are found just below the seabed, thus suggesting that they require oxygenated environment (Uchman & Wetzel, 2012 and references therein). Modern analogues of *Nereites* have been described from the South China Sea cores (Wetzel, 2002).

The ichnogenus *Nereites* (as described in Uchman, 1995, 1998) now includes forms previously assigned to *Helminthoida labyrinthica*, *Helminthoida* Schafhautl, *Scalarituha* Weller, *Neonereites* Seilacher, *Paleohelminthoida* Ruchholz. *Helminthoida* is an obsolete term not recommended for further use, as all are included in *Nereites* (Uchman, 1998).



**Figure 16:** Trace fossils at the base of massive turbidite bed, Sulaman 2. (A) *Megagraption* (B) *Megagraption*, (C) *Megagraption*, with mesh of *Thalassinoides*? (D) *Cosmorhapse* (winding tube, d1), *Palaeophycus* (stubby thick burrow, d2), (E) *Helminthorhapse* with characteristic first-order, regular, high-amplitude meanders. (F) *Paleodictyon strozzii* Meneghini (semi relief).

## DISCUSSION

### Previous reports on trace fossils in the West Crocker Formation

It is useful to briefly review previous reports of trace fossils in the West Crocker Formation to compare some of the key ichnotaxa that have been identified. Unfortunately, Stauffer (1967) did not study trace fossils but only mentioned that the well-developed flat lamination of the lutite interbeds are a “little disturbed” by burrowing. In a later study of sedimentary structures of the West Crocker Formation sediments, Tajul Anuar (1989) described some trace fossils which he identified as *Skolithos*, *?Scoyenia*, *Helminthoida labyrinthica*, *Cosmorhapse fuschi*, *Taphrelminthopsis auricularis*, and *?Thalassinoides* sp. Tajul Anuar concluded that these fossils indicate deep marine depositional environments, although in the same paper he noted that the *Skolithos/Scoyenia* association (which he may have misidentified) seems to indicate shallow marine instead of deep marine environment.

Based on the revised nomenclature of Uchman (1995, 1998), two of the species identified by Tajul Anuar (1989), *Helminthoida labyrinthica* and *Taphrelminthopsis auriculari*, are re-identified here as *Nereites* isp. and *Scolicia strozzii*, respectively. The latter has the distinctive bilobate structure with a wide and deep median furrow that are typical of this species. In addition, based on the photograph of Tajul Anuar (1989, his figure 9A), the *Scoyenia* he had identified may

be re-assigned to *Halopoa imbricata* (which is similar to that described in this paper), whereas the alleged *Skolithos* could be identified as *Planolites*.

From the Bukit Melinsung and Papar area, south of Kota Kinabalu, William *et al.* (2003) reported a “moderately common and relatively diverse” trace fossil assemblage that confirmed bathyal water depths of >1000 m. The assemblage includes *Helminthoida* and *Megagraption*(?), and common *Planolites*. Other species were also mentioned by the authors: *Ophiomorpha*, *Thalassinoides*, *Terebellina*, *Planolites* and *Palaeophycus*, *Asterosoma*, and *Rhizocorallium*. In a later paper (Lambiase *et al.*, 2008) reported abundant *Megagraption*, *Nereites*, and *Ophiomorpha rudis* in an outcrop along Jalan Sulaman, north of Kota Kinabalu (Figure 1 for location) noting that while the assemblage is diverse, “the number of beds with visible traces is low; each locality tends to have a low diversity and some are even monospecific.”

Crevello *et al.* (2007b) also reported trace fossils, including *Paleodictyon*, *Nereites*, *Helminthoida*, and *Cosmorhapse*, which occur in medium-bedded turbidites from Taman Viewpoint, a locality in the vicinity of Inanam 3 and Inanam 4 outcrops (Figure 1). They interpreted the host sandstones as the deposits of either laterally migrating channels or depositional lobes of the submarine fan. It is apparent that this general locality of the West Crocker Formation is rich in trace fossils.

Besides the above references to trace fossils in the West Crocker Formation, there were two conference presentations (abstracts) concerning trace fossils that are worth mentioning. Nizam *et al.* (2006) described briefly the trace fossils found around Kota Kinabalu area, noting the common species such as *Nereites*, *Spirorhapse*, *Megagraption*, *Paleodictyon*, *Cosmorhapse* and *Helminthoidea*, which occurred in fine- to coarse-grained thin bedded cross-laminated sandstones (Bouma Tc division). Nizam *et al.* (2008) reported more trace fossils in the area and interpret the assemblages as representing the *Zoophycos* and the *Nereites* ichnofacies. According to the authors, the *Zoophycos* ichnofacies they identified in mud-rich heterolithic beds of sandstones and siltstones included *Chondrites*, *Cosmorhapse*, *Phycosiphon*, *Planolites*, *Protapaleodictyon*, *Thalassinoides* and *Zoophycos*. The host beds were interpreted to be deposited in the levee or inter-channel areas of a submarine fan. The trace fossil assemblage, however, is atypical of *Zoophycos* ichnofacies and so the identification of some of those traces may need to be reviewed. Some forms of *Chondrites* and *Protapaleodictyon* were also reported to be common within the thin muddy sandstone deposited in the “depositional lobes”.

In addition, Nizam *et al.* (2008) recognized the pre-turbidite and post-turbidite suite within the *Nereites* ichnofacies. Pre-turbidite ichnofossils includes *Helminthoidea*, *Lorenzina*, *Nereites*, *Paleodictyon*, *Spirodesmos*, *Spirophycus*, *Spirorhapse*, *Urohelminthoidea*, and *Megagraption*. They were found within heterolithic beds of shale and sandstone/siltstone that formed levee-interchannel association. The authors also identified post-turbidites ichnofossils *Ophiomorpha*, *Skolithos*, and *Diplocraterion* within the laminated sandstones in the fining-upward channel-fill sequences. These works indicate the potential use of trace fossils in palaeoenvironmental analysis of the West Crocker Formation.

A similar assemblage of trace fossils was reported recently from the Temburong Formation in the Klias Peninsula and Labuan (Basir & Mohd Shafiq, 2019). The Temburong Formation is regarded as the finer grained (argillaceous) age-equivalent of the West Crocker Formation (Madon, 1994). The authors identified 25 ichnotaxa and classified them into 5 ethological categories as per Uchman & Wetzel (2012) and Vallon *et al.* (2016): agrichnia, repichnia, domichnia, fodinichnia, and pascichnia. The trace fossils also indicate the presence of subichnofacies similar to those found in the West Crocker Formation in this study. Lastly, Collenette (1965) photographed *Paleodictyon* in a mudstone of the Labang Formation, an age-equivalent to the Crocker Formation, in the interior of central Sabah about 100 km southwest of Gomantong.

### **Ichnofacies and its palaeoenvironmental significance**

Most of the trace fossils described in this study was found on soles of sandstone beds, and particularly abundant

in thin-bedded turbidites. Pre-depositional graptoglyptids like those described by Uchman & Wetzel (2012) are present in the studied assemblage associated with the deep marine *Nereites* ichnofacies. This ichnofacies is indicative of deposition in bathyal (>200 m) to abyssal water depths (Seilacher, 2007) which can be deeper than 2000-3000 m. Many of the forms belonging to this ichnofacies (Seilacher, 2007) have been identified; they include *Nereites*, *Cosmorhapse*, *Spirophycus*, *Spirorhapse*, and *Paleodictyon*. The various ichnospecies of the *Nereites* ichnofacies also represent mainly post-turbidite association of traces, which was produced by a community of burrowing organisms that fed on the turbidite muds during the quiescent period between turbiditic events. Besides these key deep-water traces, there are other traces, e.g. *Planolites* and *Thalassinoides* that are facies-crossing and, therefore, are not environmentally diagnostic. While most of these pre-depositional agrichnia (farmers) may have acted as traps for microbes that thrived during intra-turbidity flow events, post-depositional trace makers, e.g. *Ophiomorpha*, tended to penetrate deeper into the earlier deposited turbidite beds.

Nizam *et al.* (2008) recognized the presence of the *Zoophycos* ichnofacies, but in this study no evidence of a *Zoophycos* ichnofacies from the assemblage was found in the outcrops. Although *Zoophycos* may represent water depths >1000 m, its use as bathymetric indicator has to be treated with caution due to its extreme variability in form and occurrence (e.g. Löwemark, 2007, p. 415). As such, the depositional environment may have been shallower or in a more proximal setting, probably in slope and basin floor setting in water depths of between about 1000 and 2000 m (Uchman & Wetzel, 2012).

Graphoglyptids are the most diagnostic of the trace fossils in the *Nereites* ichnofacies. These are complex spiral and meandering patterns believed to be generated by sediment grazers and farmers (agrichnia), which often produce intricate networks of horizontal tunnels preserved as semi-relief on the soles of turbidite beds. There is a suggestion that a further subdivision of the *Nereites* ichnofacies could distinguish different parts of the submarine fan system (Seilacher, 1974; Uchman, 2007b; Uchman & Wetzel, 2012; see also Buatois & Mángano, 2011). Further work is needed in order for such an interpretation to be made.

To be preserved, the *Nereites* ichnofacies and its delicate graphoglyptid community require a low energy, low-sedimentation rate environment. For example, *Nereites* would thrive in the more distal parts compared to *Paleodictyon*. Such places include the distal portions of the submarine fan, especially the fringe of crevasse and terminal splays (Seilacher, 1974, Uchman, 2009). Hence, only a few of these forms are found in sandy turbidite facies. *Ophiomorpha rudis*, on the other hand, is thought to represent channel or inner fan lobe facies (Uchman, 2009). In the Cretaceous-Eocene flysch of the Central Pontides, Turkey (Uchman *et al.*, 2004), abundant *Ophiomorpha* is associated with more sand-rich turbiditic channel-fill and proximal

lobe facies coupled with the abundant supply of delta-fed plant detritus into the system providing nutrients to the burrowing organisms. Based on these observations, Figure 17 shows schematically how the different sub-ichnofacies of the *Nereites* ichnofacies may be spatially distributed within a typical submarine fan system. In particular, the recognition of the *Ophiomorpha* vs *Paleodictyon* ichnofacies could provide a useful environmental indicator, in addition to primary sedimentological criteria, to distinguish between higher and lower-energy parts of the system.

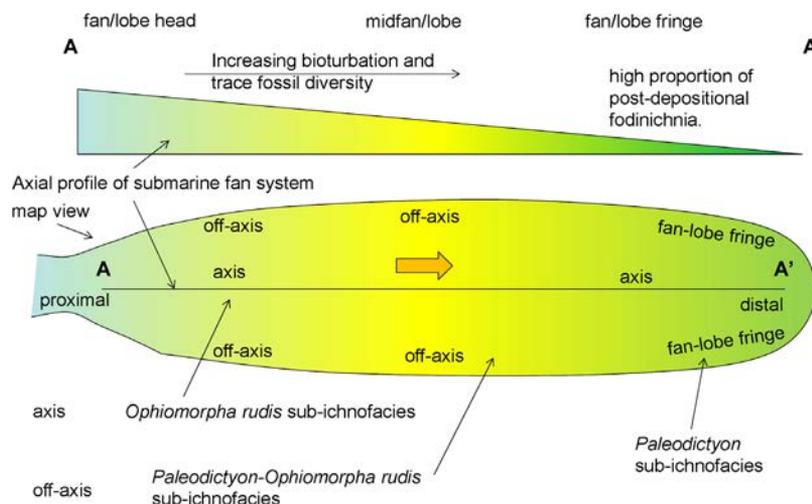
It is noted that although the trace fossils found in the West Crocker Formation are diverse, they are not widespread or ubiquitous, i.e. their occurrence is limited to only certain parts of the sequences, e.g. thin-bedded turbidite facies in proximal to mid-fan environments. *Spirophyucus* dominates particular intervals of thin-bedded turbidites at Inanam 3 and at Inanam 4. These bed-specific occurrences suggest that *Spirophyucus* tends to occur in the lower-energy facies sheltered from the main sand-rich turbidity flows where there was a period of sustained quiescence with little or no sediment supply. The mud-rich intervals may well be associated with condensed sections on the abandoned parts of the submarine fans where pelagic/hemipelagic sedimentation was dominant.

The non-ubiquity of trace fossils in the West Crocker Formation suggests that the general depositional environment may have been highly eutrophic and anoxic, and only occasionally during certain times agitated or turbid environment enabled replenishment of oxygen at the sea floor for organisms to thrive. Unfortunately, the Crocker Formation is relatively sandy (~70% sand) and dark laminated mudstones (representing pelagic basin-plain muds) are rarely observed in the outcrops studied to suggest that the environments may have been anoxic. However,

more detailed field observations are needed to investigate this possibility.

The deep-sea turbidite environment is essentially one of long periods of pelagic sedimentation that is frequently interrupted by incoming sediment gravity flows (or turbidite events). Mud-feeding organisms thrive during the background pelagic sedimentation, but the turbidite events frequently disrupt their normal lives. When conditions return to normal, so do the organisms, which graze, farm and feed on the muddy substrate before the next event. Hence, the quietest part of the turbidite system is one that is furthest or sheltered from active sediment transport, either in the distal parts of the submarine fan, or in the proximal areas that are off-axis to the main sediment transport path (e.g., mid-fan, channelised regions). This has been demonstrated in other submarine fan systems, such as in the Ainsa-Jaca basin in the Spanish Pyrenees (Heard & Pickering, 2008) where bioturbation intensity and trace-fossil diversity were found to increase away from channel-axis towards off-axis environments. In that same basin, the *Paleodictyon* sub-ichnofacies of the *Nereites* ichnofacies is characteristic of lobe fringe and fan fringe, whereas the distal basin floor has the same sub-ichnofacies but with high abundance of fodichnia components (see also Uchman, 2001). Channel axis and proximal fan have characteristic *Ophiomorpha rudis* sub-ichnofacies whereas off-axis proximal areas are characterized by a mixture of both *Ophiomorpha rudis* and *Paleodictyon* sub-ichnofacies (Heard & Pickering, 2008; Kilibarda & Schassburger, 2018). The presence of *Ophiomorpha* in these types of proximal turbidite facies may also be indicative of a well-oxygenated newly deposited turbidite (e.g. Uchman, 1998, 2009; Nielsen *et al.*, 2012; Uchman & Wetzel, 2012).

Not all muddy or mud-rich intervals of the turbidite succession are full of trace fossils, as they do not necessarily



**Figure 17:** Conceptual model of the different parts of a submarine fan system and its associated subichnofacies, belonging to the *Nereites* ichnofacies, as found in the West Crocker Formation around Kota Kinabalu. Summarised based on observations in this study as discussed in the text, as well as incorporating the observations made in other flysch sequences (e.g. Heard & Pickering, 2008).

represent the most distal or “quietest” parts of the fan system (e.g., the fan fringe). This may equally apply to slope fans as well as basin-floor fans. Hence, the presence and diversity of trace fossils may be used as potentially diagnostic tools in discriminating different parts of the fan system or different types of submarine fans. Several workers have shown that it is possible to distinguish different parts of a submarine fan in simple and complex margins by their ichnofacies associations (Seilacher, 1974; Uchman, 2007b, Uchman & Wetzel, 2012). While the *Nereites* ichnofacies is characteristic of fan fringes, the off-axis facies are typically highly bioturbated, being less affected by turbidity currents. In areas of complex topography, ponded slope “minibasins” tend to be deprived of oxygen, therefore are less bioturbated than in open simple ones. *Zoophycos*, although commonly reported from slope turbidite systems, may also occur beyond turbiditic systems and at larger depths (e.g. Löwemark, 2011). Nevertheless, it has not been observed and appears to be absent from the outcrops studied, suggesting that the trace fossil assemblages represent mainly basin-floor fan system.

It is significant to note that the interpretations above are based on the commonly assumed normal submarine fan depositional model, based primarily on our current knowledge of submarine fans in passive margins or even active margins with simple geomorphic slope geometries. The present-day complex morphology of the NW Sabah shelf-slope systems suggests that the Crocker system may be more complex than that perceived in previous interpretations.

The trace fossil assemblages in the West Crocker Formation are similar to a number of examples from deep-sea turbidite (“flysch”) systems: e.g. Eocene Hecho Group in the Ainsa–Jaca Basin, Spanish (Uchman, 2001, Heard & Pickering, 2008); Central Pondites, Turkey (Uchman *et al.*, 2004), in the Upper Cretaceous Pilwa Group of Tanzania (Nicholas *et al.*, 2006), and in the Oligocene Zuberec Formation, Liptov Basin of Central Western Carpathians (Starek *et al.*, 2019), to name a few. The somewhat sparse occurrences of trace fossils in the West Crocker Formation nonetheless provide a glimpse of biogenic activity and sediment-organism interactions in a seemingly uninhabitable deep marine environment. Taking all the outcrop locations in total, the number of sandstone beds that actually contain trace fossils is rather low, but where they occur they do so in high abundance albeit with low diversity. When present, the graptoglyptids occur in abundance in one or two specific horizons, indicating a narrow preference for certain environmental conditions and/or favourable preservation potential. It appears that this type of environment is most likely in the most distal parts of the turbidite fan system (fan lobe fringe) which are less susceptible to frequent disruptions by sediment-gravity flows. With detailed field observations and documentation, it is hoped that more trace fossils will be recovered, as their paleoenvironmental interpretation will give valuable insights into the depositional conditions and sedimentary processes of the host sediments.

## CONCLUSIONS

Trace fossil assemblages in the West Crocker Formation around Kota Kinabalu belong to the *Nereites* ichnofacies, which generally indicates depositional environments in bathyal to abyssal water depths (>2000 m). The ichnofacies is dominated by horizontal farming and feeding traces, ranging from solitary to branching tubular burrows (*Ophiomorpha*, *Palaeophycus* and *Planolites*) to meandering trails and tunnels (*Nereites*, *Cosmorhapha*, *Helminthopsis*), as well as the distinctive, pretzel or doughnut-shaped, spiriform burrows, *Spirophycus*.

Graptoglyptids are the most diagnostic of the *Nereites* ichnofacies in some parts of the West Crocker Formation. These complex spiral and meandering traces are believed to have been produced mainly by sediment farmers (agrichnia), often displaying intricate networks of mainly horizontal tunnels preserved as full or semi-relief beneath turbidite beds. Most of the common pre-depositional graptoglyptids described are present, including *Spirorhapha* and *Paleodictyon*.

The various species of the *Nereites* ichnofacies represent mainly “post-turbidite” traces, left by a community of burrowing organisms that fed on the turbiditic muds during the quiescent period between turbidity flow or mass transport events. Besides these key deep-water traces, other traces include e.g., *Planolites*, *Thalassinoides* and *Ophiomorpha*, known to be facies-crossing and, generally, not environmentally diagnostic. *Ophiomorpha* appears to be more common in sandy facies and tends to penetrate deeply into pre-existing turbidite beds.

It is possible to further subdivide the *Nereites* ichnofacies into “sub-ichnofacies” to distinguish different parts of the submarine fan system. The *Paleodictyon* sub-ichnofacies, for example, is characteristic of lobe fringe and fan fringe, whereas the distal basin floor has the same sub-ichnofacies but with high abundance of fodichnia components (Heard & Pickering, 2008). Channel axis and proximal fan has the characteristic *Ophiomorpha rudis* sub-ichnofacies, while off-axis proximal areas are characterized by a mixture of both *Ophiomorpha rudis* and *Paleodictyon* sub-ichnofacies. The presence of *Ophiomorpha* in these types of proximal turbidite facies may also be indicative of a well-oxygenated newly deposited turbidite (e.g., Nielsen *et al.*, 2012).

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