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Ichnology of shallow marine clastic facies in the Belait Formation, Brunei Darussalam

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Abstract: Trace fossil assemblages from a variety of outcropping tidal and shoreface facies in the Belait Formation of Brunei Darussalam were characterized to determine their value in distinguishing shallow marine sedimentary environments on a low energy margin. Most trace fossil assemblages in tide-dominated environments have a proximal *Cruziana* ichnofacies, although higher energy tidal channels have a distal *Skolithos* ichnofacies. Tidal sand flats tend to have more diverse and abundant traces than tidal channels. Trace fossils are more abundant in tidal mud flat facies than in tidal channels and sand flats, and whilst mud flat assemblages are more diverse than tidal channel assemblages, they are less diverse than sand flat assemblages. Generally, these assemblages are similar to those in equivalent depositional environments in higher tidal range settings.

Wave-dominated environments also have *Cruziana* assemblages, except for the upper shoreface that has a distal *Skolithos* assemblage. Lower shoreface assemblages are more abundant and diverse than upper shoreface assemblages and belong to the proximal *Cruziana* ichnofacies. Trace fossils are more abundant and diverse in offshore transition facies than in either the upper or lower shoreface and belong to the distal *Cruziana* ichnofacies; assemblages in interbedded storm sands often include a minor component of the *Skolithos* ichnofacies. These assemblages are comparable to those from wave-dominated deposits from higher energy settings, except for the upper shoreface environment which contains a lower energy assemblage than in equivalent facies elsewhere.

Trace fossils tend to be less diverse, less abundant and individual traces generally are smaller in tide-dominated depositional environments when compared to wave-dominated depositional environments. Also, *Ophiomorpha* form complex burrow systems in wave-dominated environments in contrast to simple burrows in tide-dominated environments.

Keywords: Brunei Darulssalam, Beliat Formation, trace fossil, tide-dominated environment, wave-dominated environment

INTRODUCTION

Most shallow marine clastic petroleum reservoirs in Brunei Darussalam belong to the Middle to Late Miocene Belait Formation and consist of tidal and/or shoreface sandstones. Although tidal and shoreface sandstones can be distinguished fairly readily in outcrop, there is enough similarity in grain size, sedimentary structures and bed thickness that subsurface interpretation can be difficult. The application of trace fossils to subsurface data interpretation has been successful in other parts of the world (e.g. Beynon and Pemberton, 1992). However, nearly all previous studies are based on ichnofacies established for shallow marine environments with significantly higher wave and tidal energy than on the margin of the South China Sea. Consequently, there is no ichnofacies model based on local conditions that can be applied to the subsurface.

The present study investigated the trace fossil assemblages and variations that are associated with various shallow marine depositions in Brunei Darussalam to develop a framework that can assist with the interpretation of depositional environments. Six outcrops from four different areas were studied (Figure 1). Tide-dominant facies were studied at two areas, Jalan Sungai Akar and Pantai Bukit Agok (Figures 1 and 2) and wave-dominant facies were studied at four areas, Jalan Sungai Akar, Jalan Tutong, Simpang 587, Jalan Tutong, Simpang 170 and

Figure 1: Location of the Belait Formation outcrops used in the study. The inset shows the location of the study area on the NW coast of Borneo.

Pantai Bukit Agok (Figures 1 and 3). These outcrops were chosen because they represent a wide range of tide- and wave-dominant environments that were identified in several previous studies (e.g Caalim, 2001; Klan-Ngern, 1999; Lai, 2004; Yahya Basman, 2004; Yap, 1996; Ovinda, 2005). The facies range from tidal channel to tidal flats in tide-dominated environments and upper shoreface to offshore transition in wave-dominated environments.

Trace fossil distributions were described with respect to abundance, diameter, spatial position, branching and type of infill. The degree of bioturbation was quantified using the six category ichnofabric index of Droser and Bottjer (1986), which is: (1) no bioturbation recorded, all original sedimentary structures preserved; (2) discrete, isolated trace fossils, up to 10% of original bedding disturbed; (3) approximately 10 to 40% of original bedding disturbed, burrows are generally isolated, but locally overlap; (4) last vestiges of bedding discernable; approximately 40 to 60% disturbed, burrows overlap and are not always well defined; (5) bedding is completely disturbed, but burrows are still discrete in places and the fabric is not mixed; and (6) bedding is nearly or totally homogenized.

ICHNOFACIES IN TIDE-DOMINANT ENVIRONMENTS

Tidal Channel Sandstones

Tidal channel sandstones are generally characterized by a low abundance and low diversity of trace fossils, although abundance and diversity sometimes increase slightly near bed tops. The ichnofabric indices range between 2 and 3, usually it is 2 except at the contacts with overlying units. *Ophiomorpha* are the most abundant trace fossil in this facies (Figure 4). Generally, *Ophiomorpha* burrows are vertical, do not branch and diameters do not exceed 20 mm. *Skolithos*,

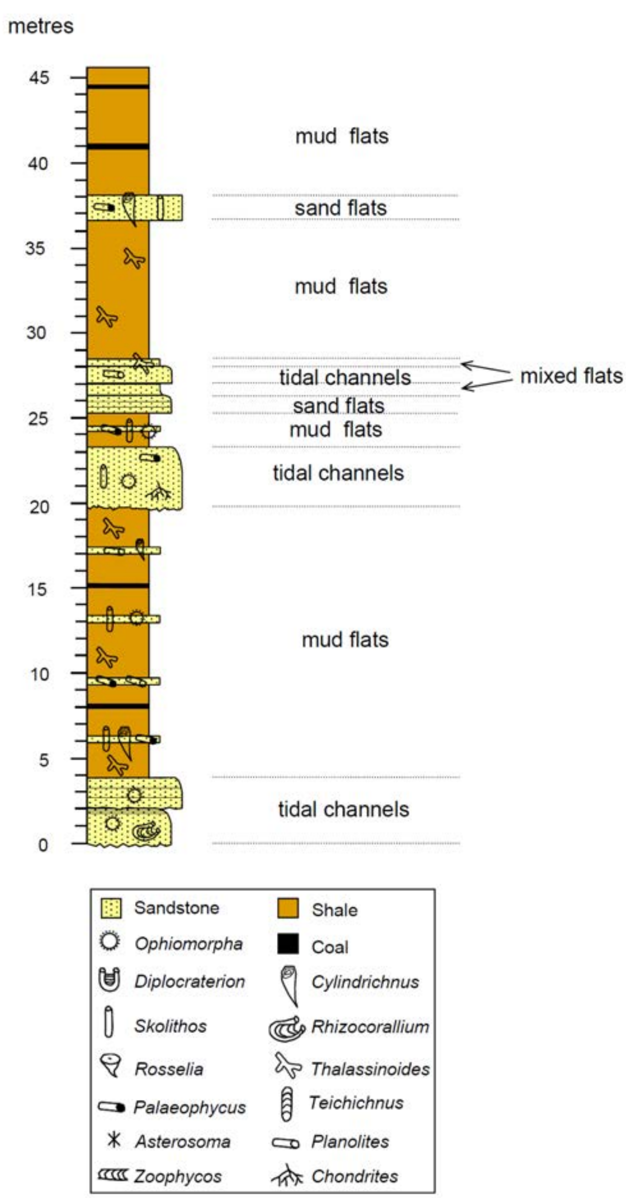

Figure 2: A representative stratigraphic log of tide-dominated facies.

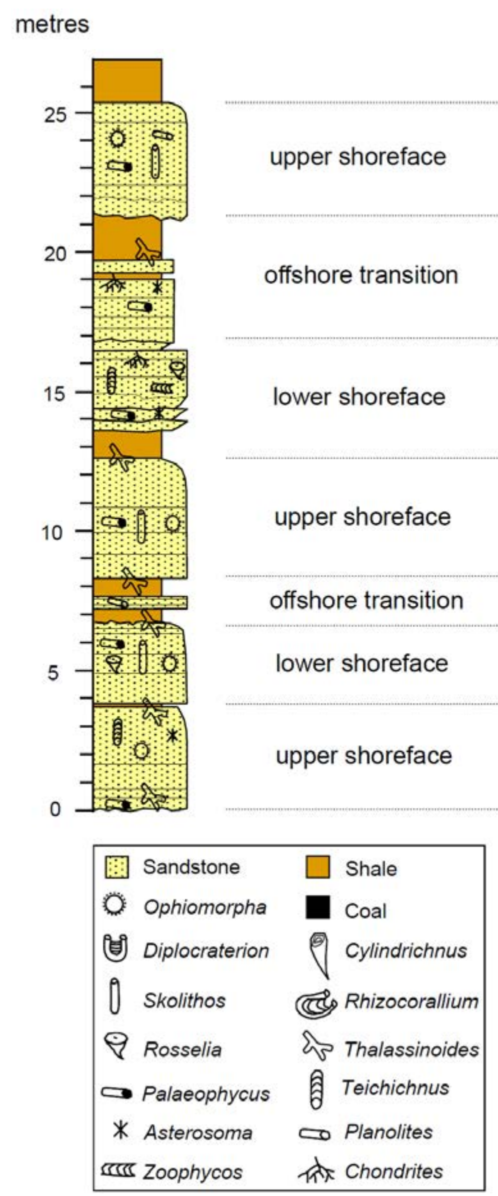

Figure 3: A representative stratigraphic log of wave-dominated facies.

Planolites, *Palaeophycus* and *Rhizocorallium* comprise this facies (Figure 5), in descending order of relative abundance. Small *Ophiomorpha* with simple burrow systems plus a few, or all, of the other trace fossils characterize most tidal channel sands.

The small burrow size (notably *Ophiomorpha*) suggests that the organisms were small because of reduced salinity, as many marginal marine organisms are smaller than their fully marine counterparts (Wightman *et al*., 1987; Beynon *et al*., 1988). Diversity and abundance are low due to harsh environmental conditions, continuously shifting substrates and overall low preservation potential (Howard and Frey, 1984). The increase in ichnofabric index and diversity near the top may be due to organisms burrowing down from the unit above. *Ophiomorpha* and *Skolithos* are mainly vertical burrows that belong to the *Skolithos* ichnofacies (Pemberton and MacEachern, 1992), as does *Palaeophycus* which is a horizontal dwelling burrow. *Planolites* and *Rhizocorallium* are horizontal feeding structures; both are associated with the *Cruziana* ichnofacies (Pemberton and MacEachern, 1992). The trace fossil assemblages in tidal channels are interpreted as the *Skolithos* ichnofacies, with a *Cruziana* ichnofacies component.

Figure 4: Small diameter, vertical *Ophiomorpha,* the most abundant trace fossils in tidal channel sandstones. The arrow points to the trace fossil and the coin is 2 cm wide.

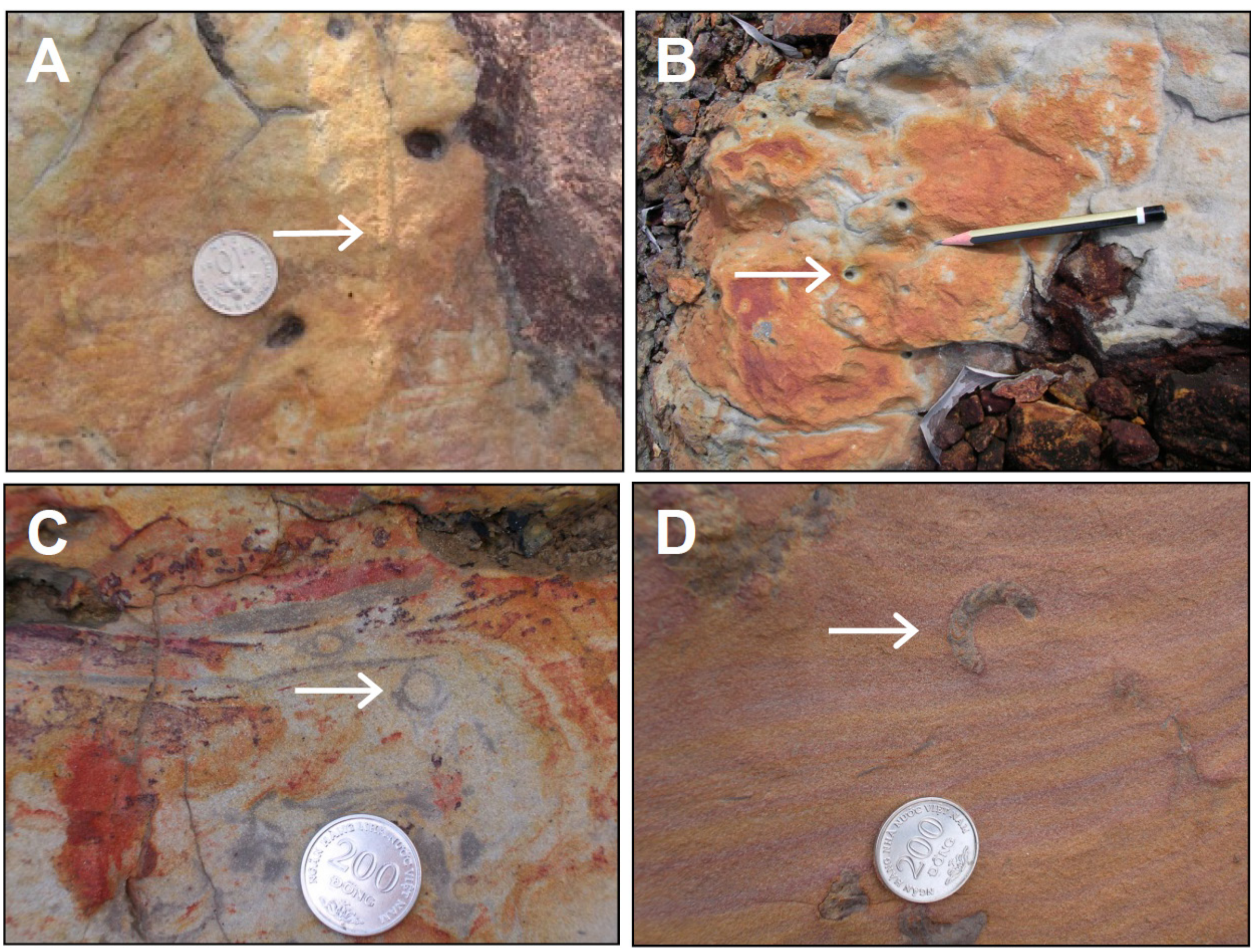

Figure 5: Common trace fossils in tidal channel sandstones, in descending order of abundance: A) *Skolithos*, B) *Planolites*, C) *Palaeophycus*, and D) *Rhizocorallium*. The arrows point to the trace fossils and the coin is 2 cm wide.

Sandy Tidal Flats

Sandy tidal flats generally are more highly bioturbated than tidal channel sandstones. Ichnofabric indices are 4 to 5 and usually increase near upper bed surfaces. Sandy tidal flats also have higher diversity compared to tidal channels with abundant *Palaeophycus, Thalassinoides* (Figure 6a) and horizontal *Ophiomorpha*, in descending order of abundance. *Planolites*, *Skolithos*, *Chondrites*, *Asterosoma* and *Cylindrichnus* (Figures 6b,c,d), in descending order of relative abundance, are less common in this facies.

The relatively high ichnofabric indices reflect relatively low energy levels with adequate food supplies for supporting a diverse group of organisms (Pemberton and MacEachern, 1992). Again, the small burrow size suggests reduced salinity. The trace fossil assemblage in tidal sand flats is interpreted as the *Cruziana* ichnofacies, with a minor contribution from the *Skolithos* ichnofacies. The *Cruziana* elements include abundant *Thalassinoides* and common horizontal *Ophiomorpha* plus the less common *Planolites*, *Chondrites* and *Asterosoma.* The *Skolithos* ichnofacies is represented by abundant *Palaeophycus*, moderately common *Skolithos* and a few *Cylindrichnus.*

Muddy Tidal Flats

Weathering obscured field observations in nearly half of the muddy tidal flat units that were studied. Trace fossils usually are visible only in silty layers or where iron cement has filled in pore space. In the field, mud flats appear to have low ichnofabric indices (2 to 3) and low diversity, although this is likely to be an underestimation because muddy facies normally are more highly bioturbated than sandy facies (Pemberton and MacEachern, 1992). Silty beds have a higher ichnofabric index (3 to 4) and higher diversity, which is probably more accurate for the muddy tidal flat facies.

Thalassinoides, Ophiomorpha, Palaeophycus, Skolithos, Planolites, Cylindrichnus, Chondrites and *Diplocraterion* (Figure 7A) dominate this facies, in descending order of abundance. Some *Thalassinoides* are large with diameters up to 10 cm. The *Ophiomorpha* do not branch and have relatively small diameters. Most *Ophiomorpha*, *Cylindrichnus*, *Skolithos*, *Chondrites* and *Diplocraterion* were observed in silty units. Muddy tidal flats can be characterized by relatively high ichnofabric indices and diversity with abundant *Thalassinoides*.

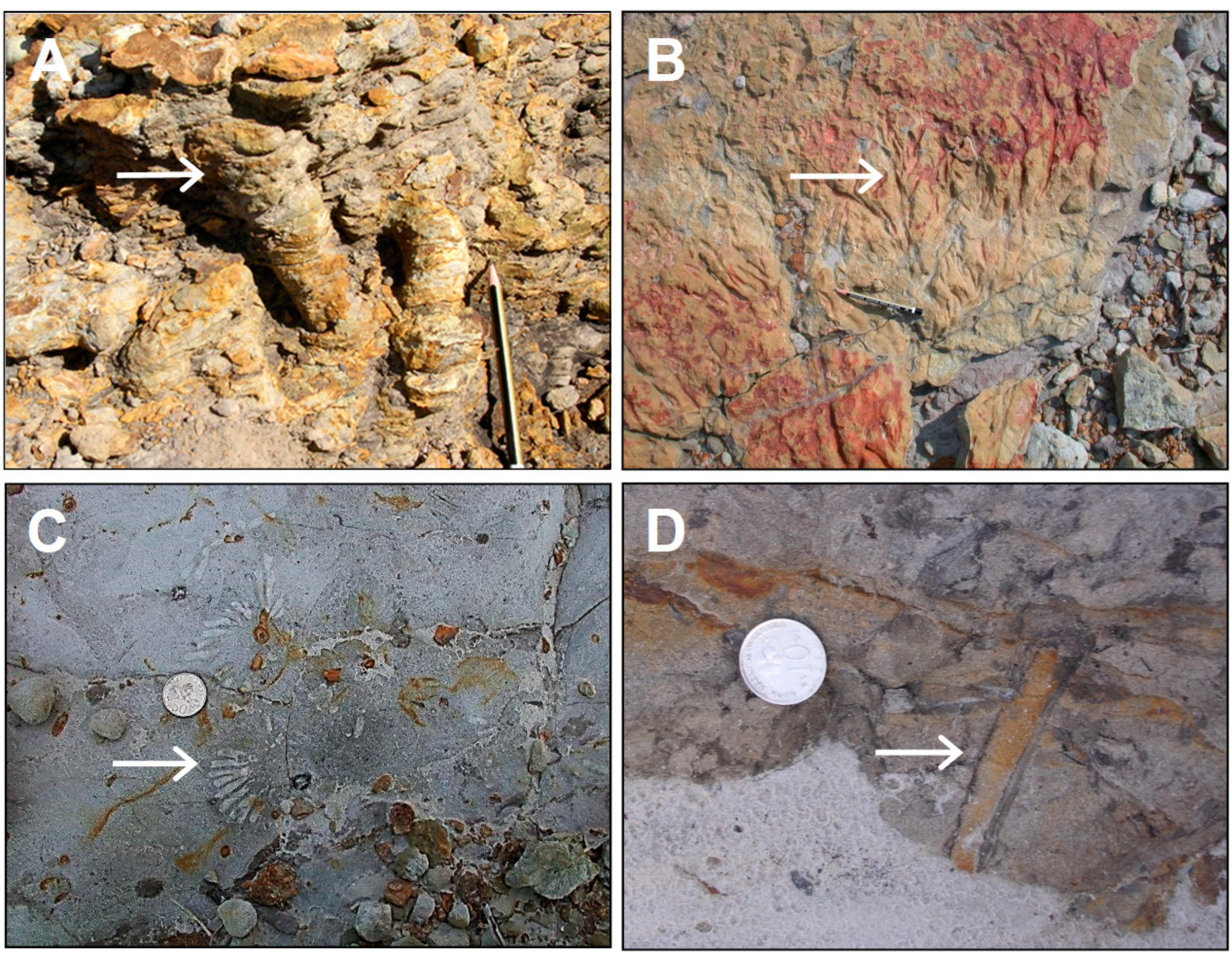

Figure 6: Common trace fossils in tidal flat sandstones, in descending order of abundance: A) *Thalassinoides*, B) *Chondrites*, C) *Asterosoma* and D) *Cylindrichnus.* The arrows point to the trace fossils and the coin is 2 cm wide.

The trace fossil assemblage in tidal mud flats is interpreted as the *Cruziana* ichnofacies, with a component of the *Skolithos* ichnofacies. *Cruziana* ichnofacies elements include robust *Thalassinoides* and moderately common *Planolites* and *Chondrites*. *Skolithos* ichnofacies elements are *Ophiomorpha, Skolithos, Cylindrichnus* and *Diplocraterion,* although most of the *Ophiomorpha, Skolithos, Cylindrichnus* and *Diplocraterion* occur in the silty beds.

ICHNOFACIES IN WAVE-DOMINANT ENVIRONMENTS

Upper Shoreface Sandstones

In general, upper shoreface sandstones have slightly higher ichnofabric indices and higher diversities than the tidal channel, sandy tidal flat or muddy tidal facies. Ichnofabric indices range from 2 to 4 and normally increase to 5 or 6 near the upper bed boundaries. *Ophiomorpha* are abundant with diameters up to 40 mm (Figure 8 A, B). *Ophiomorpha* burrows are vertical, sub-vertical and horizontal, with simple burrow systems. *Thalassinoides* are abundant at bed contacts with muddy units. *Palaeophycus, Asterosoma, Skolithos*, *Teichichnus* (Figure 8C) and *Chondrites* occur in descending order of abundance. Abundant *Ophiomorpha* with simple burrow systems characterizes upper shoreface sandstones, especially when they occur in conjunction with some or all of *Thalassinoides, Palaeophycus, Asterosoma, Skolithos*, *Teichichnus* and *Chondrites*.

High ichnofabric indices and high diversity in upper shoreface sandstones means that the wave-dominated environments were more favorable for organisms compared to the tide-dominated environments, probably because of normal marine salinities plus abundant oxygen and food supplies (Howard and Frey, 1984; Frey and Howard, 1985). Large *Ophiomorpha* and *Thalassinoides* burrows mean bigger animals, another indicator of a favorable environment. The trace fossil assemblage is interpreted as the *Skolithos* ichnofacies, with a considerable contribution from the *Cruziana* ichnofacies. *Skolithos* ichnofacies elements include abundant *Ophiomorpha*, common *Skolithos and Palaeophycus*. *Cruziana* elements include *Thalassinoides*, horizontal *Ophiomorpha, Asterosoma*, *Chondrites* and rare *Teichichnus*.

Figure 7: *Diplocraterion*, a common trace fossil in tidal flat mudstones.

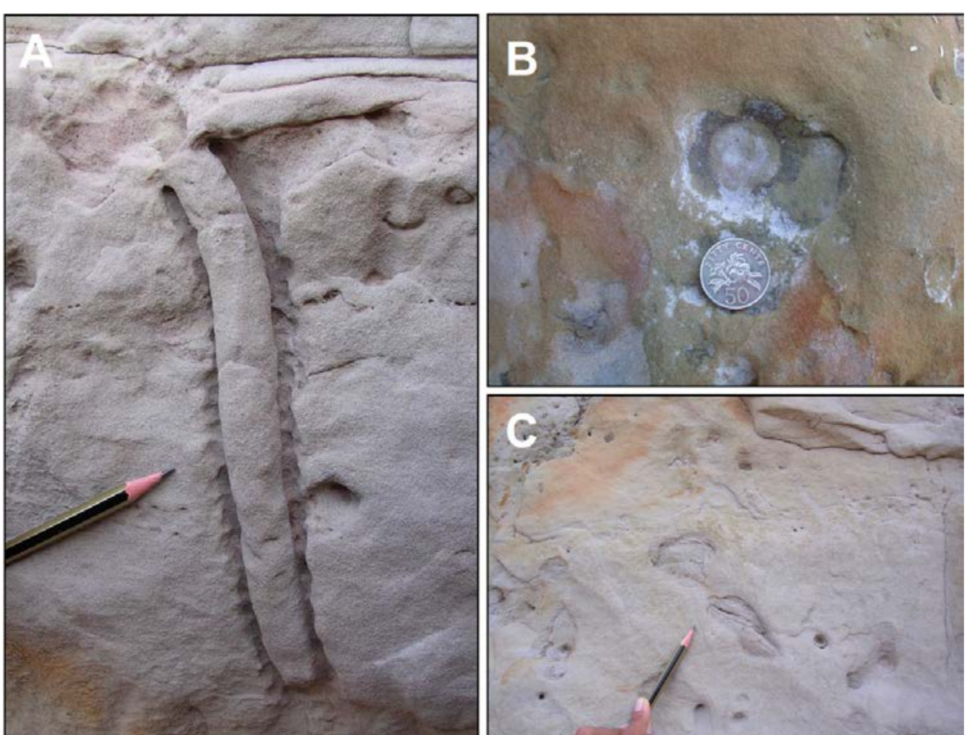

Figure 8: Common trace fossils in upper shoreface sandstones, A) and B) cross-sectional and bedding plane views of a large *Ophiomorpha* respectively, and C) *Teichichnus*. The coin is 2 cm wide.

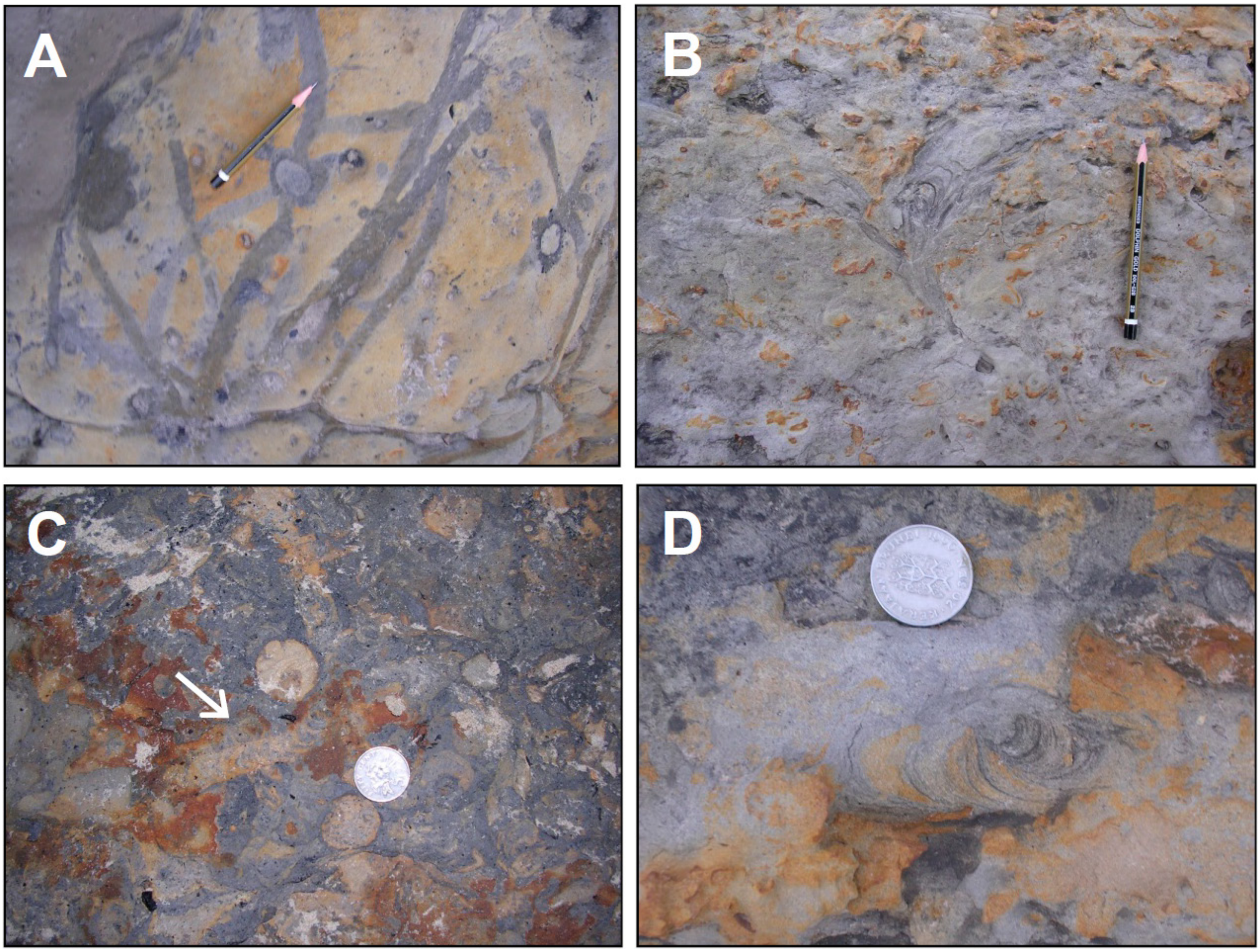

Figure 9: Common trace fossils in lower shoreface sandstones: A) "boxwork" *Ophiomorpha*. B) *Rosselia,* C) and D) cross-sectional and bedding plane views of *Zoophycos,* respectively. The coin is 2 cm wide.

Lower Shoreface Sandstones

Generally, diversity and ichnofabric indices in lower shoreface sandstones are similar to those in upper shoreface sandstones at 2 to 4, but increase to 5 near the upper bed contacts. Large diameter *Ophiomorpha* are the most abundant traces and most are horizontal with complex burrow systems known as 'box-work' morphology (Figure 9A), although some are vertical or horizontal and do not branch. *Thalassinoides* are abundant at the contacts with muddy beds and they also form complex burrow systems. *Chondrites, Asterosoma, Skolithos, Palaeophycus, Planolites, Rosselia* (Figure 9B), *Zoophycos* (Figures 9C,D) and *Teichichnus* are common as well. Abundant *Ophiomorpha* and *Thalassinoides* with complex burrow systems characterize lower shoreface sandstones. They can occur with either a few or all of *Chondrites, Asterosoma, Skolithos, Palaeophycus, Planolites, Rosselia, Zoophycos* and *Teichichnus*.

High ichnofabric indices, high diversity and abundant *Ophiomorpha* and *Thalassinoides* with complex burrow systems indicate lower energy conditions than in the upper shoreface environment. The trace fossil assemblage is interpreted as the *Cruziana* ichnofacies, with a minor contribution from the *Skolithos* ichnofacies. *Cruziana* elements include abundant horizontal *Ophiomorpha* plus *Thalassinoides* and to a lesser degree *Chondrites, Planolites, Asterosoma, Rosselia, Teichichnus* and *Zoophycos. Skolithos* components are the vertical *Ophiomorpha, Skolithos* and *Palaeophycus.*

Offshore Transition Mudstones with Interbedded Storm Sands

The offshore transition mudstones and interbedded storm sands can be characterized by abundant *Thalassinoides* that form complex burrow systems, especially when they occur in conjunction with either a few or all of *Ophiomorpha, Asterosoma, Chondrites, Skolithos, Cylindrichnus, Teichichnus, Rhizocorallium* and *Zoophycos.* Ichnofabric indices are moderate (2 to 4) but some beds have indices up to 6. Weathering obscured field observation of muddy units; the actual ichnofabric indices and diversity of offshore transition facies may be higher than upper shoreface and lower shoreface sandstones.

The exceptionally high bioturbation index in some beds may be due to increased food and oxygen levels during storms and the vertical *Ophiomorpha, Skolithos* and *Cylindrichnus* may indicate opportunistic colonization after storm events (MacEachern and Pemberton, 1992). The assemblage is interpreted as the *Cruziana* ichnofacies with an imprint from the *Skolithos* ichnofacies, mostly as opportunistic colonizers in storm beds. *Cruziana* ichnofacies elements include abundant *Thalassinoides* common *Asterosoma* and lesser common *Chondrites, Teichichnus, Rhizocorallium* and *Zoophycos.* The *Skolithos* ichnofacies elements are *Ophiomorpha, Palaeophycus, Skolithos* and *Cylindrichnus.*

DISCUSSION

Wave Energy, Tidal Range and Trace Fossil Assemblages

Previous studies of shallow marine trace fossil assemblages that related ichnofacies to depositional environment focused on strata were interpreted to have been deposited on margins with moderate wave and tidal energy (e.g. Pemberton and Frey, 1985; MacEachern and Pemberton, 1992, and Beynon and Pemberton, 1992). However, wave energy on the NW Borneo margin has been minimal since at least the middle Miocene because of limited fetch in the South China Sea (Lambiase and Abdul Razak Damit, 2004; Lambiase and Suraya Tulot, 2013). Also, there is no outcrop or subsurface evidence that tidal ranges have been appreciably larger than the present day micro- to mesotidal conditions; the margin is therefore characterized as a low energy setting (Lambiase and Abdul Razak Damit, 2004; Lambiase and Suraya Tulot, 2013).

The energy level of the depositional environment is one of the important controls on trace fossil assemblages (Ekdale *et al.*, 1984), so it could be expected that the ichnofacies in the Belait Formation vary somewhat from their higher energy counterparts. However, the trace fossil assemblages in the tide-dominated environments of the Belait Formation show very little variation from higher energy settings. A mixture of simple horizontal and vertical structures, common to both the *Skolithos* and *Cruziana* ichnofacies, characterizes ichnofossil associations in tide-dominated environments regardless of tidal range (Beynon and Pemberton, 1992). Similarly, individual trace fossils are small compared to their respective fully marine counterparts in all tide-dominated settings.

Most of the wave-dominated environments in the Belait Formation also are similar to their higher energy equivalents. Lower shoreface sandstones are mostly a *Cruziana* ichnofacies with some *Skolithos* ichnofacies components in the Belait Formation and in environments with higher wave energy (Raychaudhuri *et al.*, 1992). Diversity and abundance also are similar in both settings. A typical offshore transition suite is a diverse *Cruziana* assemblage including *Zoophycos* and *Helminthopsis* (MacEachern and Pemberton, 1992). The Belait Formation offshore transition assemblage is a diverse *Cruziana* assemblage that includes *Zoophycos*.

Upper shoreface sandstones are the only facies in which the Belait Formation trace fossil assemblages vary from those in higher energy settings. The *Skolithos* ichnofacies occurs in both cases, but assemblages from high energy environments clearly reflect the high energy conditions (MacEachern and Pemberton, 1992) whilst the Belait Formation assemblage includes proportionately more lower energy *Skolithos* ichnofacies traces and more elements of the *Cruziana* ichnofacies. This yields a relatively low energy signature for the Belait Formation upper shoreface assemblage, which accurately reflects the energy conditions in the depositional environment.

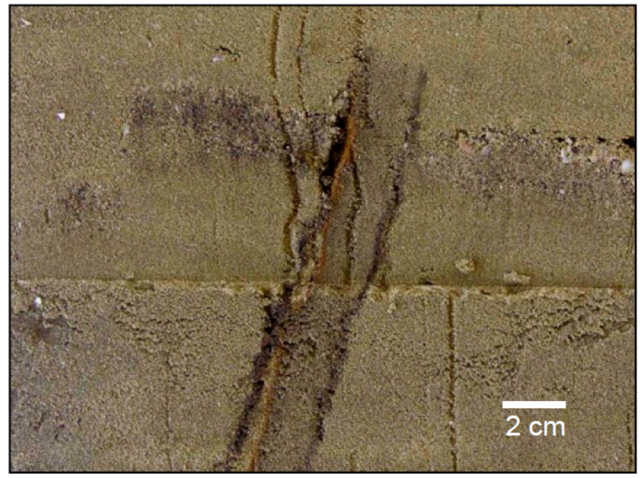

Figure 10: An *Ophiomorpha* burrow collected in a box core near the low tide line on the beach in Brunei Darussalam. (“D” is after Lambiase and Suraya Tulot, 2013).

Recent studies on the low-energy, modern Brunei coast indicate a similar distribution of burrowing organisms. *Ophiomorpha* and other *Skolithos* ichnofacies burrows were collected in box cores on the beach near the low tide line (Figure 10) and there are anemones living in the upper shoreface in only 3 m of water that are capable of producing *Cruziana* ichnofacies traces (Dashtgard and Gingras, 2012). The significant *Cruziana* component in the upper shoreface represents a shoreward shift of that ichnofacies relative to its occurrence in higher energy systems.

A similar shoreward shift in the trace fossil assemblages occurs within the offshore transition environment in the Belait Formation on the Klias Peninsula. There, tempestites interbedded with mudstones are dominated by the mixed *Skolithos* and *Cruziana* ichnofacies traces that are typical of storm sands (Pemberton and Frey, 1985) but there is a subordinate component of the outer shelf to slope *Zoophycos* ichnofacies and approximately 10% of the assemblage belongs to the deepwater *Nereites* ichnofacies (Tan, 2010). This suggests that relatively shallow (i.e. above storm wave base), low energy environments can mimic significantly deeper water environments with respect to other controls on the distribution of burrowing organisms (e.g. substrate, sedimentation rate, oxygen and nutrient supply).

Interpretation of Depositional Environments

Belait Formation trace fossils have very similar assemblages in tide-dominated and wave-dominated environments and are highly variable with respect to abundance and diversity. The differences between the tide-dominated and wave-dominated assemblages are not significant enough to distinguish those environments. However, assemblages have less diversity, traces are less abundant and individual traces generally are smaller in tide-dominated depositional environments than in wave-dominated depositional environments. Also, *Ophiomorpha* form complex burrow systems in wave-dominated environments in contrast to simple burrows in tide-dominated environments. These characteristics provide general guidelines for interpreting depositional environment. Robust individual traces, complex burrow systems and the traces *Zoophycos* and *Rosselia* are restricted to wave-dominated environments but they are not common enough to be useful environmental discriminators.

CONCLUSIONS

The trace fossils assemblages in the Belait Formation in Brunei Darussalam lead to the following conclusions:

- The pervasive *Cruziana* and *Skolithos* assemblages allow easy recognition of a shallow marine setting.
- Tidal channel sandstones have a relatively low energy *Skolithos* ichnofacies whilst sandy and muddy tidal flats have a *Cruziana* ichnofacies.
- Upper shoreface sandstones have a relatively low energy *Skolithos* ichnofacies and lower shoreface sandstones have a *Cruziana* ichnofacies. Offshore transition mudstones have a *Cruziana* ichnofacies and there is an imprint of the *Skolithos* ichnofacies in interbedded storm beds. *Zoophycos* and *Rosselia* are restricted to the wave-dominated environments.
- Generally, there are no significant differences between the Belait Formation trace fossil assemblages and those from tide-dominated environments in higher tidal range settings.
- Trace fossil assemblages in wave-dominated environments in the Belait Formation are comparable to those from higher energy settings except for upper shoreface sandstones which have a lower energy assemblage than equivalent facies elsewhere.
- There are some differences between the ichnofacies in tide-dominant and wave-dominant environments, but generally, those environments are too similar to be distinguished solely by trace fossil assemblages.

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