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A new age interpretation for the Meluhu Formation in Toronipa peninsula, the southeast arm of Sulawesi, Indonesia

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Abstract: The offshore area in the northeast of Kendari city, the southeast arm of Sulawesi, is an area with favourable hydrocarbon prospectivity shown by numerous oil and gas seeps in the surrounding coastal area. It is a frontier basin in eastern Indonesia, known as the Manui Basin. An exploration well named Abuki-1 was drilled in 1990 suggested a Miocene transgressive sequence as a potential reservoir and source rock at this basin. However, this unit has no analogous exposure in the onshore area resulting in the lack of study and knowledge of this potential Miocene unit. Therefore, we revisit the sedimentary rocks exposure nearby Abuki-1 well in the Toronipa peninsula to study about its sedimentary facies and palynological contents. These outcrops by previous researchers were included in Toronipa Member of Meluhu Formation, and a Triassic age was suggested for this unit. By contrast, our result shows that these exposures are Middle to Late Miocene in age as indicated by the occurrence of the *Florschuetzia* group pollens (*Florschuetzia trilobata*, *F. levipoli*, and *F. meridionalis*). The absence of Plio-Pleistocene pollen and spores index fossils (*Stenochlaena milnei* group, *Dacrycarpus imbricatus*, and *Phyllocladus*) supports the Middle to Late Miocene age interpretation. A wave-dominated estuary depositional model is proposed based on the presence of river-dominated, mixed-energy, and wave-dominated facies associations. We suggest that the studied sediments are the outcrop analogues for the Middle to Late Miocene transgressive sequence found in Abuki-1 well. Furthermore, we recommend that these Miocene estuary-fill complexes should have excellent hydrocarbon potential. The reservoir potential is the sand deposits of the fluvial, tidal, washover, and shoreface facies with moderately to well-sorted characteristics. The source rocks candidate is the mud of lagoon, tidal flat, floodplain, and marine offshore facies. Moreover, the Manui Basin, with its Miocene estuarine deposits, requires further study to reveal its hydrocarbon accumulation potential.

Keywords: Manui Basin, wave-dominated estuary, Toronipa, southeast Sulawesi

INTRODUCTION

The study area is located at the Toronipa peninsula, southeast arm of Sulawesi, about 25 km to the northeast of Kendari City (Figure 1A). Based on the regional geological map of the southeast arm of Sulawesi, the sedimentary rock units in the study area are regarded as Toronipa member of the Meluhu Formation and suggested as Triassic in age (Rusmana *et al*., 1993; Simandjuntak *et al*., 1993; Surono, 1994; Surono & Bachri, 2002). The basin in the study area is known as the Manui Basin, and it is one of the frontier basins in eastern Indonesia with favourable hydrocarbon prospectivity, shown by numerous oil and gas seeps in the surrounding area (Patmosukismo *et al*., 1989; Satterlee *et al*., 1990; Satyana, 2017). To the north in the offshore of the Toronipa peninsula, an exploration well named Abuki-1 was drilled in 1990. Satterlee *et al*. (1990) reported that in this well, the Middle to Late Miocene sandstone was the best quality sandstone reservoir rock while its interbedded mudstone was rich in organic content, suggesting potential hydrocarbon source rock.

However, there is no published literature about the presence of Middle Miocene sediments in the coastal area. This has resulted in the lack of study and knowledge of the potential Miocene unit of Abuki-1 well. The surrounding rock exposures in the Manui Basin, according to Rusmana *et al*. (1993), Surono (1994), and Surono & Bachri (2002) was Pre-Tertiary in age. In addition, Nugraha & Hall (2018), concluded that the Middle Miocene sediments in the SE arm Sulawesi were eroded or never deposited.

Therefore, we revisit the sedimentary rock exposed in the Toronipa peninsula to study its sedimentary facies and palynological age, and this paper aims to present the result and interpretation of the investigation. A depositional model for the sedimentary sequence of the outcrops of the Toronipa peninsula exhibited in this paper is expected to be a starting point for modelling the Middle to Late Miocene sediments in the Manui Basin.

Geological setting

The oldest Australian continental crust rock in the Kendari - Toronipa area is the Palaeozoic Metamorphics (Figures 1B; Rusmana *et al*., 1993; Milsom, 2000). The Mesozoic sediments of Australasia origin are terrestrial to marginal marine Meluhu Formation, deep water Tokala Formation, and deep water carbonate chert of Matano Formation (Rusmana *et al*., 1993; Surono, 1994; Milsom,

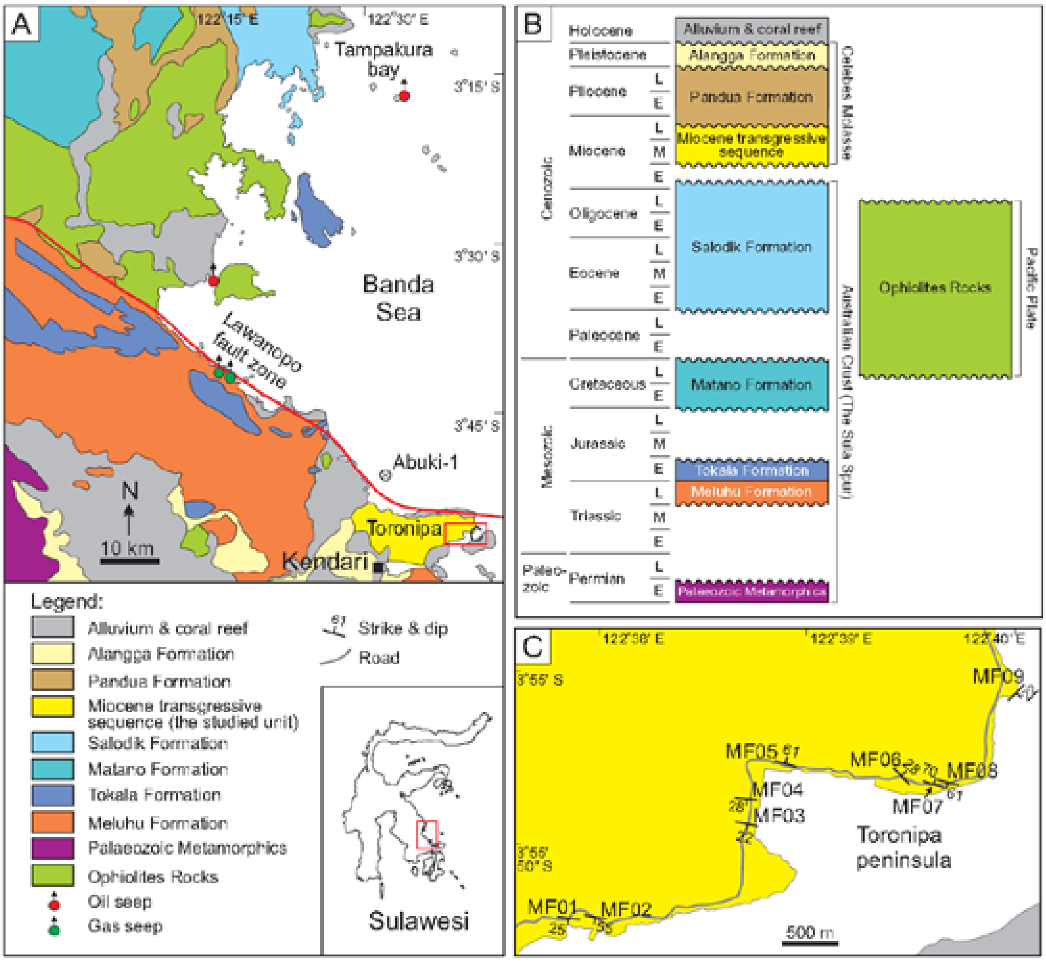

Figure 1: Location map of the study area. A) Geological map of the Kendari and surrounding areas, the southeast arm of Sulawesi (modified from Rusmana *et al.*, 1993). The study area is shown by the red box. B) Stratigraphic framework of the Kendari and surrounding areas. Modified from Satterlee *et al.* (1990), Rusmana *et al.* (1993), and Milsom (2000). C) The location map of the sites of the outcrop stratigraphic sections.

2000). The Eocene to Early Miocene carbonate of the Salodik Group represents the Cenozoic sediments of the Sula Spur micro-continent. The Cretaceous to Oligocene East Sulawesi Ophiolite is originating from the mid-oceanic ridge and oceanic plateau of the Pacific Plate (Kadarusman *et al*., 2004; Panggabean & Surono, 2011).

The Early Miocene collision of the Sula Spur with the north Sulawesi volcanic arc, followed by Neogene rollback-related extension, is believed to be responsible for the forming of the high mountains and deep basins of Sulawesi and the Banda Sea area (Nugraha & Hall, 2018; Hall, 2019). Following the Early Miocene collision, a series of Miocene to Pliocene siliciclastic deposition known as the Celebes Molasse was accumulated (Nugraha & Hall, 2018). In the study area, it consists of Late Miocene to Pliocene Pandua Formation and Quaternary sediments of Alangga Formation (Rusmana *et al*., 1993).

METHODS AND MATERIALS

This study is based on outcrops of roadside exposures, and beach cliff faces along the east side of the Toronipa peninsula (Figure 1C). The workflow of facies analysis performed in this study comprises of description, classification, and interpretation (Anderton, 1985; Dalrymple, 2010). The description of the sedimentary facies unit included of lithology, grain size, texture, sedimentary structures, and bed contact, and was recorded into sedimentological logs for each observation site. Dalrymple (2010) suggests the establishment of facies based on the characteristics that have genetic significance. In this study, the facies was defined mainly based on lithology and sedimentary structures. The closely related facies that occur in intimate physical association with each other than combined into facies associations which correspond to a unique depositional environment (Dalrymple, 2010). The interpretations of facies associations, amongst many others, were mainly based on Miall (2006) for the river-dominated deposit, Dalrymple (1992) for the mixed-energy deposit, and Clifton (2006) for the wave-dominated deposit.

Nine selected samples comprised of carbonaceous mudstone and siltstone were palynologically analyzed using standard palynological procedure (Wood *et al*., 1996). The main objective of this palynological analysis was to determine the age of the studied section and to support the depositional environment interpretation. The palynological analysis was performed at Pusat Survei Geologi (Centre for Geological Survey), Ministry of Energy and Mineral Resources, Indonesia. The processing of the samples involved treatment using HF, HCl, H_2SO_4, and gravity separation using $ZnCl_2$. Two slides per sample were observed using a light microscope with a magnification of 400x and 1000x. Pollen and spores identification was mainly based on Germeraad *et al*. (1968) and Anderson & Muller (1975), among other resources.

RESULTS AND DISCUSSION

Facies and facies association

The studied deposits consist of 17 sedimentary facies (Table 1). These are grouped into three facies associations: river-dominated, mixed-energy, and wave-dominated (Figure 2).

A) River-dominated facies association (FA1)

This depositional unit is 3 - 5.5 m thick and exposed at MF01 and MF09 sites (Figures 2A and 3). The river-dominated facies association is composed of six lithofacies; Trough cross-bedded sandstone (St), Planar cross-bedded sandstone (Sp), Low-angle cross-bedded sandstone (Sl), Massive to faintly laminated sandstone (Sm), Laminated mudstone, siltstone, and sandstone (Fl), and Massive mudstone and siltstone (Fm) facies. St facies starts the succession of this FA at the bottom trough Sp, Sl, or Sm facies. Overall, the sequence shows a fining upward trend with the Fl and Fm facies cap the sandstones facies. The description of the facies of FA1 is provided below.

Facies 1, Trough cross-bedded sandstone (St):

This facies consists of grey to reddish-grey medium-grained sandstone with moderately sorted texture. Clay clasts are found locally above the basal part of the sequence. The trough cross-strata are grouped in cosets up to 3 m thick with rare solitary sets. The individual set varies in thickness from 15 to 70 cm. Basal boundaries are mostly erosional. A single solitary bed of this facies with a thickness of 15 cm is found between the massive mudstone layer.

Facies 2, Planar cross-bedded sandstone (Sp):

The planar cross-strata comprises of grey to a reddish-grey, moderately sorted fine- to medium-grained sandstone. The planar cross-strata mainly appears as cosets up to 1.5 m thick with rare solitary sets. The set thickness is ranging from 10 to 60 cm with sharp lower and upper boundaries. The angles of foreset laminae are between 10° to 20°. Most of the contact between foreset laminae and lower bounding surface is tangential.

Facies 3, Low-angle cross-bedded sandstone (Sl):

This facies differs from the Sp facies with having low-angle (less than 10°) foreset laminae. It consists of fine- to medium-grained sandstone with moderate sorting and grey to reddish-grey in color. Bed thickness reaches up to 60 cm. The low-angle cross-strata is less common than the St and Sp facies.

Facies 4, Massive to faintly laminated sandstone (Sm):

The Sm facies is only found at the MF09 site and is assigned to structureless sandstones with locally faint lamination. This facies is reddish-grey and occurs as thick, blocky units consisting of fine sandstone. The lower boundaries of this unit are sharp, overlying the St facies.

Facies 5, Laminated mudstone, siltstone, and sandstone (Fl):

This facies is attributed to interlayered of very fine-grained sandstone with siltstone and mudstone lamination. The sandstones are grey, and small ripples are preserved locally. In some places, the siltstone and mudstone are carbonaceous. Unit thickness is 40 cm and underlying by the St facies with erosive contact.

Facies 6, Massive mudstone and siltstone (Fm):

This facies consists of structureless mudstone and siltstone. It is dark grey and red in color. In some places, it shows platy and blocky structures. The Fm facies is found overlying the Sp, Sl, and Sm facies and commonly underlain by the St facies with erosive contact. In some places, the Fm facies occurs interlayered with Fl facies. The thickness of Fm facies is varying from 30 to 100 cm.

Interpretation:

The trough and planar cross-stratified sandstones (St and Sp) were developed by the migration of 2D and 3D dunes in response to unidirectional currents (Allen, 1963; Miall, 1977). The associated clay clast at the base of the trough represents lag deposits resulting from intraformational erosion (Surono, 1994; Miall, 2006). The low-angle cross-bedded sandstone (Sl) were formed as scouring fills, washed-out or humpback dunes, and antidunes (Miall, 2006). The massive sandstone with faint lamination (Sm) are the deposits of sediment gravity flows in small channels resulting from bank collapse (Miall, 2006). Post-depositional modifications such as dewatering and bioturbation might also produce a massive texture (Miall, 2006). Laminated mudstone, siltstone, and sandstone facies (Fl) were deposited by suspension in overbank areas and from weak traction currents (Miall, 2006). The massive mudstone and siltstone (Fm) represent the deposition in the floodplain areas wherein clay- dan silt-sized debris deposited by the suspended load (Nichols, 2009). The platy and blocky structures and red color of the Fm facies suggest post-depositional modification by pedogenetic processes and oxidizing conditions (Miall, 1977; Foix *et al*., 2013; Scherer *et al*., 2015). The grey massive mudstone and siltstone were formed in the distal floodplain, which is poorly drained and commonly waterlogged (Miall, 2006; Foix *et al*., 2013).

Table 1: Sedimentary facies of each facies association with their depositional environment interpretation and palynological characteristics.

Facies Association	Facies		Textures	Structures	Interpretation	Palynological characteristics
River-dominated facies association (FA1)	F1	Trough cross-bedded sandstone (St)	Medium-grained sandstones with occasional intraformational clasts	Trough cross-bedding	Fluvial channel	- Poor recovery and low diversity of pollen and spore. - The presence of regional flora (*Podocarpus*), lowland forest and grassland vegetation. - Moderate abundance of freshwater algae, diatom and fungal spore.
	F2	Planar cross-bedded sandstone (Sp)	Fine- to medium-grained sandstones	Planar cross-bedding		
	F3	Low-angle cross-bedded sandstone (Sl)	Fine- to medium-grained sandstones	Low-angle planar cross-bedding		
	F4	Massive to faintly laminated sandstone (Sm)	Fine-grained sandstones	Massive with occasional horizontal laminations.		
	F5	Laminated mudstone, siltstone, and sandstone (Fl)	Mudstone, siltstone, and very fine-grained sandstones with occasional carbonaceous mudstone lamination	Fine lamination and some small ripples	Flood plain	
	F6	Massive mudstone and siltstone (Fm)	Mudstone and siltstone	Massive		
Mixed-energy facies association (FA2)	F7	Cross-bedded sandstone with reactivation surface and mud drapes (Std)	Medium-grained sandstones and centimeter bedded of mud layers	Cross-bedding, reactivation surface, and mud drapes	Tidal channel	- Moderately rich recovery and diversity of pollen and spore. - Characterized by the occurrence of mangrove and back mangrove vegetation. Mixed with regional background vegetation, lowland forest, freshwater peat swamp, riparian and grassland vegetation. - High abundance of freshwater algae, diatom and fungal spore.
	F8	Interlaminated sandstone and mudstone (Si)	Alternation of very fine-grained sandstones and mudstone.	Horizontal stratification with rhythmic alternation and occasional ripples	Tidal flat	
	F9	Lenticular, wavy, and flaser bedded sandstone (Ht)	Alternation of very fine-grained sandstones and mudstone.	Cross-lamination and mud drapes		
	F10	Organic-rich mudstones and coals (FmC)	Carbonaceous mudstones and coal	Massive to laminated mudstone and coal layers	Marsh	
	F11	Massive to laminated mudstone and siltstone with burrow (Fmb)	Mudstone and siltstone with occasional very fine-grained sandstones intercalation	Massive to laminated	Lagoon	
	F12	Horizontally laminated sandstone with wave ripple (Slw)	Fine-grained sandstones	Horizontal stratification with occasional wave ripples	Washover	
Wave-dominated facies association (FA3)	F13	Cross-bedded sandstone (Sc)	Medium-grained sandstones	Trough and planar cross-bedding	Upper shoreface	- Poor recovery and low diversity of pollen and spore. - The presence of regional flora (*Podocarpus*), lowland forest and grassland vegetation. - Low abundance of freshwater algae and fungal spore.
	F14	Hummocky and swaley cross-bedded sandstone (Shsc)	Fine-grained sandstones	Hummocky and swaley cross-bedding	Lower shoreface	
	F15	Horizontally bedded sandstone (Shb)	Fine-grained sandstones	Horizontal stratification		
	F16	Interbedded sandstone and mudstone (Flsm)	Very fine-grained sandstones and mudstone	Horizontal stratification with occasional hummocky cross-bedding in sandstone	Lower shoreface to offshore transition	
	F17	Laminated mudstone and siltstone with thin sandstone bed (Fmss)	Mudstone, siltstone, and very fine-grained sandstone	Horizontal lamination	Offshore	

FA1 is interpreted as a deposit of the meandering river system. The interpretation is based on the occurrence of fining-upward sequence with stacked unidirectionally-oriented cross-strata at the base bounded by erosive surfaces, in places with mud clasts, assign as a channel filled with point bar deposit (Miall, 2006). It is then followed by floodplain or overbank sediments (Fm and Fl facies) which was produced by the waning stage of a river flood (Donselaar & Overeem, 2008). The fluvial point bar sandstone capped by floodplain deposit with pedogenic feature suggests a mature meandering river sequence (Galloway & Hobday, 1996; Miall, 2006; Donselaar & Overeem, 2008).

B) Mixed-energy facies association (FA2)

This facies association is found at MF02, MF04, MF07, and MF08 sites (Figures 2B and 4). The depositional unit thickness is up to 14.5 m. It comprises of six lithofacies namely; Cross-bedded sandstone with reactivation surface and mud drapes (Std), Interlaminated sandstone and mudstone (Si), Lenticular, wavy, and flaser bedded sandstone

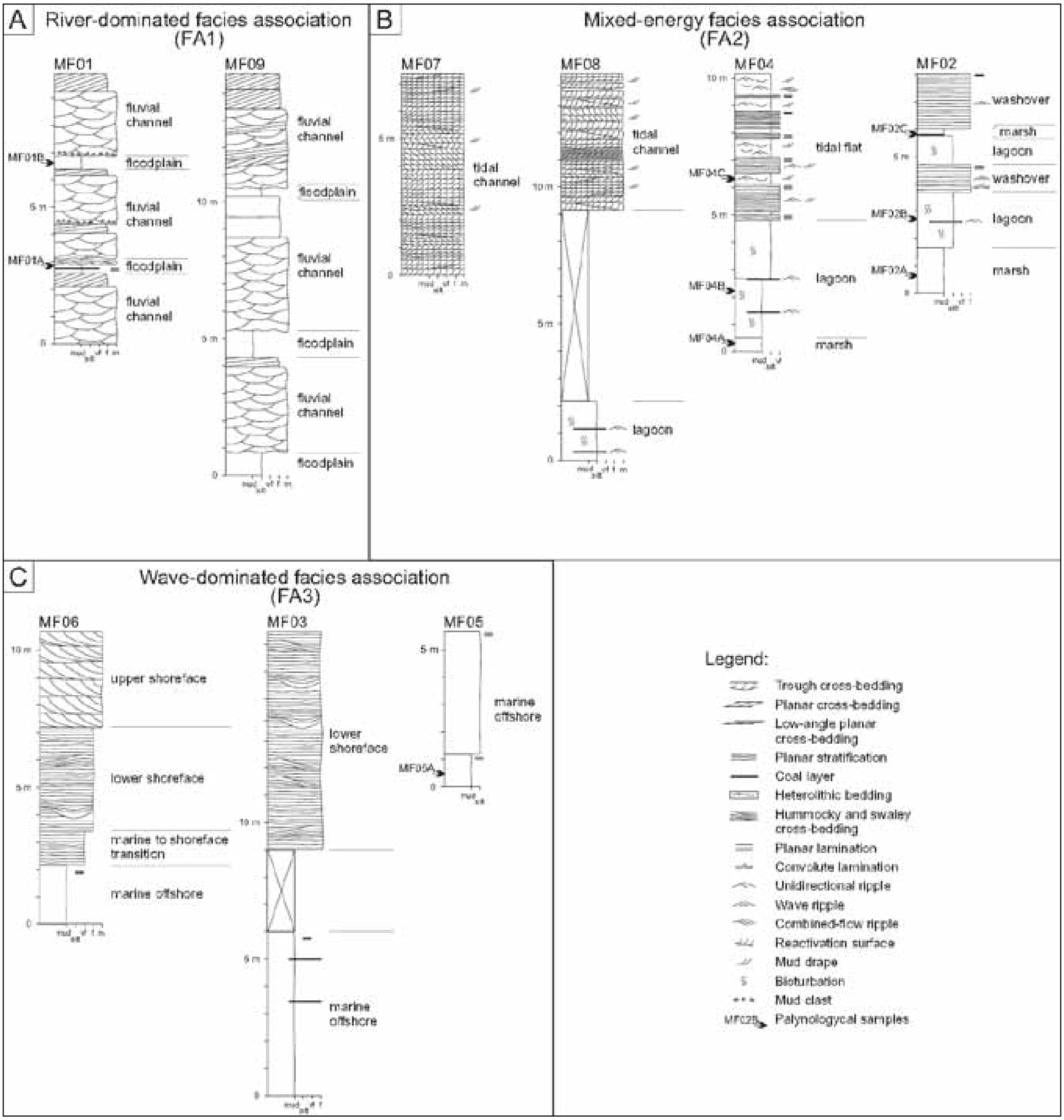

Figure 2: The measured section of outcrops in the Toronipa peninsula, exhibits the river-dominated (A), mixed-energy (B), and wave-dominated facies associations (C).

(Ht), Organic-rich mudstones and coals (FmC), Massive to laminated mudstone and siltstone with burrow (Fmb), and Horizontally laminated sandstone with wave ripple (Slw).

Facies 7, Cross-bedded sandstone with reactivation surface and mud drapes (Std):

This facies is characterized by moderately sorted, grey to reddish-grey, cross-bedded medium-grained sandstone. Planar cross-bedded is less common than the trough sets. Their basal boundaries are mostly erosional with less sharp contacts. They mostly appear as cosets with thickness up to 2.5 m. The set thickness ranges from 5 to 30 cm. Thin centimeter bedded of mud layers that lack of lamination are commonly found separating the coset of cross-bedded strata. Minor erosion surfaces within the cross-stratification known as reactivation surface are locally observed. In places, millimeter thin mud layers recognized as mud drapes are found between the bottom of the foreset. Less common of opposite dipping foresets of

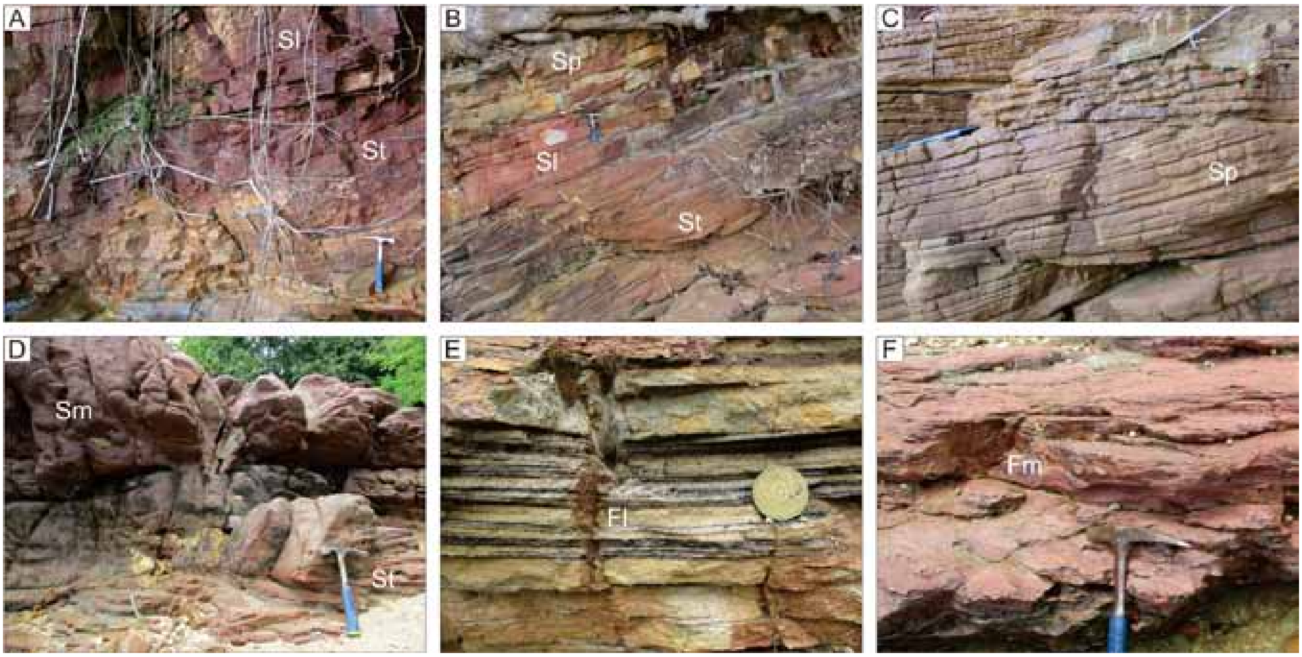

Figure 3: Field photographs of the sedimentary facies in the river-dominated facies association. A) Coset of trough cross-bedding (St) overlaying by low-angle cross-bedded sandstone (Sl). B) Successions of trough cross-bedding (St), low-angle cross-bedded sandstone (Sl), and planar cross-bedded sandstone (Sp). C) Detail of the planar cross-bedded sandstone (Sp). D). Trough cross-bedded sandstone (St) overlaying by massive to faintly laminated sandstone (Sm). E) The interlayered of very fine-grained sandstone with siltstone and mudstone lamination (Fl facies). F) The massive mudstone and siltstone facies (Fm).

the cross-strata are observed locally. The total thickness of this facies is 5.5 (MF08) and 7.5 m (MF07).

Facies 8, Interlaminated sandstone and mudstone (Si):

This facies consists of a horizontally laminated alternation of white to grey moderately to well-sorted, very fine-grained sandstones with dark grey carbonaceous mudstone. Plant debris is common in the mudstone lamination. The rhythmic thick-thin horizontal layer of sand and mud are common. Occasional mud draped asymmetric ripples present in the sandstone layer. Basal sharp contacts are frequent in the sandstone with rare erosional base. The total thickness of this facies varies from 10 to 75 cm.

Facies 9, Lenticular, wavy, and flaser bedded sandstone (Ht):

The Ht facies is characterized by heterolithic bedding of thin-bedded mudstones alternating with ripple-cross-laminated, very fine-grained sandstones. The mudstones are carbonaceous and grey in color, whereas the sandstones are white and moderately to well-sorted. Mud drapes mostly line the individual cross-laminae with various thicknesses up to a few millimeters. The ripples are mostly asymmetrical and unidirectional. Cross-laminae show oppositely dipping foresets occur locally. Rare combined-flow ripples present in the sandstone layer. Lenticular, wavy, and flaser structures are recognized based on the varying proportion between sandstone layers and mudstone layers. Individual bedding packages are up to 25 cm thick. Alternation of thicker and thinner bundles of sandstone or mudstone dominated interval is also observed. The Ht facies is found alternating with the Si facies.

Facies 10, Organic-rich mudstones and coals (FmC):

This unit comprises of blackish organic-rich mudstone with massive or laminated structure. A coal layer with a thickness of 3 cm is found at the MF02 site. The thickness of this facies is ranging from 0.25 to 1.6 m.

Facies 11, Massive to laminated mudstone and siltstone with burrow (Fmb):

This facies consists of light and dark grey massive to laminated, mostly carbonaceous, mudstone and siltstone. In some places, the bioturbated layer filled with carbonaceous material is observed. Bioturbation in this unit is low in diversity. Organic matter debris is abundant in some layers. Centimeter-thick rippled sandstone occurred locally as lenses intercalation. The facies thickness is about 1 to 4.5 m.

Facies 12, Horizontally laminated sandstone with wave ripple (Slw):

The characteristic of this facies is well sorted, horizontal to wavy stratification fine-grained sandstone. This facies is whitish-grey in color and exhibits a slightly erosive base. Convolute laminae is observed in some layers, as well as occasional wave ripple. The thickness of this unit is about 1 to 2 m.

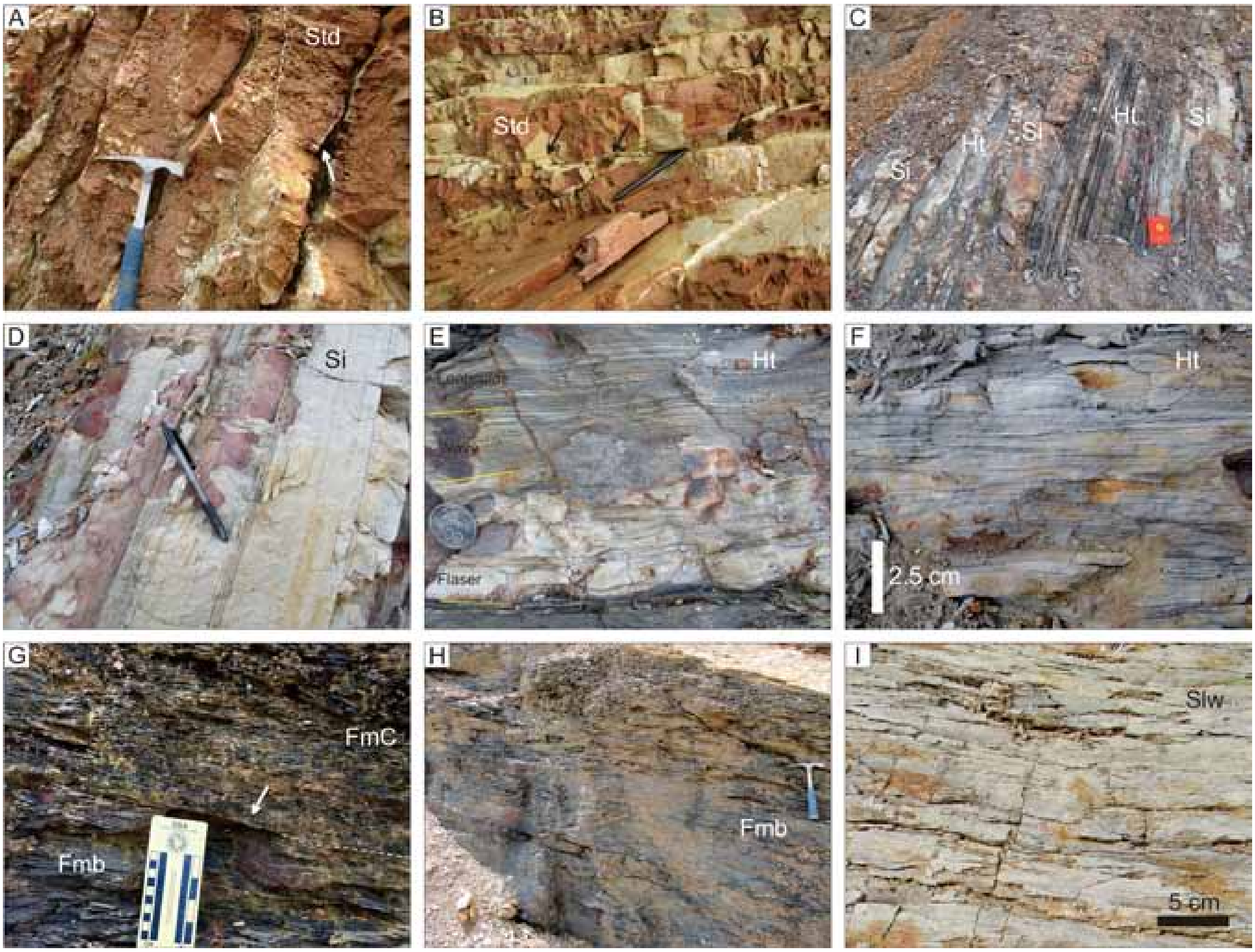

Figure 4: Field photographs of the sedimentary facies in the mixed-energy facies association. A) The cross-bedded sandstone of Std facies, showing reactivation surface (white line) and fluid mud (white arrow) separating the cross-stratification. B) The Std facies with mud drapes (black arrow). C) Alternating of Si facies with the Ht facies. D) Detail of interlaminated sandstone and mudstone (Si facies) displaying a rhythmic thick-thin horizontal layer of sand and mud. E) Lenticular, wavy, and flaser bedding structures of Ht facies. The cross-laminae are mostly mud draped. F) Rare combined-flow ripples of Ht facies. G) Organic-rich mudstones of FmC facies with centimeter bed of coal (white arrow) overlaying the massive to laminated mudstone and siltstone (Fmb facies). H) Thick bed of massive to laminated mudstone and siltstone of the Fmb facies. I) Horizontal lamination of sandstone with wave ripple (Slw facies).

Interpretation:

The migration of 2D- and 3D-bedforms within channels produced the cross-bedded sandstone (Allen, 1963). A reactivation surface is a minor erosion surface within the cross-strata, produced by erosion of part of a bedform when the current is reversed (Dalrymple, 1992; Nichols, 2009). The mud drapes within the cross-stratification are formed during slack water stages in the tidal cycle (Nichols, 2009). The centimeter-thick mud layers found between the coset of cross-bedded strata are interpreted as fluid mud deposits that commonly occurred in the conditions of mixed saline and freshwater (Ichaso & Dalrymple, 2009; Li *et al.*, 2018). The less common opposite dipping foresets suggest a predominantly current flowing in one direction for a period of time, followed by a change in another period of opposite flow. Therefore, the Std facies is interpreted as a tidal channel deposit. The alternation of flat laminated sandstone and mudstone (facies Si) is interpreted as tidal bedding that is produced by cyclic conditions as one of several types of rhythmites (Davis, 2012). The currents during the flood or ebb tide move deposits the sand while the mud is accumulated as suspended sediment during slack water condition (Davis, 2012). The Si facies is interpreted as an intertidal flat deposit with the occasional mud draped asymmetric ripples are deposited in the very shallow subtidal environment.

The heterolithic bedding with lenticular, wavy, and flaser structures is also deposited by the combination of relatively high and relatively low energy conditions (Reineck & Singh, 1973; Davis, 2012). The common presence of mud drapes in the cross-laminae and the occasional presence of oppositely dipping foresets suggest a deposition controlled by the tidal process. The rare occurrence of combined-flow ripples suggests a minor wave influence into the successions. As with the Si facies, the Ht facies is also interpreted as an intertidal flat deposit. The associated organic-rich mudstones layer with thin coals bed (FmC facies) are assigned as the supratidal/marsh deposit in the margin of the tide-dominated depositional environment.

The above tidal deposits (the Std, Si, Ht, and FmC facies) are associated with the Fmb and Slw facies. The massive to laminated mudstone and siltstone (Fmb facies) are interpreted as a lagoon deposit. This facies was deposited in a back-barrier low-energy condition where the deposition consists mainly of fine-grained sediments (Boggs, 2006). The intensely bioturbated layers indicate a relatively lagoonal calm hydraulic conditions (Nishikawa & Ito, 2000). The intercalation of the thin bed of rippled sandstone suggests a shallow water environment (Murakoshi & Masuda, 1992). The organic material occurring locally abundant within carbonaceous mudstone might have originated from the vegetation along the shores of the lagoon (Nichols, 2009). The well-sorted, horizontal to wavy stratification fine-grained sandstone (Slw facies) is attributed to the washover deposit. This facies is formed when high wave activity during storm surges overwash the sand into the back-barrier lagoon (Boggs, 2006). Convoluted laminae is interpreted as resulted from the dewatering of rapidly deposited loose sand (Murakoshi & Masuda, 1992). As a summary, FA2 with a close association of tidal channel, tidal flat, marsh, lagoon, and washover deposits is suggested as sediment accumulation in a central basin of an estuary with the mixed-energy regime.

C) Wave-dominated facies association (FA3)

The total thickness of this depositional unit is up to 18.5 m. It was observed at the MF03, MF05, and MF06 sites (Figures 2C & 5). This FA consists of five lithofacies, which shows coarsening upward successions. The facies included in this association are Cross-bedded sandstone (Sc), Hummocky and swaley cross-bedded sandstone (Shsc), Horizontally bedded sandstone (Shb), Interbedded sandstone and mudstone (Flsm), and Laminated mudstone and siltstone with thin sandstone bed (Fmss).

Facies 13, Cross-bedded sandstone (Sc):

This facies is characterized by composite sets of planar or trough cross-bedded, well-sorted medium-grained sandstone. In places, the cross-bedding has a high-angle foreset (more than 20°). The cross-bedding set thicknesses range from 20 to 50 cm. The contact of this facies and overlying Shsc facies (F14) is sharp. The total thickness of this facies is 3.5 m and is only found at the MF06 site.

Facies 14, Hummocky and swaley cross-bedded sandstone (Shsc):

The Shsc facies consists of well-sorted fine-grained sandstone displaying hummocky and swaley cross-stratification. Undulating sets of cross-laminae with both convex-up (hummocks) and concave-up (swales) are present. The cross-sets thickness is between 15 - 35 cm. The beds have a sharp base. This facies thickness is 2 - 3 m and is found together with Shb facies (horizontally bedded sandstone).

Facies 15, Horizontally bedded sandstone (Shb):

This facies is assigned to units of planar parallel stratification that occurred between the Shsc facies. The sandstones are fine grain size, well-sorted, with sharp basal contact. The Shb facies ranges between 50 cm and 1.5 m in thickness, with cm-thick beds.

Facies 16, Interbedded sandstone and mudstone (Flsm):

This facies is composed of interbedded very fine-grained sandstone and mudstone. The sandstones are well-sorted, and the beds are sharp-based. The sandstone beds are ranging from 10 to 20 cm in thickness, while the mudstone beds thickness varies from 3 to 20 cm. The intercalated sandstones are commonly parallel bedded with rare hummocky cross-stratified. The thickness of this facies at the MF06 site is 1.25 m.

Facies 17, Laminated mudstone and siltstone with thin sandstone bed (Fmss):

The Fmss facies consists of mm thick mudstone and siltstone displaying parallel lamination. Locally, thin cm thick of very fine-grained sandstone is found in the thick mudstone/siltstone interval. The total thickness of this facies is ranging from 2.1 to 6 m. At the MF06 site, this facies is overlain by the Flsm facies.

Interpretation:

The Sc facies is interpreted to be formed by migration of 2D and 3D dunes in response to fairweather longshore and onshore currents in an upper shoreface environment (Walker & Plint, 1992; Clifton, 2006). The hummocky and swaley cross-bedded sandstone (Shsc facies) are thought to be characteristic of storm conditions in the lower shoreface environment (Walker & Plint, 1992; Nishikawa & Ito, 2000). The Shsc facies is interpreted to form by dominant oscillatory current during storm events due to strong waves (Harms *et al.*, 1975; Dumas & Arnott, 2006). The Shb facies with planar stratification (quasi-planar-laminae) is interpreted as a high energy combined flow deposits, formed during the storm event (Arnott, 1993; Nishikawa & Ito, 2000). The Flsm facies is assigned as a lower shoreface to offshore transition deposit. It is deposited between mean fairweather wave base and mean storm wave base as a storm-generated sand sheet (Hamblin & Walker, 1979; Murakoshi & Masuda, 1992). The laminated mudstone and siltstone (Fmss facies) are interpreted as offshore deposit, accumulated in the area below storm wave base where mudstone and siltstone deposition predominant. The thin, very fine-grain sandstone interbedded with the mudstone/siltstone is represented the exceptional storms that have some effect in the offshore area (Nichols, 2009).

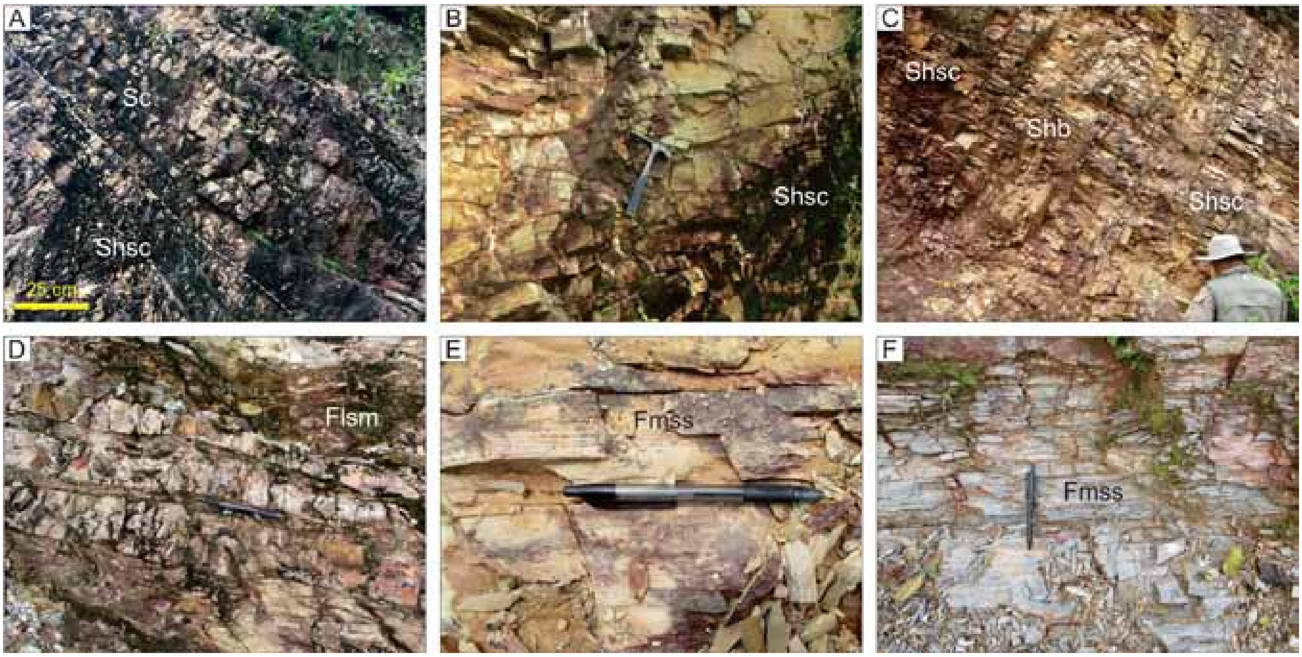

Figure 5: Field photographs of the sedimentary facies in the wave-dominated facies association. A) The cross-bedded sandstone facies (Sc) overlaying the Shsc facies. B) Detail of the hummocky and swaley cross-bedded sandstone facies (Shsc). C) Alternating of Shsc facies with Shb facies (horizontally bedded sandstone). D) Interbedded of sandstone and mudstone of the Flsm facies. E & F) Laminated mudstone and siltstone of the Fmss facies.

In summary, FA3 deposits are interpreted to have developed in a wave-dominated shoreface setting which characterized by the coarsening-upward successions that begin with laminated mudstone and siltstone bioturbated (Fmss facies) and pass upward into cross-bedded sandstone (Sc facies) (Walker & Plint, 1992; Clifton, 2006; Plint, 2010). The presence of hummocky and swaley cross-beds support the wave domination in the environment of deposition (Boggs, 2006; Nichols, 2009).

Palynology

Two of nine samples (MF02B and MF02C) contain moderate palynomorphs (more than 90 grains) while the rest are lack of fossils (less than 40 grains) (Figure 6). The poor productivity from most of the samples is attributed to the subsequently oxidizing conditions of the depositional environments, which are often exposed to the surface (e.g., floodplain and marsh). Generally, palynomorph preservation is good, allowing identification of some essential morphological features. The overall diversity of the palynomorph is low. Twenty-one pollen and spore palynomorphs type are identified, sixteen of which are pollen grains, five are spores, and the rest of the grains are freshwater algae, diatom, fungal spore, and testate amoebae. Three groups of pollen (mangrove, back mangrove, and freshwater species) are distinguished based on Hillen (1986) and Morley (1990). Mangrove taxa are the species that are more or less tolerant of salt or brackish water, while the back mangrove taxa are the plant with a limited tolerance to the salt or brackish water (Hillen, 1986). Furthermore, the freshwater species is comprised of all of the rest identified pollen type. Selected palynomorphs are illustrated in Figures 7 and 8.

Age of the sediments

Previous workers have assigned the age of the Meluhu Formation in southeastern Sulawesi as Middle to Late Triassic (Rusmana *et al*., 1993; Simandjuntak *et al*., 1993; Surono, 1994; Surono & Bachri, 2002). From bottom to top of its stratigraphic position, the Meluhu Formation is arranged by Toronipa, Watutaluboto, and Tuetue Members as a conformable continuous sequence (Surono, 1994, 1997). The Toronipa and Watutaluboto Members contain no fossils for age indicators (Surono, 1994). The Triassic age determination for the Meluhu Formation was based on the presence of bivalves (*Halobia* sp. and *Daonella* sp.) and ammonites (*Preflorianites* sp. and *Tropites* sp.) in the youngest rock member, the Tuetue Member (Rusmana *et al*., 1993; Surono, 1994). The presence of saccate pollen (mostly *Falcisporites* spp.) from the palynological examination of a sample of the Tuetue Member supports the Triassic age interpretation (Surono, 1994). Noteworthy, palynomorphs of this sample are extremely sparse, mostly thin, and highly corroded (Surono, 1994). In addition, detrital zircon U-Pb dating of Meluhu Formation by Ferdian *et al*. (2012) resulted that this rock unit is not older than Late Triassic.

The present palynological analysis of this formation suggests a Middle to Late Miocene age based on the occurrence of the *Florschuetzia* group pollens (Figure 6 & 7). The genus *Florschuetzia* lineage has been widely used for dating Miocene sediments throughout the southeast Asian region (Germeraad *et al*., 1968; Morley, 1977, 1991; Rahardjo *et al*., 1994; Yakzan *et al*., 1996; Lelono, 2007; Mao & Foong, 2013; van Gorsel *et al*., 2014). We interpret that the Triassic fossils found by the previous worker are most probably reworked fossils, as suggested by the thin, highly corroded, and extremely sparse of the palynomorphs (Surono, 1994).

The presence of important marker species such as *Florschuetzia trilobata*, *F. levipoli*, and *F. meridionalis* in samples MF02B and MF04C indicate an age of Middle to Late Miocene, comparable to the *F. meridionalis* Zone of Lelono (2007). This zone is corresponding to the N11 - 18 of Blow (1969) planktonic foraminifera zonation (Lelono, 2007) or 13.82 - 5.33 Ma (Morley *et al*., 2016). The absence of *Stenochlaena milnei* group straightens the relative age of the sediments into 13.82 - 7.5 Ma (Morley *et al*., 2016). The absence of *Dacrycarpus imbricatus* and *Phyllocladus* support the age interpretation that not younger than Late Miocene (Morley, 2002). The co-occurrence of *Acacia*, Dipterocarpaceae, *Lagerstroemia*, Myrtaceae pollen, Poaceae pollen, *Podocarpus*, *Polypodiidites*, and Rhizophoraceae type indicates the Tertiary age interpretation for the analyzed samples (Germeraad *et al*., 1968; Morley, 1977, 2003, 2018).

Depositional model

The discontinuous nature between the outcrop sites in the study area complicates the depositional model reconstruction of the Middle to Late Miocene deposits. However, based on the three facies associations recognized in the studied area, a wave-dominated estuary depositional model is proposed (Figure 9; Heap *et al*., 2001). An estuary is a depositional setting where interaction between the river and marine (wave and/or tide) processes occurred (Dalrymple *et al*., 1992). The high frequency of fining upward channelized deposits of FA1 indicate the river process. The presence of freshwater palynomorph taxa without the occurrence of mangrove and back mangrove taxa in samples of FA1 supports the river deposit interpretation. The occurrence of mud drapes in a cross bed and tidal rhythmites of FA2 is diagnostic tidal sedimentary structures (Boyd *et al*., 2006). The co-occurrence of mangrove, back mangrove, and freshwater species in samples of the lagoon and tidal flat facies of FA2 suggests an environment with mixed of the river and marine processes. The presence of hummocky and swaley cross-stratification in FA3 suggests the domination of the wave process (Clifton, 2006). Thus, the three FA observed in the study area are thought of as representing the three dominating depositional processes in an estuary that are river-dominated, mixed-energy, and wave-dominated.

Furthermore, the proposed depositional model can be divided into three zones: 1) an inner zone, river-dominated zone (FA1); 2) the mixed-energy central zone, a relatively low-energy area wherein the long term tidal currents are approximately balanced by river currents (FA2); and 3) an outer zone dominated by waves processes (FA3) (Dalrymple *et al*., 1992; Boyd *et al*., 2006; Dalrymple, 2010). The tripartite distribution of lithofacies, coarse - fine - coarse (FA1 - FA2 - FA3), is the indication of a wave-dominated estuaries depositional setting (Rahmani, 1988; Dalrymple *et al*., 1992).

Palynological data shows a mixture of regional and local vegetation components in the estuarine deposits. The regional background vegetation was the wind-pollinated montane rain forest of *Podocarpus*. This indicates an establishment of mountainous topography in southeast arm of Sulawesi at Middle to Late Miocene as suggested by Morley *et al*. (2016) and Nugraha & Hall (2018). The local flora is mostly represented by mangrove vegetation of Rhizoporaceae, *Florschuetzia meridionalis* (cf. *Sonneratia alba*), and *Avicennia*, which grows along the shores of the lagoon. Van

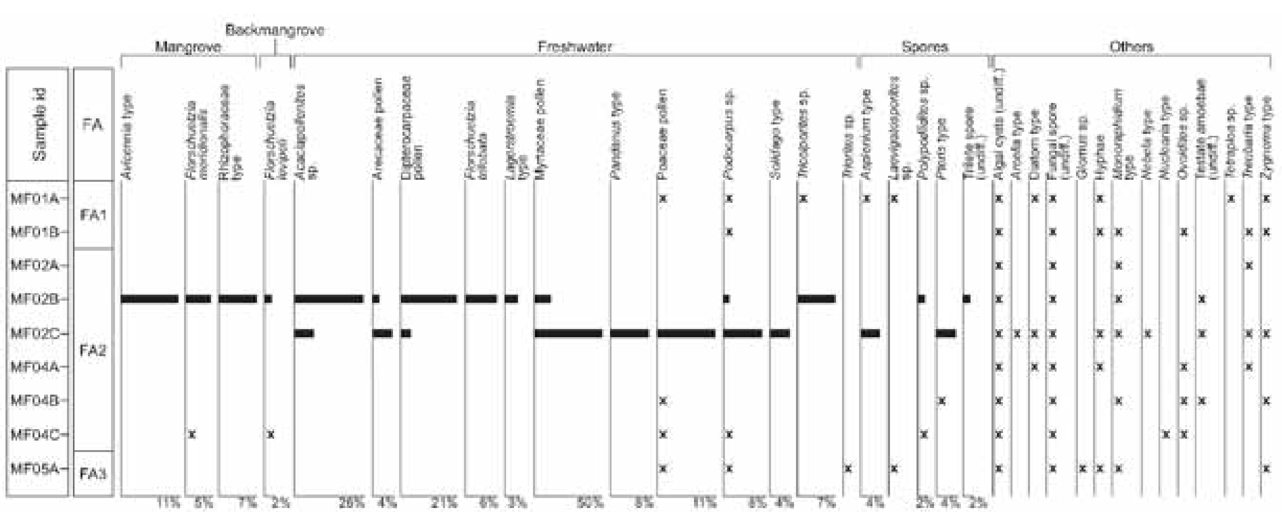

Figure 6: Palynomorph occurrences from the studied sediments of the Toronipa peninsula. The presence of a taxon in samples with less than 40 grains is indicated by "X" mark.

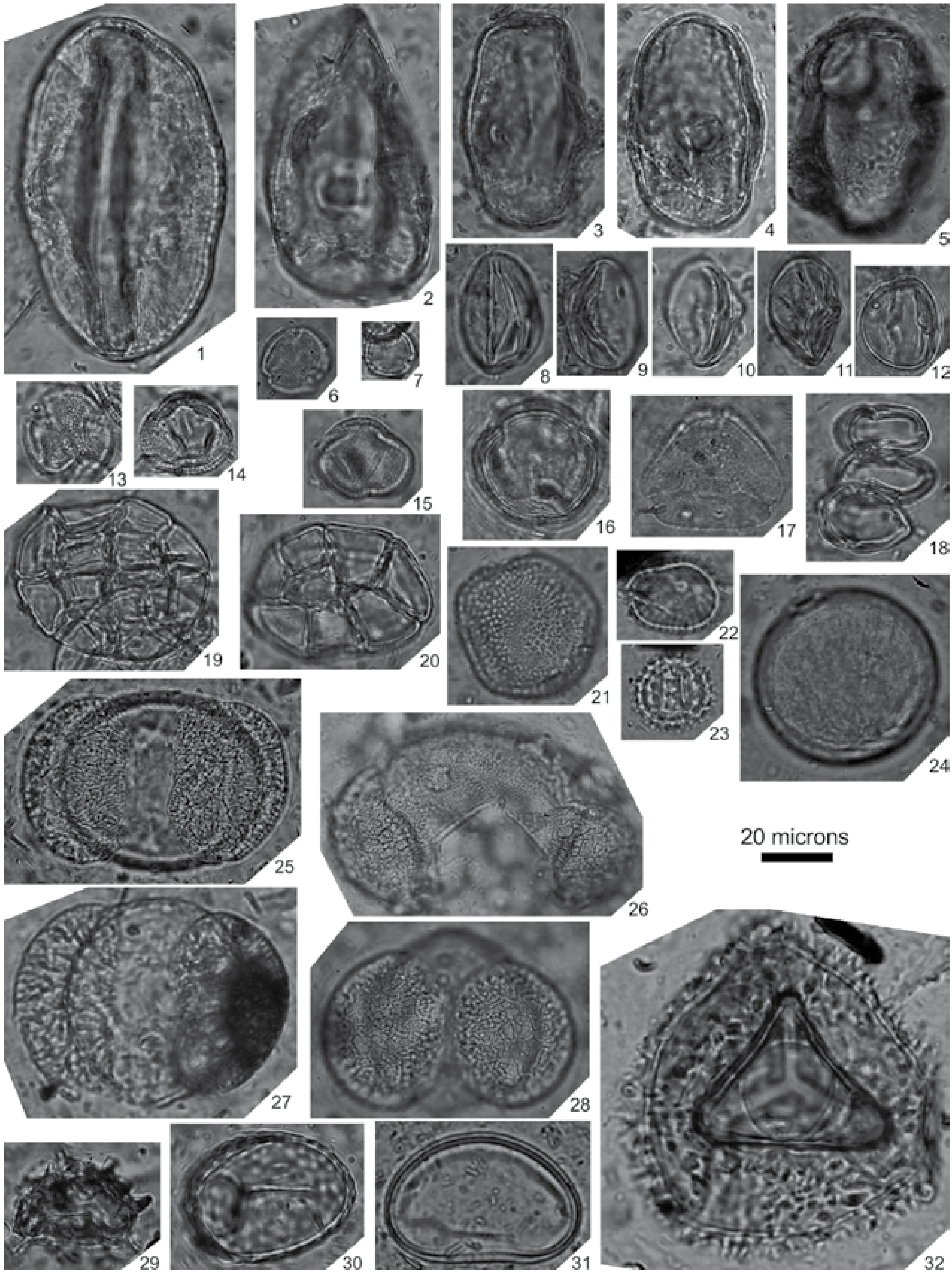

Figure 7: Photomicrograph of selected palynomorphs. 1 & 2) *Florschuetzia meridionalis*. 3 - 5) *Florschuetzia levipoli*. 6 & 7) Rhizophoraceae type. 8 - 11) *Florschuetzia trilobata*. 12) *Lagerstroemia* type. 13 & 14) *Avicennia* type. 15 & 16) Dipterocarpaceae pollen. 17 & 18) Myrtaceae pollen. 19 & 20) *Acaciapollenites* sp. 21) Arecaceae pollen. 22) *Pandanus* type. 23) *Solidago* type. 24) Poaceae pollen. 25 - 28) *Podocarpus* sp. 29) *Asplenium* type. 30) *Polypodiidites* sp. 31) *Laevigatosporites* sp. 32) *Pteris* type.

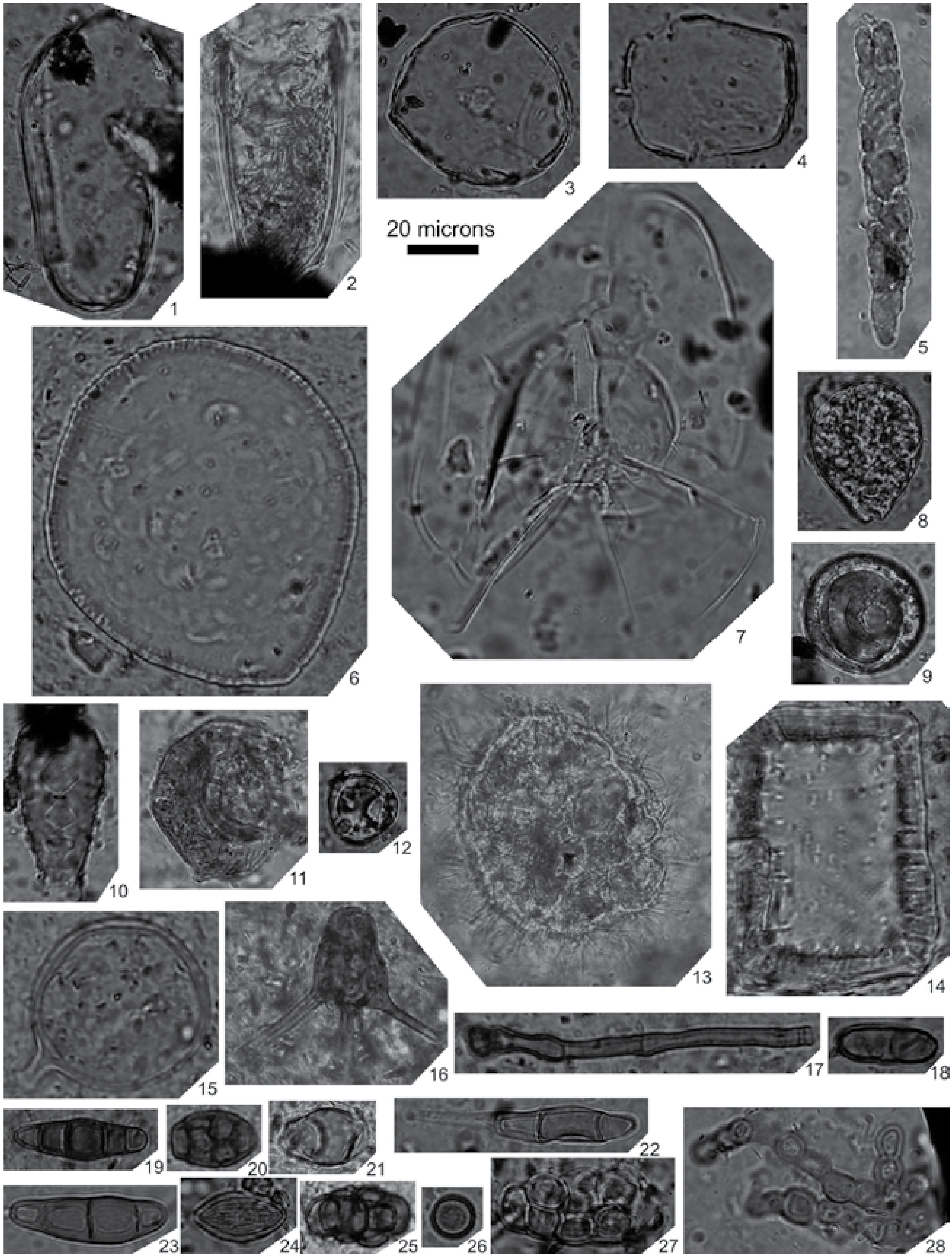

Figure 8: Photomicrograph of selected palynomorphs. 1 & 2) *Ovoidites* sp. 3 & 4) *Zygnema* type. 5) *Monoraphidium* type. 6) Algal cysts (undifferentiated). 7) *Treubaria* type. 8) *Nebela* type. 9) *Arcella* type. 10 - 12) Testate amoebae (undifferentiated). 13) *Nuclearia* type. 14) Diatom type. 15) *Glomus* sp. 16) *Tetraploa* sp. 17) Hyphae. 18 - 28) Fungal spore.

der Kaars (1991) suggested that during the Middle and Late Miocene around the Sulawesi, extensive mangrove vegetation was present. The back mangrove flora, which located on the landslide of a true mangrove, is represented by *Florschuetzia levipoli* (cf. *Sonneratia caseolaris*). The pollen assemblages of the analyzed samples also display a variety of pollen type deriving from plant communities upstream such as lowland forest (Dipterocarpaceae, *Acacia*, *Tricolporites* sp., and *Triorites* sp.), freshwater peat swamp (Myrtaceae, Arecaceae, *Florschuetzia trilobata*, and *Lagerstroemia*) and Riparian fringe (*Pandanus*). The presence of Poaceae and *Solidago* shows a contribution by pollen of grassland vegetation.

The studied section is interpreted as a part of an incised-valley system which consists of an incised valley with fluvial incisions and its estuarine deposit fill. The fluvial incision in the study area is interpreted as promoted by tectonic uplift in response to the collision between the Sula Spur with the north Sulawesi volcanic arc at the Early Miocene (ca. 20 Ma) (Nugraha & Hall, 2018). The Early Miocene sediments are not found in the study area. This fluvial incisions deposit in the southeast Sulawesi is probably represented by the braided river/alluvial fan deposit of the Tolitoli Conglomerate (Surono, 1995; Hall, 2012). This lower Miocene ophiolitic debris conglomerate is the oldest-known 'molasse' sequence of Sulawesi (Hall & Wilson, 2000).

The next tectonic phase in the study area was an extension of the Sula Spur related to the Banda arc subduction rollback, which was initiated at about 16 - 15 Ma (Spakman & Hall, 2010; Hall & Sevastjanova, 2012; Pownall *et al*., 2016). Later, this earliest phase of extension resulted in the opening of the North Banda Sea Basin between 12.5 and 7 Ma (Hinschberger *et al*., 2000, 2003). The Middle Miocene extension event was widespread and linked to both subsidence and uplift of parts of Sulawesi (Nugraha & Hall, 2018).

In the study area, this Middle Miocene extension event is interpreted resulted in the subsidence of the basin, which continued until the Late Miocene. During the subsidence, the base-level rise and the incised-valleys turned into an estuarine environment. The sediment of FA1 and FA2 was deposited as the estuarine deposit fill, and the shoreface deposit of FA3 is interpreted to be accumulated following the highstand stage. The changes from estuarine to shoreface deposits in the study area suggest a deepening upward succession related to Middle to Late Miocene subsidence of the basin. 1.175 feet of a deepening upward succession from inner sublittoral - deltaic to outer sublittoral sediments aged Middle to Late Miocene is reported from Abuki-1 well (Satterlee *et al*., 1990). Continuous subsidence during Middle and Late Miocene was also found in Buton island as indicated by a deepening succession from sublittoral to upper bathyal deposits (Fortuin *et al*., 1990; Smith & Silver, 1991; Nugraha & Hall, 2018).

The implication for hydrocarbon potential in the Manui Basin

The Middle to Late Miocene transgressive sequence discovered in Abuki-1 is the primary reservoir objective and source rock potential in the Manui Basin (Satterlee *et al*., 1990). The porosity of the sandstone in this well ranges from 26 - 30%, and the mudstone has a high TOC value ranging from 1.06 to 3.74% (Satterlee *et al*., 1990). This unit has no outcrop analog in the nearby onshore area of the Toronipa peninsula, as the nearby coastal rocks exposure has been suggested as Triassic in age. Meanwhile, the present study is the first to identify the presence of Middle to Late Miocene sediments in the onshore area of southeast Sulawesi near the Abuki-1 well. Therefore, it is suggested that the studied sediments are the outcrop analogs for the Middle to Late Miocene transgressive sequence found in Abuki-1 with an estuarine fill depositional setting.

It is recommended that these Miocene estuary-fill complexes should have excellent hydrocarbon potential as indicated by Clifton (1982). The reservoir potential is the sand deposits of the fluvial, tidal, washover, and shoreface facies with moderately to well-sorted characteristics. The mud of lagoon, tidal flat, floodplain, and marine

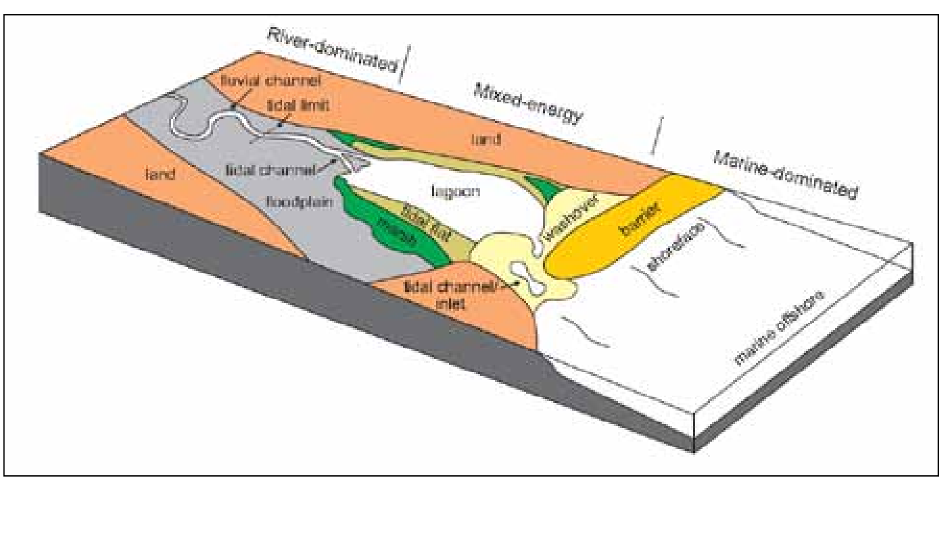

Figure 9: The proposed wave-dominated estuary depositional model for the Middle to Late Miocene transgressive sequence of the Toronipa peninsula sediments. Modified from Heap *et al*. (2001).

offshore facies is the source rocks candidate. The estuary is one of the most biologically productive sedimentary environments (Clifton, 1982). The potential structural traps are the anticlinal nose associated with the Lawanopo fault (Satterlee *et al*., 1990). The likely stratigraphic traps are the intercalation of sand and mud facies in the estuary-fill complexes that provide impermeable barriers (Clifton, 1982). The seal also acting as the burial sediments is represented by the Pliocene and Pleistocene sediments (Satterlee *et al*., 1990). In addition, the onshore SE Sulawesi is characterized by the common presence of oil and gas seepages (Satterlee *et al*., 1990; Davidson, 1991; Satyana, 2017). Having the above situation, it is strongly recommended to study the Miocene estuary-fill deposits appearing in the study area in order to reveal its hydrocarbon accumulation potential.

CONCLUSION

The sedimentary rocks outcrop in the Toronipa peninsula is Middle to Late Miocene in age based on the occurrence of the *Florschuetzia* group pollens (*Florschuetzia trilobata*, *F. levipoli*, and *F. meridionalis*). A wave-dominated estuary is proposed for the depositional environment of this unit, as proved by the occurrence of river-dominated, mixed-energy, and wave-dominated facies associations. This Middle to Late Miocene sediments is interpreted to be deposited at the early extension phase of the Sula Spur related to the Banda arc subduction rollback. Furthermore, it is predicted that this Miocene estuary-fill complexes of the Manui Basin shall contain excellent hydrocarbon potential as suggested by the presence of numerous sand facies, organic-rich mudstone interval, and oil and gas seepages in onshore SE Sulawesi area.

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