RISET
Geologi dan Pertambangan
Indonesian Journal of Geology and Mining
https://jrisetgeotam.lipi.go.id

Research article

Ichnofossils characteristics in the pelagic and siliciclastic carbonate turbidites of Weda Formation, Halmahera Island

Angga Jati Widiatama[1,3], Lauti Dwita Santy[2], Aries Kusworo[2]

[1] Department of Geological Engineering, Sumatra Institute of Technology, Jl. Terusan Ryacudu, Way Huwi, Kec. Jati Agung, Kabupaten Lampung Selatan, Lampung
[2] Center for Geological Survey, Geological Agency. Jl. Diponegoro No.57 Bandung
[3] Center for Research and Innovation of Earth and Mineral Technology, ITERA, Jl. Terusan Ryacudu, Way Huwi, Kec. Jati Agung, Kabupaten Lampung Selatan, Lampung

Riset Geologi dan Pertambangan
Indonesian Journal of Geology and Mining
Vol.32, No 1 pages 59–70

doi:
10.14203/risetgeotam2022.v32.1147

Keywords:
Ichnofossil,
Turbidite,
Weda Formation,
Halmahera

Corresponding author:
Angga Jati Widiatama
E-mail address: angga.widiatama@gl.itera.ac.id

Article history
Received: 29 January 2021
Revised: 13 November 2021
Accepted: 4 April 2022

ABSTRACT The Weda Formation in Lili River, Dorosagu, East Halmahera consists of siliciclastic and pelagic carbonates deposited in a submarine fan environment. Research on the Weda Formation in the northern part of Halmahera Island is relatively sparse because most of research about Weda formation has been carried out in the southern part of Halmahera Island. The lack of road access and remote location have implication in the lack of intensive research on this formation. This study aims to determine the relationship between the intensity and diversity of ichnofossils in the submarine fan facies association of the Weda Formation. Sedimentological studies include sedimentary texture, sedimentary structure, turbidite material type, and layer thickness. While the study of ichnofossils includes the identification of ichnofossil, classification of behavior, intensity, diversity in sedimentary layers, and the factors that influence them during deposition. There are eight types of ichnofossil observed in the Lili River, *Ophiomorpha, Thalassinoides, Rhizocorallium, Palaeophycus, Zoophycos, Chondrites, Lorenzinia,* and *Spirorhaphe*, which are found in three facies associations (FA): submarine fan channel facies association (FA1), submarine fan lobe facies association (FA2), and submarine fan distal facies association (FA3). The submarine fan channel facies characterized by the presence of *Ophiomorpha* and *Thalassinoides* in low intensity and low diversity due to unstable environmental conditions-high stress due to intensive turbidite currents. The submarine fan lobe facies show a higher density and diversity where ichnofossil is classified into two based on the substrate in the flysch deposits. *Rhizocorallium, Thalassinoides,* and *Palaeophycus* ichnofossil were formed in the sand substrate, while *Zoophycos* and *Chondrites* ichnofossil were formed in the shale substrate. *Palaeophycus, Zoophycos, Chondrites, Lorenzinia,* and *Spirorhaphe* ichnofossil were found in the submarine fan distal facies associated with high intensity indicating low energy and low sedimentation rates.

INTRODUCTION

Study of ichnofossils provides detailed information on the environmental parameters associated with the depositional processes. This study can be applied as a basis for facies analysis in turbidite deposits (Seilacher, 1977; 2007; Frey, 1990; Bromley, 1996; Heard and Pickering, 2008; Monaco et al., 2010; Cummings and Hodgson, 2011; Bayet-Goll et al., 2014). The study of ichnofossils used to analyze sediment conditions during deposition by analyzing the characteristics of ichnofossils, the character of turbidite deposits, and their relationship to nutrient and oxygen supply (Savary, 2004).

Integrated ichnofossil and sedimentological study is a powerful method in interpreting depositional environment (Bayet-Goll et al., 2015). Research on ichnofossils and fabrication has been studied by several researchers in Indonesia: Arifullah et al. (2015), Arifullah et al. (2016), Zonneveld et al. (2017), Rudyawan and Oo (2018), Arifullah and Zaim (2019), and Zonneveld et al. (2019). Theses studies mainly carried out in transitional environment. While research on ichnofossils in turbidite deposits is still limited (i.e Pratama, 2019).

Abundance high variation of ichnofossils are found in pelagic limestones and fine sandstones part of turbidite clastic deposits of the Weda Formation in the northern Dorosagu (Kusworo et al., 2013). However, this study did not explain the relationship between ichnofossil facies and sedimentary rock facies associations with their fossil characteristics.

The Weda Formation has been studied mainly in southern part of Halmahera Island, whereas that in the northern area was poorly studied (Supriatna, 1980, Nichols and Hall, 1991; Wicaksono et al., 2012). The aim of the study is to determine the intensity of ichnofossils in submarine fan facies of the Miocene Weda Formation based on outcrops in the North of Halmahera Island.

Good exposure of outcrops makes it possible to observe the characters of sediments and ichnofossils formation. Sedimentological studies include grain size texture, sediment structure, turbidite material type, and layer thickness. While ichnofossils studes include the identification of types and behavior classification of the ichnofossils, their intensity in the sediment layer, and other factors that control the deposition of turbidites.

REGIONAL GEOLOGY

Weda Formation consists of alternating sandstones and siltstones, marl, limestones, and conglomerate, which contains pyroxene andesite, serpentinite, and gabbro within the sandstone matrix. The sandstones consist of arkose sandstone, conglomeratic sandstone, and greywacke sandstone. While claystone consists of greenish claystone containing gastropods, bivalves, coral, resin, and coal; silty claystone, and sandy limestone (Supriatna, 1980). Weda Group consists of several members that includes Superak conglomerate, Akelamo limestones, Dufuk sandstone-claystones, and Gola marls (Nichols and Hall, 1991). While the Saolat marl is also included in this formation (Hall et al., 1988). The thickness of the formation is more than 650 meters (Supriatna, 1980), but Nichols and Hall (1991) interpreted the thickness as up to 3000 meters. The Weda Formation is of Middle Miocene to Pliocene age. These rocks spread out widely in the eastern part of Halmahera Island, from Weda Bay in the southern part of Halmahera Island to Morotai Island in the north (Figure 1).

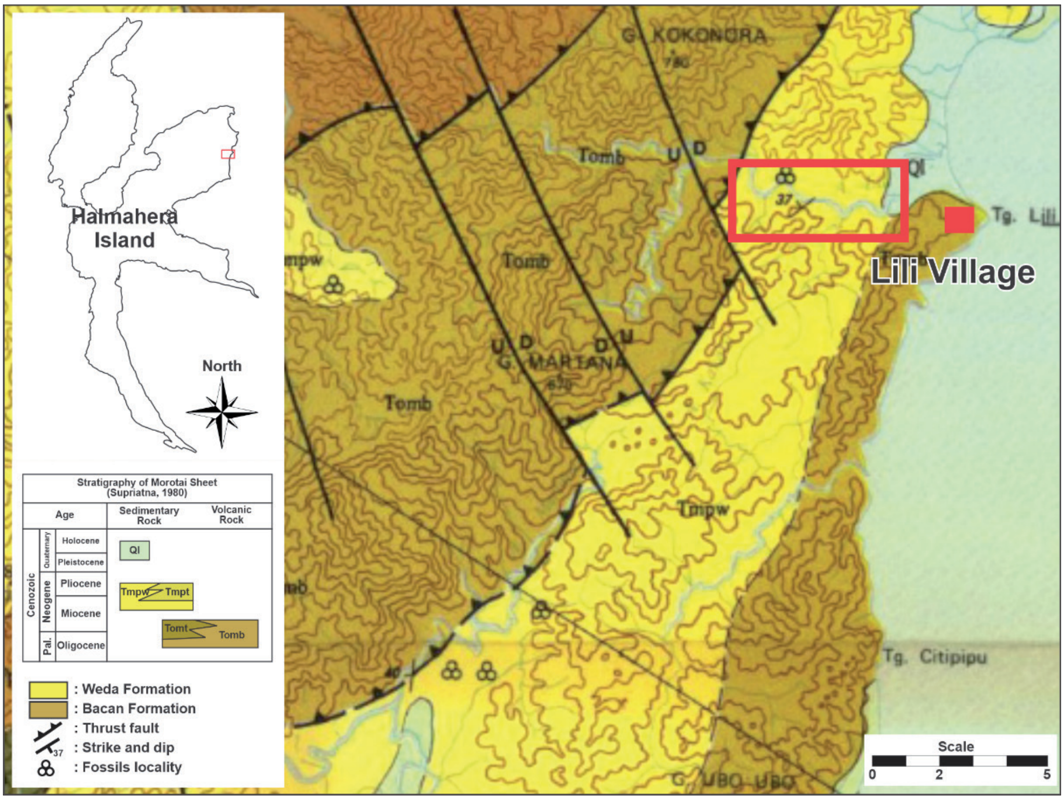

Figure 1. Geological map of Morotai sheet (Supriatna, 1980).

METHOD

The studied area is located in Lili River, Lili Village, Dorosagu District, East Halmahera Regency. The river expose sedimentary rocks with an abundant variety of ichnofossils. One single traverse containing the best outcrop was selected and it has eight representative observation points (Figure 2). The research method includes facies analysis to classify them in facies associations using measured stratigraphic sections to describe the stacking pattern sequences, rock types, grain sizes, and sedimentary structures. Identification of ichnofossils was carried out with the guidance of ichnofossils atlas (IRG, 1998) and the division of ichnofossil facies according to Pemberton et al. (1992) and MacEachern et al. (2010). The intensity of ichnofossil excavation was evaluated in each rock layer according to the bioturbation index scale proposed by Bann et al. (2008) which consists of seven intensity classes, namely: d=0 (absent), d=1 (sparse), d=2 (uncommon); d=3 (moderate); d=4 (common); d=5 (abundant), d=6 (complete). The research area can be reached by sea by wooden boat from Bula to Tanjung Lili for 4 hours long trip. The traverse location is 3 km from Tanjung Lili Harbor to the west.

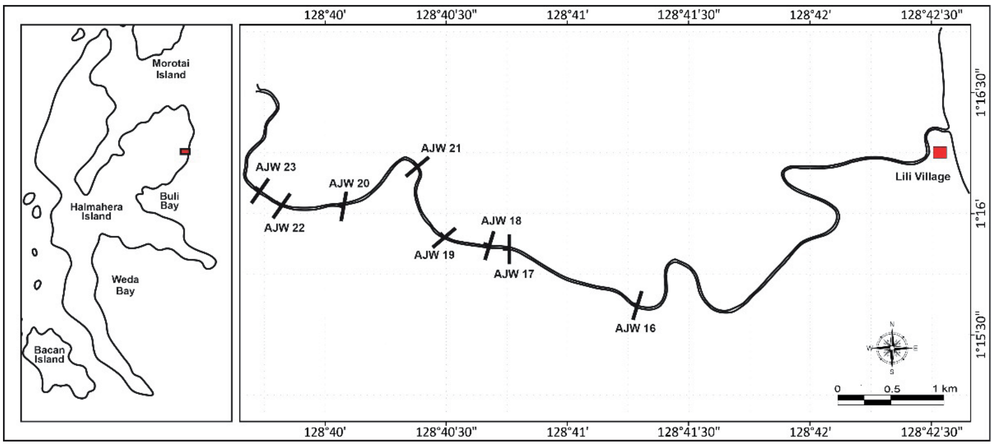

Figure 2. Traverse map of the studied area.

SEDIMENTOLOGY

The measured thickness of the Weda Formation in Lili River is 58 meters and can be differentiated into seven facies (Figure 3), namely: conglomeratic sandstone facies (F1), coarse sandstone facies (F2), medium sandstone facies (F3), fine sandstone facies (F4), claystone facies (F5), wackestone facies (F6), and mudstone facies (F7). Based on the stacking pattern of the Weda Formation facies in the Lili River traverse, it can be classified into three sedimentary facies associations (FA), namely submarine fan channel facies association (FA1), submarine fan lobe facies association (FA2), and submarine fan distal facies association (FA3).

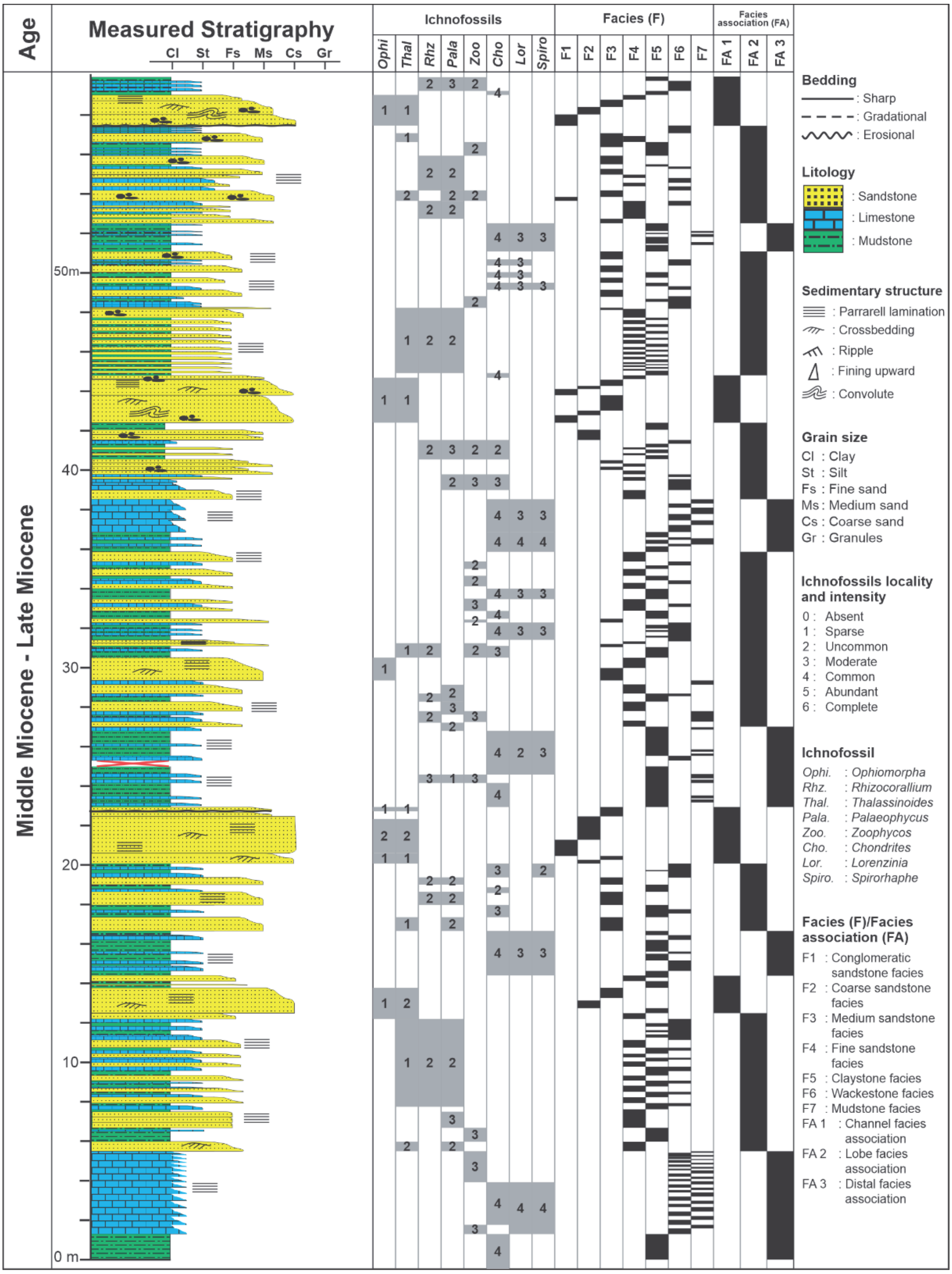

Figure 3. The measured stratigraphy coloumn of Weda Formation in Lili River.

Facies association 1 (FA1) submarine fan channel

This facies association is composed of coarse sandstone facies, medium sandstone facies, fine sandstone facies (Figure 4a), conglomeratic sandstone facies found locally (Figure 4b) with fragments of metamorphic rock (serpentinite), igneous rock (andesite and basalt), coral fragments, and mollusca shells (4g, 4h, and 4i images). The conglomeratic sandstone form channel geometry with sedimentary structures such as parallel lamination, convolute (Figure 4c), cross lamination (Figure 4d), and the layers are gradually fining upwards. Organic material in the form of broken tree trunks with a size of 2-6 cm is present with moderate to very abundant intensity. Bouma sequence (1962) was found to be incomplete, including; Tab, Tabc, and Tabcd in the channel submarine fan facies association. Ichnofossils in the channel submarine fan facies association are found in sand-sized sediment with low-intensity. Ichnofossils of *Ophiomorpha* and *Thalassinoides* with an intensity of 1-2 found in medium sandstone layer while the fine sandstone (part of Td of the Bouma sequence) shows an abundance of *Chondrites* with an intensity of 4.

Facies association 2 (FA2) submarine fan lobe

The submarine fan lobe facies association is composed by fine sandstone, medium sandstone, and wackestone limestone facies with sedimentary structures such as parallel lamination, parallel bedding, slump, flame, dish structure (Figure 4e), and ripple. The sandstone layer ranges from 5-12 cm thick with predominantly composed by plagioclase minerals, rock fragments, reworked foraminifera and mud as matrix (Figure 4j), while the wackestone limestone layer (Figure 4f) ranges from 8-15 cm with predominant bioclastic components of planktonic foraminifera. Incomplete Bouma sequence (Tbcd, Tcd, and Tcd) was found in this facies association. Ichnofossils in the submarine fan lobe facies association are found in sand-sized sediment with medium-intensity. The ichnofossils of *Rhizocorallium*, *Thalassinoides*, *Palaeophycus*, and *Zoophycos* have been found with an intensity of 3. The wackestone layer shows an abundance of ichnofossils of *Zoophycos* and *Chondrites* with an intensity of 3.

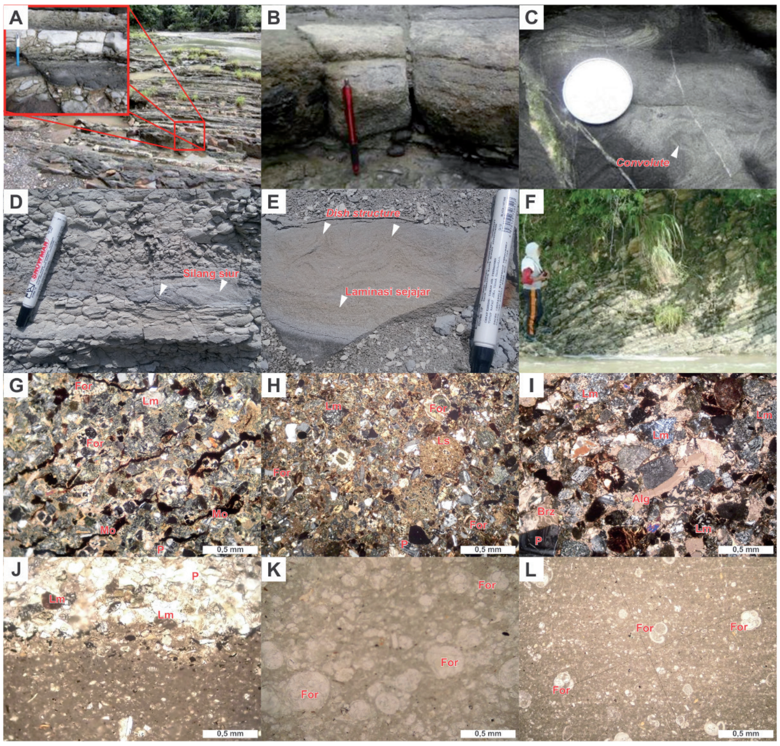

Figure 4. (a) Interbedded sandstone and wackestone, (b) conglomeratic sandstone layers, (c) convoluted sandstone, (d) cross-lamination sandstone, (e) parallel lamination of sandstone and dish structure, (f) layered wackestone. Sandstone petrography, Lm=fragments of metamorphic rocks, Ls=fragments of sedimentary rocks, P=Plagioclase, For=Foraminifera, Alg=Algae, Mo=Organic material, (g, h, i) allochemic sandstone, (j) contact between the sandstone and mudstone, (k) foraminifera planktonic wackestone, and (l) foraminifera planktonic mudstone.

Facies association 3 (FA3) distal to the submarine fan

The distal submarine fan facies association is characterized by interbedded of fine sandstone, claystone, wackestone, and mudstone facies with a thickness of ranges from 5-10 cm. The sedimentary structures developed in this facies association include parallel lamination, parallel bedding, and ripple. Fine sandstone consisted of planktonic foraminifera and plagioclase minerals, while the wackestone limestone layer (Figure 4k) consisted of planktonic foraminifera (Figure 4l). The presence of ichnofossils in the distal submarine fan facies association is quite abundant. In the sandstone layer, there are ichnofossils of *Zoophycos*, *Palaeophycus*, *Chondrites*, and *Lorenzinia* with an intensity of 4. The wackestone layer shows an abundance of ichnofossils of *Zoophycos*, *Chondrites*, *Lorenzinia*, and *Spirorhaphe* with an intensity of 4.

ICHNOFOSSIL

There are eight recognizable ichnofossils in the submarine fan facies association of the Weda Formation. Some ichnofossils exist in different depositional environments, but some are locally found in a certain depositional environment. Ichnofossils identified as *Ophiomorpha*, *Thalassinoides*, *Rhizocorallium*, *Palaeophycus*, *Zoophycos*, *Chondrites*, *Lorenzinia*, and *Spirorhaphe*.

Ophiomorpha

It has an irregular tube shape, filled with agglutinated sediment lumps/pellets on its walls, the texture of the stuffing is coarser than the grain size of the rock layers, and the tunnel bulges at the branching section, with the tunnel orientation being vertical and/or horizontal (Figure 5a). *Ophiomorpha* ichnofossils are formed as a result of dwelling or residence traces. *Ophiomorpha* ichnofossils are formed spare to uncommon intensity (BI=1-2). These ichnofossils were found in the amalgamation of the medium-coarse sandstone facies. The presence of these ichnofossils is designated by relatively observable primary sedimentary structures and low diversity of ichnofossils. Based on the trace fossils behavioral classification (Ekdale et al., 1984) *Ophiomorpha* are included in Domichnia which is the domain formation of ichnofossil-forming animals. These ichnofossils were formed in a high-current environment, thus, in a high-energy area (Bromley and Ekadele, 1984). According to Pemberton et al. (1992) and MacEachern et al. (2010), the ichnofossils are abundant from the Jurassic to the Holocene in brackish water to marine shoreface environment and deep marine environment (Crimes et al., 1981).

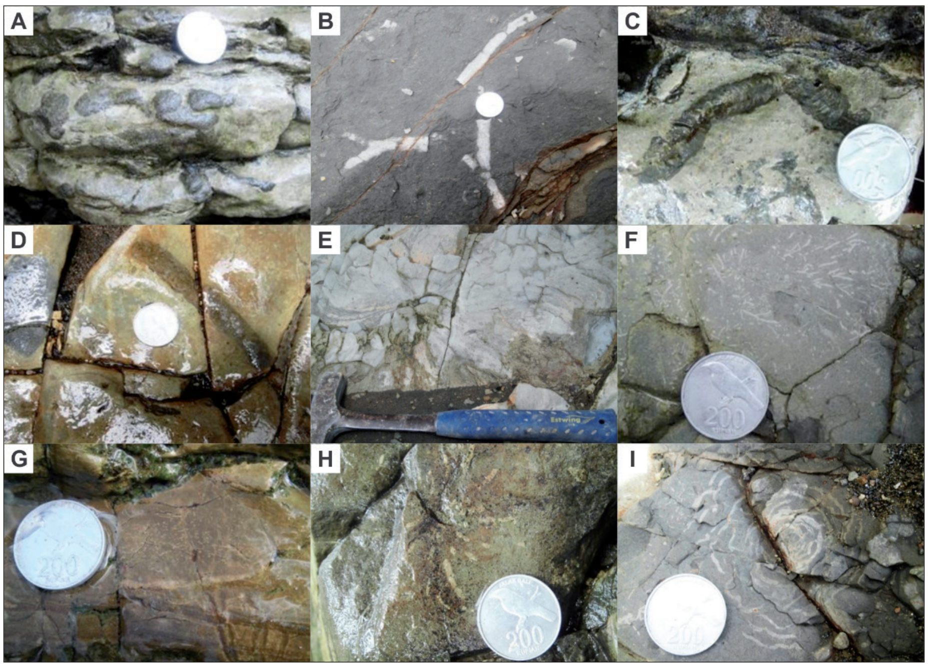

Figure 5. Ichnofossil of Weda Formation in the Lili River section
(a) *Ophiomorpha*, (b) *Thalassinoides*, (c) *Rhizocorallium*, (d) *Palaeophycus*, (e) *Zoophycos*, (f-g) *Chondrites*, (h) *Lorenzinia*, and (i) *Spirorhaphe*.

Thalassinoides

A three-dimensional shape ichnofossil consists of a horizontal cylindrical tunnel, generally branched, and nongrooved (Figure 5b). The diameter of these ichnofossils ranges from 1-3 cm, with a length of ranges from 10-40 cm. The host sediment layer and the ichnofossil filling sediment show different colors and grain sizes which have coarser grains than the host layer. The ichnofossils of *Thalassinoides* formed spare to uncommon intensity (BI=1-2). These ichnofossils are found in the amalgamation of the medium-coarse grained sandstone facies. The existence of these ichnofossils is indicated by relatively observable primary sedimentary structures and the low variety of ichnofossils. Based on the trace fossils behavioral classification (Ekdale et al., 1984), Domichnia is a permanent domain for ichnofossil-forming animals, including suspension eaters, deposit eaters, or even carnivores. These ichnofossils are formed as a result of dwelling and/or feeding traces, and their contents are collected from suspension sedimentation (Frey et al., 1984; IRG, 1998). *Thalassinoides* are interpreted formed in environments with low to high currents (Bromley, 1984). According to Pemberton et al. (1992) and MacEachern et al. (2010), these ichnofossils can be found in the lower shoreface to offshore environments.

Rhizocorallium

It has a curved shape, has two body parts connected by spreiten (excavation groove), and there is a trace filling in the form of material finer than the host rock (Figure 5c). *Rhizocorallium* was formed uncommon to moderate intensity (BI=2-3). These ichnofossils are found in the fine to medium-grained sandstone facies. The presence of *Rhizocorallium* is characterized by spreiten structure. Based on the trace fossils behavioral classification (Ekdale et al., 1984) they are classified as fodinichnia or traces of deposit feeder animals as a result of semi-permanent dwelling and sediment processing for food. These ichnofossils were formed as a result of dwelling traces thought to have been formed by crustaceans (IRG, 1998). The existence of the excavation channel indicates the rapid deposition of sediment in an environment with medium-high currents (Bromley, 1984). These ichnofossils are associated with the *Cruziana* ichnofacies which refer to marine depositional environments (Pemberton et al., 1992; MacEachern et al., 2010).

Palaeophycus

This ichnofossil has an unbranched shape, distinctive tunnel plane, smooth tube walls, cylindrical-shaped, horizontally-diagonally directed. Filled material is similarly to host rock (Fig. 5d). *Palaeophycus* existed uncommon to moderate intensity (BI=2-3). These ichnofossils formed in the fine to medium sandstone facies. The presence of these ichnofossils is characterized by relatively observable primary sedimentary structures and a low-medium variety of ichnofossils. These ichnofossils are formed because of dwelling traces and or can be formed as the result of feeding whose contents are passively accumulated (IRG, 1998). Based on the trace fossils behavioral classification (Ekdale et al., 1984), domichnia is a permanent domain for ichnofossil-forming animals, including suspension eaters, deposit eaters, or even carnivores. *Palaeophycus* ichnofossils are interpreted to have formed in a low sedimentation rate environment (Bromley, 1984; Pamberton et al. 1992). These ichnofossils can be found in terrestrial, transitional, and marine environments (MacEachern et al., 2010).

Zoophycos

Zoophycos has a rounded shape, sheeted, with concentrated spreiten, circle-shaped, and the excavation groove is horizontally oriented parallel to the direction of the excavation (Figure 5e). Trace fossils of *Zoophycos* formed common to abundant intensity (BI=4-5). These ichnofossils were found in the wackestone to fine sandstone facies. The existence of these ichnofossils is characterized by unclear primary sedimentary structures and low-medium diversity of ichnofossils. *Zoophycos* were formed as a result of the feeding and grazing of animals (IRG, 1998). Based on the trace fossils behavioral classification

(Ekdale et al., 1984), they are included in fodinichnia or traces of deposit feeder animals as a result of semi-permanent habitation and sediment processing for food. These ichnofossils are interpreted to have formed in an environment with calm currents, slow sedimentation rates, and moderate energy intensity (Bromley, 1984). These ichnofossils are associated with *Zoophycos* ichnofacies and can be found in marine environments, especially in offshore (Pemberton et al., 1992; MacEachern et al., 2010).

Chondrites

It is a branched root-shaped system with a uniform diameter, nonintersecting, the branches are generally inverted 'Y' shape (Fig. 5f-5g). *Chondrites* are common in wackestone layers. This trace fossil is characterized by the dominance of single colonies which are characterized by common intensity (IB=4). These trace fossils were formed as a result of feeding or foraging traces (IRG, 1998). Based on the trace fossils behavioral classification (Ekdale et al., 1984) they are included in fodinichnia or traces of deposit feeder animals as a result of semi-permanent habitation and sediment processing for food. These ichnofossils are interpreted as formed in an environment with low to moderate energy, produced by living things that can adapt to low oxygen environments (Bromley, 1984). These ichnofossils are associated with the ichnofacies *Cruziana* to *Zoophycos* and can be found in marine environments, especially offshore (Bromley and Ekdale, 1984; Pamberton et al., 1992; MacEachern et al., 2010).

Lorenzinia

It has a star-like shape, radial, centered in the middle, the stuffing is coarser than the host rock, and the complete radial shape has dimensions ranging from 3-6 cm (Figure 5h). *Lorenzinia* was found in the wackestone layer. This ichnofossil is characterized by the dominance of multiple colonies that are marked by moderate to common intensity (IB=3-4). Based on the trace fossils behavioral classification (Ekdale et al., 1984), agrichnia consists of structures with horizontal tunnels arranged in a double spiral regular geometric pattern which is a characteristic feature of environments with fine-grained, pelagic, or hemipelagic deposits. These ichnofossils are interpreted to have been created with low currents and low energy, produced by living creature that can adapt to low oxygen environments (Bromley, 1984). These ichnofossil associated with *Nereites* ichnofacies (Pamberton et al., 1992; MacEachern et al., 2010) and can be found in marine environments, especially offshore (Ekdale, 1984).

Spirorhaphe

It is a horizontally oriented trace fossil, rotating on one axis, a cylindrical tube, filled with coarser material than the host rock, the complete radial form has dimensions ranging from 4-10 cm (Figure 5i). *Spirorhaphe* is found in the wackestone layer. This ichnofossil is signified by the dominance of multiple colonies which are characterized by moderate to common intensity (IB=3-4). These ichnofossils were formed as a result of farming or gardening traces (IRG, 1998). Based on the trace fossils behavioral classification (Ekdale et al., 1984), agrichnia consists of structures with horizontal tunnels arranged in a double spiral regular geometric pattern which is a characteristic feature of environments with fine-grained, pelagic, or hemipelagic deposits. These ichnofossils are interpreted to have been formed by low-energy currents produced by living creature that could adapt to low-oxygen environments (Bromley, 1984). These ichnofossils are associated with *Nereites* ichnofacies (Pamberton et al., 1992; MacEachern et al., 2010) and can be found in marine environments, especially the offshore (Bromley and Ekdale, 1984; Pamberton et al., 1992; MacEachern et al., 2010)

DISCUSSION

Stress conditions relate to the physical and chemical conditions of the submarine fan environment controlled by turbidity currents greatly influence the presence of ichnofossil-forming fauna (Savary, 2004; Cummings and Hodgson, 2011; Bayet-Goll et al., 2014; Callow et al., 2014; Heard et al., 2014; Monaco and Trecci, 2014). Living conditions accompanying faunal existences are controlled by hydrodynamic conditions, oxygen, organic matter content, substrate movement, and sedimentation rate (Cummings and Hodgson, 2011; Bayet-Goll et al., 2014; Callow et al., 2014; Monaco and Trecci, 2014). Therefore, the different facies relationships of the supporting submarine environment will give different responses to the intensity of the ichnofossil-forming fauna.

In the study area, the channel submarine fan facies association showed low ichnofossils occurrence as compared to the lobe and the distal submarine fan facies association of the Weda Formation. This is indicated by the presence of *Ophiomorpha* and *Thalassinoides* with low intensity. The low ichnofossils existences are probably related to unstable environmental conditions. An environment that has high stress due to the intense working turbidite currents (Uchman, 1992; 1998). The behavior of ichnofossil-forming animals is as domichnia that adapts to currents acting on the surface of the substrate (Ekdale et al., 1984) in submarine fan turbidit deposit. Turbidite currents and coarse-grained sediments produce unconsolidated sediment layers thus creating a relatively nutrient-rich top layer of substrate (Callow et al., 2014).

The lobe submarine fan facies association shows higher ichnofossils than the channel submarine fan. The behavior of trace-forming animals in this facies association can be divided into two based on the type of substrate. In the sand substrate, ichnotrace fossil-forming animals are domichnia which forms the ichnofossils of *Rhizocorallium*, *Thalassinoides*, and *Palaeophycus*. This makes up episodes of sandstone formation in flysch deposits which are still controlled by turbidite currents (Uchman, 1992; 1998). Meanwhile, on shale and wackestone substrates, the behavior of ichnofossil-forming animals is classified as fodinichnia which forms *Zoophycos* and *Chondrites* as sedimen accumulated with a low sedimentation rate, allowing the emergence of colonies of living things on the surface of the substrate (Uchman and Wetzel, 2011).

The distal submarien fan facies association showed the highest ichnofossils compared to the channel and lobe facies association. Ichnofossils formed include *Palaeophycus*, *Zoophycos*, *Chondrites*, *Lorenzinia*, and *Spirorhaphe*. The behavior of ichnofossils-forming animals in the distal submarine fan facies association is classified as fodinichnia which has a low energy level and low sedimentation rate (Seilacher, 2007; Uchman and Wetzel, 2011). The increase strengthens the imprint on the distal submarine fan facies association which is thought to be related to the decrease in sedimentation rate, layer thickness, and sediment grain size (Heard and Pickering, 2008; Monaco, 2008; Bayet-Goll et al., 2014; Heard et al., 2014). It is also thought to be influenced by the low erosion rate and the high nutrient content in the fine-grained layer (Heard and Pickering, 2008). The presence of ichnofossils influenced by turbidity currents, distal submarine fan, sediment rich in organic matter, and minimum oxygen condition (Bromley and Ekdale, 1984; Leszczynski, 1991; Wetzel, 1991). The model for the distribution of ichnofossils in pelagic siliciclastic carbonate turbidites of weda formation shown in Figure 6.

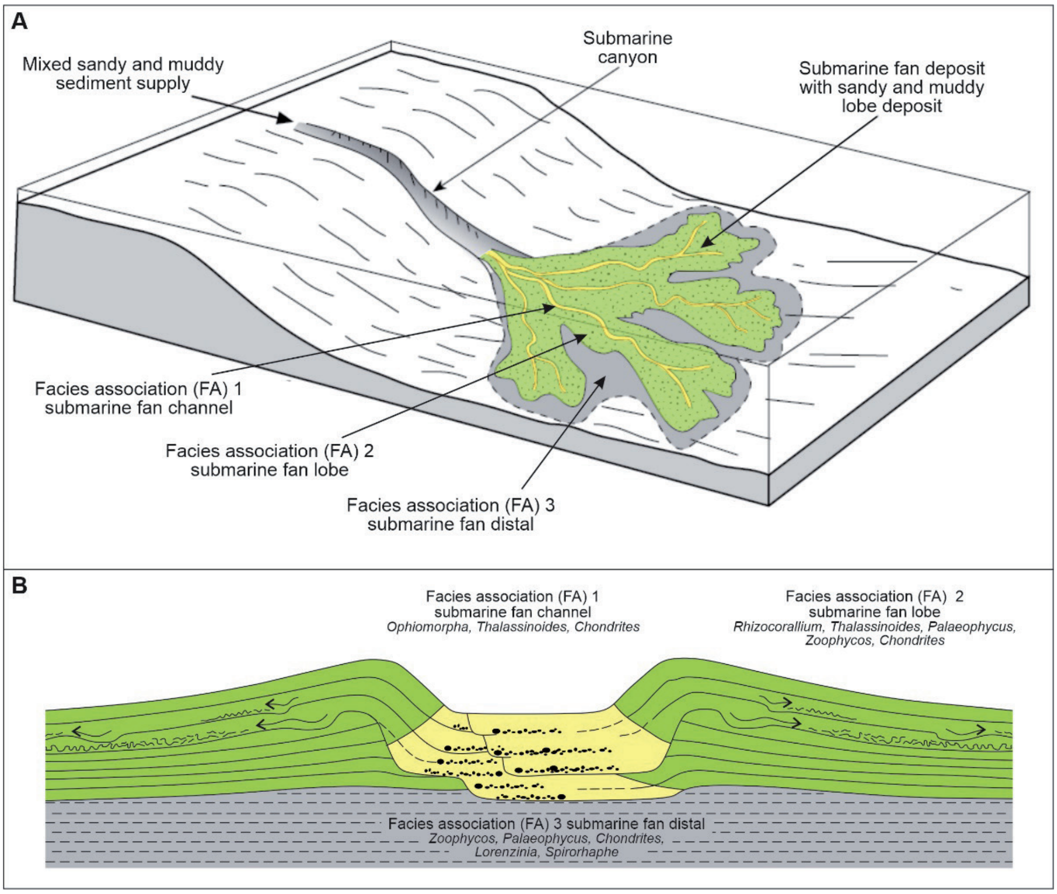

Figure 6. The distribution model of ichnofossils in pelagic siliciclastic carbonate turbidites of weda formation (a) Model of the mixed submarine fan between sand and mud, based on Nichols (2009) and (b) Cross section model of submarine fan facies based on Posamantier and Walker (2006).

CONCLUSIONS

The Weda Formation in the study area was deposited in submarine fan environment which can be divided into three sedimentary facies associations, namely submarine fan channel facies associations, submarine fan lobe facies associations, and submarine fan distal facies associations, all of them have variations in the appearance of ichnofossils due to the control of life-supporting environmental conditions. The submarine fan channel facies association has a low intensity of ichnofossils due to high environmental stress, periodic turbidite currents, and rapid deposition so it is less supportive of life and preservation of ichnofossils. The submarine fan lobe facies association has two variations of trace fossil groups based on the behavioral classification of domichnia and fodinichnia ichnofossils which indicate a relatively more quite environment than the channel facies association, while the submarine fan distal facies association has the most abundant ichnofossil intensity compared to the submarine fan channel and lobe facies associations. Submarine fan distal facies associations indicates more quiet environment and supports animal colonies when sediment deposited.

ACKNOWLEDGMENT

We acknowledge the Head of Lili Village and Togutil Tribe who have accepted, helped, and protected us during research activities in the Lili River. We also thank the Kao Bay Basin Dynamics Team who have assisted field data collection, and everyone who helped us during this research.

REFERRENCES

Arifullah, E., Zaim, Y., dan Aswan, A. B. The Potential of Ichnofossil for The Interpretation of Depositional Environment Condi-tions: an Example from Outcrop Studies in Samarinda, Kutai Basin East Kalimantan. Proceedings Joint Convention HAGI-IAGI-IAFMI-IATMI Balikpapan 2015

Arifullah, E., Zaim, Y., Aswan, D., Diponegoro Ariwibowo, Y. E., dan Ilham, M. 2016. The Significance of Ichnofabric Analysis for Sedimentological Interpretation: an outcrop study at Palaran, Samarinda Area, Kutai Basin, Indonesia. Proceedings Geosea XIV Congress and 45th IAGI Annual Convention 2016

Arifullah, E. dan Zaim, Y. 2019. Tiering Style and Its Interpretation: Ichnofabric Study in Balikpapan Formation, Kutai Basin, Indonesia. Journal of Mathematical & Fundamental Sciences, 50(1)

Bann, K.L., Tye, S.C., MacEachern, J.A., Fielding, C.R., dan Jones, B.G., 2008. Ichnological and sedimentologic signatures of mixed wave and storm dominated deltaic deposits: Examples from the Early Permian Sydney Basin, Australia. *In* Hampson, G., Steel, R., Burgess, P., dan Dalrymple, R., (Eds.), *Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy*. SEPM Special Publication 90, p 293-332

Bayet-Goll, A., Neto de Carvalho, C., Moussavi-Harami, R., Mahboubi, dan A., Nasiri, Y., 2014. Depositional environments and ichnology of the deep-marine succession of the Amiran Formation (Upper Maastrichtiane-Paleocene), Lurestan Province, Zagros Folde Thrust Belt, Iran. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 401, 13-42

Bayet-Goll, A., Neto de Carvalho, C., Mahmudy-Gharaei, M.H., dan Nadaf, R., 2015. Ichnology and sedimentology of a shallow marine Upper Cretaceous depositional system (Neyzar Formation, Kopet-Dagh, Iran): palaeoceanographic influence on ichnodiversity. *Cretaceous Reaserch*, 56, 628-646

Bessho, B., 1944. Geology of the Halmahera islands. *Geographical Journal* (LVI), 664, 145-203

Bouma, A. H., 1962. *Sedimentology of Some Flysch Deposits*. Elsevier: Amsterdam

Bromley, R.G. dan Ekdele A.A., 1984. Composite Ichnofabric and Tiering of Burrow. *Geo.Magz.* v.123. h. 59-65

Bromley, R.G., 1996. *Trace Fossils: Biology, Taphonomy and Application*. Chapman and Hall, London, 361p.

Callow, R.H.T., Kneller, B., Dykstra, M., and McIlroy, D., 2014. Physical, biological, geochemical and sedimentological controls on the ichnology of submarine canyon and slope channel systems. *Marine and Petroleum Geology* 54, 144-166

Crimes, T.P., Goldring, R., Homewood, P., Stuijvenberg. J., dan Winkler, W., 1981. Trace Fossil Assemblages of Deep Sea Fan Deposit, Gumigel and Schlieren (Cretaceous-Eocene), *Eclogae Geologicae Helvetiae* 74, 953-995

Cummings, J.P. and Hodgson, D.M., 2011. Assessing controls on the distribution of ichnotaxa in submarine fan environ-ments, the Basque Basin, Northern Spain. *Sedimentary Geology* 239, 162-187

Ekdale, A. A., Bromley, R. G., dan Pemberton, S. G. 1984. *Ichnology: The Use of Trace Fossils in Sedimentology and Stratig-raphy*. SEPM Short Course 15. 317p.

Frey, R.W., Pemberton, S.G., dan Fagerstorm, J.A., 1984 Morphological, ethological, and environmental significance of the ichnogenera Scoyenia and Ancorichnus. *Journal of Paleontology*, v. 58, 511-528

Frey, R.W., Pemberton, S.G., dan Saunders T.D.A., 1990. Ichnofacies and bathymetry: a passive relationship. *Journal of Paleontology*, v.64, 55-158

Hall, R., Audley-Charles, M. G., Banner, F. T., Hidayat, S. dan Tobing, S. L., 1988. Late Paleogene-Quaternary geology of Halmahera, eastern Indonesia. *J. GeoL Soc. London* 145, 577-590

Heard, T.G., dan Pickering, K.T., 2008. Trace fossils as diagnostic indicators of deepmarine environments, Middle Eocene Ainsa-Jaca Basin, Spanish Pyrenees. *Sedimentology* 55, 809-844

Heard, T.G., Pickering, K.T., dan Clark, J.K., 2014. Ichnofabric characterization of a deepmarine clastic system: a subsurface study of the Middle Eocene Ainsa System, Spanish Pyrenees. *Sedimentology* 61, 1298-1331

Ichnology Research Group, 1998. *Ichnology Atlas* Version 1.0

Kusworo, A., 2013.Preliminary report on survey activities for the Kao Bay Basin, Halmahera, Maluku. The Center for Geological Survey (unpublished). In Bahasa

Leszczynski, S., 1991. Trace-fossil tiering in flysch sediments: examples from the Guipúzcoan flysch (Cretaceouse-Paleogene), northern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 88, 167-184

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., dan Bann, K.L., 2010. Ichnology and facies model. *In* James, N.P. dan Dalrymple, R.W. *Facies Model 4*. Geotext 6. GAC. 591p.

Monaco, P., 2008. Taphonomic features of Paleodictyon and other graphoglyptid race fossils in Oligo-Miocene thin-bedded turbidites of Northern Apennines flyschdeposits (Italy). *Palaios* 23 (10), 667-682

Monaco, P., Milighetti, M., and Checconi, A., 2010. Ichnocoenoses in the Oligocene to Miocene foredeep basins (Northern Apennines, central Italy) and their relation to turbidite deposition. *Acta Geologica Polonica* 60 (1), 53-70

Monaco, P., and Trecci, T., 2014. Ichnocoenoses in the Macigno turbidite basin system, Lower Miocene, Trasimeno (Umbrian Apennines, Italy). The *Italian Journal of Geosciences*, 133, 116-130

Nichols, G., 2009. *Sedimentology and Stratigraphy*, Blackwell Publishing, UK

Nichols, G.J. dan Hall, R., 1991. Basin formation and Neogene sedimentation in a backarc setting, Halmahera, eastern Indonesia. *Marine and Petroleum Geology* 8. 50-61

Pemberton, S.G., Frey, R.W., Ranger, M.J., dan MacEachern, J., 1992. The Conceptual Framework of Ichnology: *SEPM Applications of Ichnology to Petroleum Exploration*. SEPM: Canada

Posamantier dan Walker, 2006. Deep-water turbidites and submarine fans. In: Crossey, L.J. dan McNeill, D.S. (Eds.), Facies *Models Revisited* SEPM Special Publication 84, Tulsa, Oklahoma, U.S.A. 399-520

Pratama, A.C.J. 2019. Studi fosil fejak Formasi Halang daerah Cipari dan sekitarnya, Kabupaten Cilacap, Jawa Tengah, Tesis Program Magister, Institut Teknologi Bandung

Rudyawan, A., dan Oo, T. Z. 2018. Ichnofossils study of paleocene sediment source rock cores from Bintuni basin, West Papua, Eastern Indonesia. In IOP Conference Series: Earth and Environmental Science (Vol. 162, No. 1, p. 012034)

Savary, A., 2004. Calciturbidite Dynamics and Endobenthic Colonisation: Example from A Late Barremian (Early Creaceous) Succession in Southeastern France. *Palaeo* 211. 221-239

Seilacher, A., 1977. Pattern analysis of Paleodictyon and related trace fossils. *In*: Crimes, T.P. dan Harper, J.C. (Eds.), *Trace Fossils 2*, Geological Journal, Special Issue 9, pp. 289e334. London

Seilacher, A., 2007. Trace *Fossil Analysis. Springer Verlag*, Berlin, 226p.

Supriatna, Sam., 1980. Geological Map Sheet Morotai, North Maluku 1:250,000 Scale, Geological Research and Development Center: Bandung

Uchman, A., dan Wetzel, A., 2011. Deep-sea ichnology: the relationships between depositional environment and endobenthic organisms. *In*: Hüneke, H., Mulder, T. (Eds.), *Developments in Sedimentology*, 517-556

Uchman, A., 1992. An opportunistic trace fossil assemblage from the flysch of the Inoceramian beds (Campanian-Paleocene), Bystrica zone of the Magura Nappe, Carpathians, Poland. *Cretaceous Reaserch* 13, 539-547

Uchman, A., 1998. Ichnology of the Rhenodanubian flysch (Lower Cretaceouse-Eocene) in Austria and Germany. *Beringeria* 25, 65-171

Wetzel, A., 1991. Ecologic interpretation of deep-sea trace fossil communities. *Palaeogeography, Palaeoclimatology, Palaeoecology* 85, 47-69

Wicaksono, A., Faridsyah, W.A. dan Priasmara, F.D., 2012. Depositional Facies and Structural Analysis Based on Field Observation of Fritu Area, Halmahera Island. IPA Proceeding of 36th Annual Convention and Exhibition, Jakarta.

Zonneveld, J. P., Zaim, Y., Aswan, A., Rizal, Y., Gingras, M. K., Gunnell, G. F., dan Ciochon, R. 2017. Surficial tracks produced by mudskippers (periophthalmus & periophthalmodon) in fine-grained coastal successions: implications for the vertebrate colonization of land. In GSA Annual Meeting in Seattle, Washington, USA-2017. GSA

Zonneveld, J.P., Zaim, Y., Rizal, Y., Aswan, A., Hascaryo, A., Adani, N., Fortuin, A., Gingras, M., Larick, R. dan Ciochon, R., 2019. Ichnology of a Seasonally-Dominated Deltaic/Estuarine Complex: The Pleistocene Palaeo-Kambinaru River, Sumba, East Nusa Tenggara, Indonesia. In 2019 AAPG Annual Convention and Exhibition