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RESEARCH ARTICLE

Discovery of Marine Macrozoobenthos Fossils in the River of Wonocolo Geosite, Indonesia

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Abstract Wonocolo Geosite is a geoheritage known for the existence of the Kawengan Anticlinal Trap, which is the only one in the world, causing oil to be found in shallow locations. This condition has allowed for traditional mining since the Dutch colonial era and continues today. Geological history states that the anticlinal structure was formed when the Indo-Australian plate collided with the Eurasian plate, resulting in folds and uplift of the seafloor above the surface. However, there has not been much research supporting the truth of the theory. Therefore, evidence is needed to support the uniqueness of the Wonocolo Geosite. The fossil collection method was carried out simultaneously with the collection of substrates at the upstream, middle, and downstream riverbeds using 20 cm diameter PVC pipes at a depth of 10 cm.This study found marine macrozoobenthos fossils during substrate sampling in the upstream, middle, and downstream river beds using a PVC pipe with a diameter of 20 cm at a depth of 10 cm. The samples were then identified in the laboratory, revealing fossils from the deep sea. The fossils found include Azooxanthellate (Cnidaria), which lives at depths of up to 2000 m; Dentaliida (Mollusca) which lives at depths of 500-7000 m and Foraminifera which also live in the deep sea. This phenomenon is unusual, considering that the fossils were found in a river far from the sea at an altitude of 250 MASL. Therefore, the discovery of marine macrozoobenthos fossils at the bottom of the Wonocolo River strengthens the theory of the formation of the Wonocolo Formation from a raised seabed which is also an important asset supporting the Wonocolo Geoheritage.

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1. Introduction

Bojonegoro National Geopark was established inaugurated in November 2017, featuring one of its Geoheritage key, the Wonocolo Traditional Oil Mine. The area has several uniqueness. Historically, a total of 225 old oil wells in this area are relics of the Dutch East Indies Government since 130 years ago (Adiarsa et al., 2019; Dariyo, 2020; Elvania et al., 2023; Rahmawati et al., 2021a). Culturally, petroleum exploitation activities are still carried out simply using traditional equipment (Rahmawati et al., 2021b, 2021a). Geologically, the area is the only shallowest oil trap in the entire world due to the existence of the Kawengan Anticlinal structure formed through geological processes (Hariyadi et al., 2016; Kusumayudha et al., 2021; Setiawan et al., 2021).

The Kawengan Anticlinal structure was discovered in 1894 by the Dutch and began to be developed in 1926 by Bataafsche Petroleum Maatschappij (BPM) (Adiarsa et al., 2019; Naumi & Trilaksana, 2015). The structure of the Kawengan Anticline is located in the northern part of the East Java Basin (Adiarsa et al., 2019; Choiriah et al., 2023; Soeparyono, 1988), which was formed at the beginning of the Tertiary period when the Indo-Australian plate submerged under the Eurasian plate, with a position extending west-east from the LRembang zone (Hariyadi et al., 2016; Setiawan et al., 2021). This anticline basin is formed through the process of inversion and reactivation of old faults, giving rise to the emergence of new folds and faults (Hariyadi et al. 2016).

The Wonocolo Formation is located around the Wonocolo and Cepu regions and is vertically located directly above the Bulu Formation. This formation has a thickness of 89 – 600 m, is lower to middle Late Miocene, and is composed of loam to sandstone, which is rich in planktonic foraminifera (Hariyadi et al., 2016; Setiawan et al., 2021). These formations are deposited in open marine environments (neritic zone) to upper bathyal (Hariyadi et al., 2016; Setiawan et al., 2021).

Based on this geological history, it is believed that the Wonocolo formation in the past was deposited in a shallow to deep marine environment, which was then lifted upwards to form folds due to geological activities in the form of plate movements. This condition makes the Wonocolo are currently at an average altitude of more than 250 meters above sea level (MASL). However, there has not been much study to prove the theory.

This study aims to identify marine benthic fossils found at the bottom of the Bungsu River and Kragsaan River in the Wonocolo Traditional Oil Mining Area. This study found marine benthic fossils during sampling at the bottom of Bungsu and Kragsaan Rivers in Wonocolo Traditional Oil Mining Area. The discovery of these fossils is expected to serve as evidence that strengthens the formation theory of Wonocolo Area.

2. Methods

Both rivers, Bungsu and Kragsaan are within the traditional oil mining areas and receive wastewater discharged from these activities (Figure 1). The fossil discovery occurred during macrozoobenthos sampling on riverbed substrates at three stations, namely upstream, middle, and downstream of the Bungsu River (SB) and Kragsaan (SK). In both rivers, station in the upstream part of the river (SB-1 and SK-1) is the source area of the spring, the station in the middle of the river (SB-2 and SK-2) is the part that receives wastewater produced from the oil mining activities, and station in the downstream (SB-3 and SK-3) is located in the middle of the Wonocolo forest.

Based on geological formation, most of the sampling stations in this study are in the Wonocolo formation (SB1, SB2, and SK1). However, there are several points in the Ledok Formation (SK2 and SB3), and some are in the Mundu Formation (SK3). Based on the estimated time of formation of geological formations, the Wonocolo Formation was formed in the late lower Miocene era which formed 10 million years ago, while the Ledok Formation was formed in the late upper Miocene era which formed 8 million years ago, and the Mundu Formation was formed in the Pliocene era which formed 5 million years ago (Setiawan et al., 2021).

At each station, the substrate is taken from the right, left, and middle banks of the river using a PVC pipe of 20 cm diameter buried at 10 cm depth. The substrate is sieved with a 1 mm eye-sized strainer for macrozoobenthos. The retained biota wasere then identified in the laboratory at 1000x microscope magnification. Foraminifera identification is done conducted using the MIRACLE (Microfossile Image Recovery and Circulation for Learning and Education) identification key sourced from official website of the University of California, Los Angeles (UCLA).

3. Result and Discussion

During the course of the study, 2 fossil specimens of *Cnidaria*, 113 specimens *Mollusca* and 289 specimens *Foraminifera* have been found. The data revealed that the further downstream, the more various species of fossils there are. When observed based on the time range of the formation of the geological formation of the river flow, it can be seen that the river formations in the upstream part of both the Bungsu and Kragsaan Rivers are younger than the downstream part of the river. The upstream part of the river includes the Wonocolo Formation which was formed around 10 million years ago, while the downstream part of the Bungsu River which is located in the Ledok Formation which was formed 8 million years ago; whereas , and the downstream part of the Kragsaan

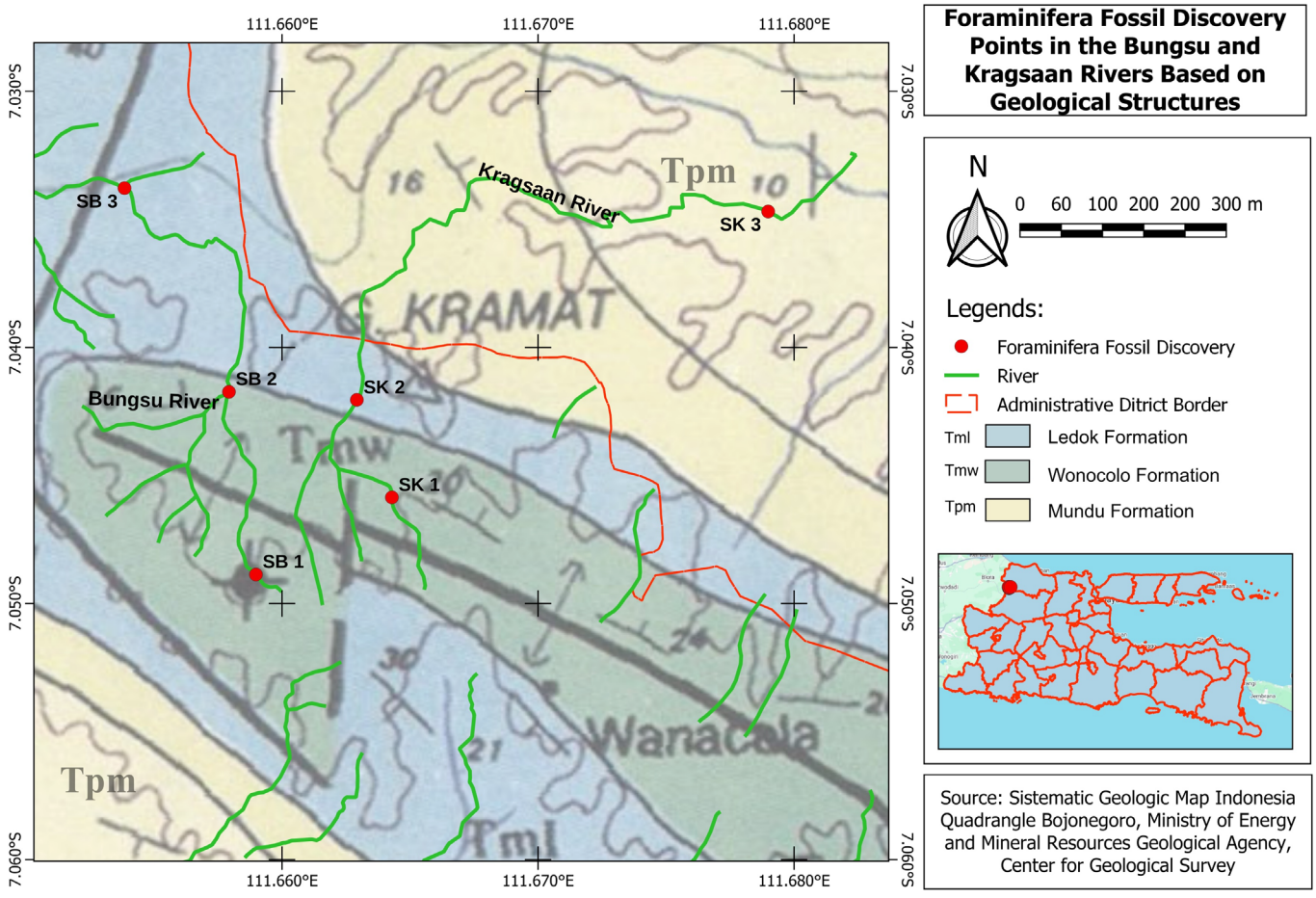


Figure 1. Location of Marine Benthic and Foraminifera Fossils Discovery in River Bungsu and River Kragsaan Based on Geologycal Structure Location of Marine Benthic and Foraminifera Fossils Discovery in River Bungsu and River Kragsaan (green dots)

River which is located in the Mundu Formation which was formed 5 million years ago. The detailed fossil discoveries are listed in Table 1.

Fossil of Cnidaria

The marine macrozoobenthos fossils found in this study were identified as belonging to the phylum Cnidaria, class Anthozoa, subclass *Hexacorallia,* and the order *Scleractinia.* *Scleractinia* commonly known as "stony corals" or "true corals" (Hendricks, 2019), with a skeleton made of calcium carbonate aragonite (Fukami et al., 2008). They can live solitary or in colonyize and are usually found in habitats ranging from shallow to deep water. Identification to the species level found two *Scleractinia* fossils, i.e., *Sphenotrochus hancocki* (Bastida-zavala et al., 2013; Cairns, 2003) and *Fungiacyathus paliferus* as shown in Ffigure 2. Both species are azooxanthellate

Table 1. Marine Benthic and Foraminifera Fossils in River Bungsu (SB) and River Kragsaan (SK), Wonocolo

Phylum	Orders of Species	Bungsu River			Individual Sub Totals	Kragsaan River			Individual Sub Total	Individual Total
		SB-1	SB-2	SB-3		SK-1	SK-2	SK-3		
Cnidaria	***Scleractinia***									
	Sphenotrochus hancocki	-	-	-	0	-	-	1	1	1
	Fungiacyathus paliferus	-	-	-	0	1	-	-	1	1
	Σ	**-**	**-**	**-**	**0**	**1**	**-**	**1**	**2**	**2**
Mollusca	***Dentaliida***									
	Dentallium sp.	-	2	25	27	8	1	75	84	111
	Dentalina amchitkaensis	-	-	-	0	-	1	1	2	2
	Σ	**-**	**2**	**25**	**27**	**8**	**2**	**76**	**86**	**113**
Foraminifera	***Rotaliida***									
	Ammonia beccarii	4	6	11	21	-	3	40	43	64
	Elphidium sp	2	2	-	4	-	-	-	0	4
	Textularia sp.	-	-	12	12	-	1	39	40	52
	Amphistegina sp	-	6	-	6	-	-	-	0	6
	Globotruncana linneiana	-	-	10	10	-	1	24	25	35
	Σ	**6**	**14**	**33**	**53**	**0**	**5**	**103**	**108**	**161**
	Vaginulinida									
	Vaginulina sp.	2	2	5	9	-	2	17	19	28
	Lenticulina gutticostata	-	-	7	7	-	-	33	33	40
	Robulina aculeata	-	-	1	1	-	-	2	2	3
	Σ	**2**	**2**	**13**	**17**	**0**	**2**	**52**	**54**	**71**
	Allogromiida									
	Robulus sp.	1	1	-	2	-	-	-	0	2
	Σ	**1**	**1**	**-**	**2**	**0**	**0**	**0**	**0**	**2**
	Loftusiida									
	Cyclammina sp.	-	-	3	3	19	1	14	34	37
	Σ	0	0	**3**	**3**	19	1	14	**34**	**37**
	Nodosariide									
	Nodosaria sp.	1	-	-	1	-	-	-	0	1
	Nodosaria sinulata	-	1	2	3	-	-	9	9	12
	Nodosaria deceptoria	-	-	1	1	-	-	4	4	5
	Σ	**1**	**1**	**3**	**5**	**0**	**0**	**13**	**13**	**18**
	Total Species	**4**	**6**	**9**		**1**	**5**	**9**		
	Total Individual	**10**	**20**	**77**	**107**	**28**	**10**	**259**	***297***	**404**

Source: Primary Data Processing, 2023

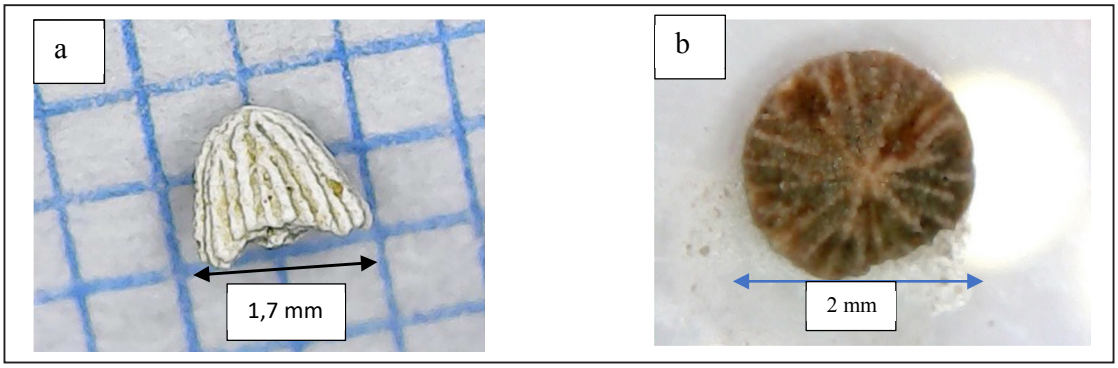
corals, which is a group of corals (*Anthozoa*) that do not have unicellular photosynthetic symbiont either *Zooxanthella* or *Dinoflagellata* (Filander et al., 2021; Wagner et al., 2011). They obtain s food not from the process of photosynthesis of their symbionts, but by capturing various forms of plankton. In that way of life, a kind of azooxanthellate can live in the sea to a depth of 200-1000 m with dim sunlight (Santodomingo et al., 2013), because it does not require sunlight for photosynthesis (Wagner et al., 2011). The Ocean Biogeographic Information System (OBIS, 1994) stated that *Fungiacyathus paliferus* can live on the seabed with depths from 69-2000m (Encyclopedia of Life, 1994). The bathimetric distribution of azooxanthellate is not only determined by light; the changes in salinity, temperature, nutrients and sediment across the depth gradient played an important role in the existence and richness of azooxanthellate species (Santodomingo et al., 2013). The findings of azooxanthellate species in River Kragsaan bed support the theory that Wonocolo was once a seabed that was then uplifted due to geological activities formed during the Indo-Australian Plate subsidence under the Eurasian Plate at the beginning of the Tertiary. This is certainly very interesting, considering that fossils of this type of coral were found in the riverbed located far from the sea at an altitude of 250 meters above sea level (MASL).

Fossils of Mollusca

In addition to Cnidaria, macrozoobenthos fossils from phylum Mollusca were also found, *i.e.,* class *Scaphopoda,* order *Dentaliida* (Sepulveda et al., 2016). The identification at the species level, show that the specimens obtained are *Dentallium sp.* and *Dentalina amchitkaensis* as shown in figure 3. Like other members of the class Scaphopoda, *Dentaliida* (tusk shell) has a slender body and small size, with a shape and color resembling to ivory (Dulcey, 2020; Gordillo, 2021; Thompson, 2022; Wirawan, 2016). The shell is slightly curved with a hollow inside and both ends are open with one end larger than the other and there is a rib-like line (Souza & Caetano, 2021). *Dentaliida* occupies bathyal and abyssal substrate habitats on coarse sediments with a mixture of sandy fractions as well as shell detritus (Kaim, 2012), by living immersing its head in a soft substrate. Almost 70% of the class Scaphopoda, including *Dentaliida*, is found below a depth of 500 m, the rest is found at depths of 3000 - 7000 m (Dulcey, 2020; Lindberg, 2001; Wirawan, 2016); (Gordillo, 2021). This information further strengthens the theory of the origin of the Wonocolo mainland which started from a deep sea floor. The existence of *Dentaliida* in the marine environment is also related to the existence of Foraminifera (Buosi et al., 2020; Lindberg, 2001). This is due to the eating habits of the order *Dentaliida,* which often preys on Foraminifera (Lindberg, 2001). Hence the discovery of *Dentaliida* and *Foraminifera* in abundance in the same riverbed, also further supports the theory of the formation of present Wonocolo land from seabed.

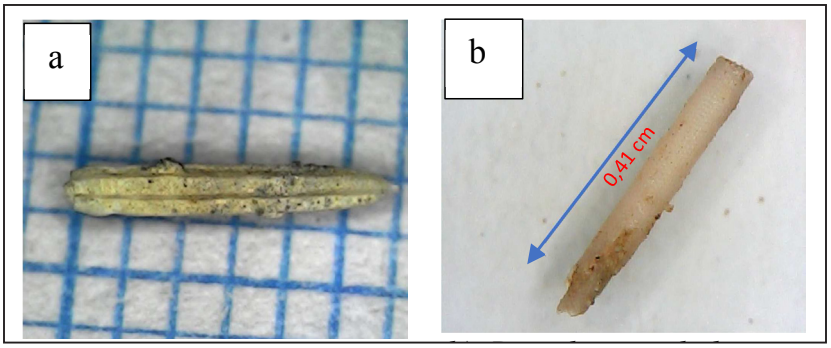
Fossils of Foraminifera

Foraminifera is a group of single-celled microorganisms that have calcium carbonate or silica shells. *Foraminifera* has high sensitivity to environmental conditions such as sediment type, oxygen concentration, organic matter flux, and quality or pollution of the aquatic environment (Dessandier, 2018). They belong to five orders and 13 species.. Foraminifera bears witness to the Earth's evolutionary process and records



a). Sphenotrochus hancocki b). Fungiacyathus paliferus.

Figure 2. *Scleractinia* fossils found in rRiver of Wonocolo Geosite



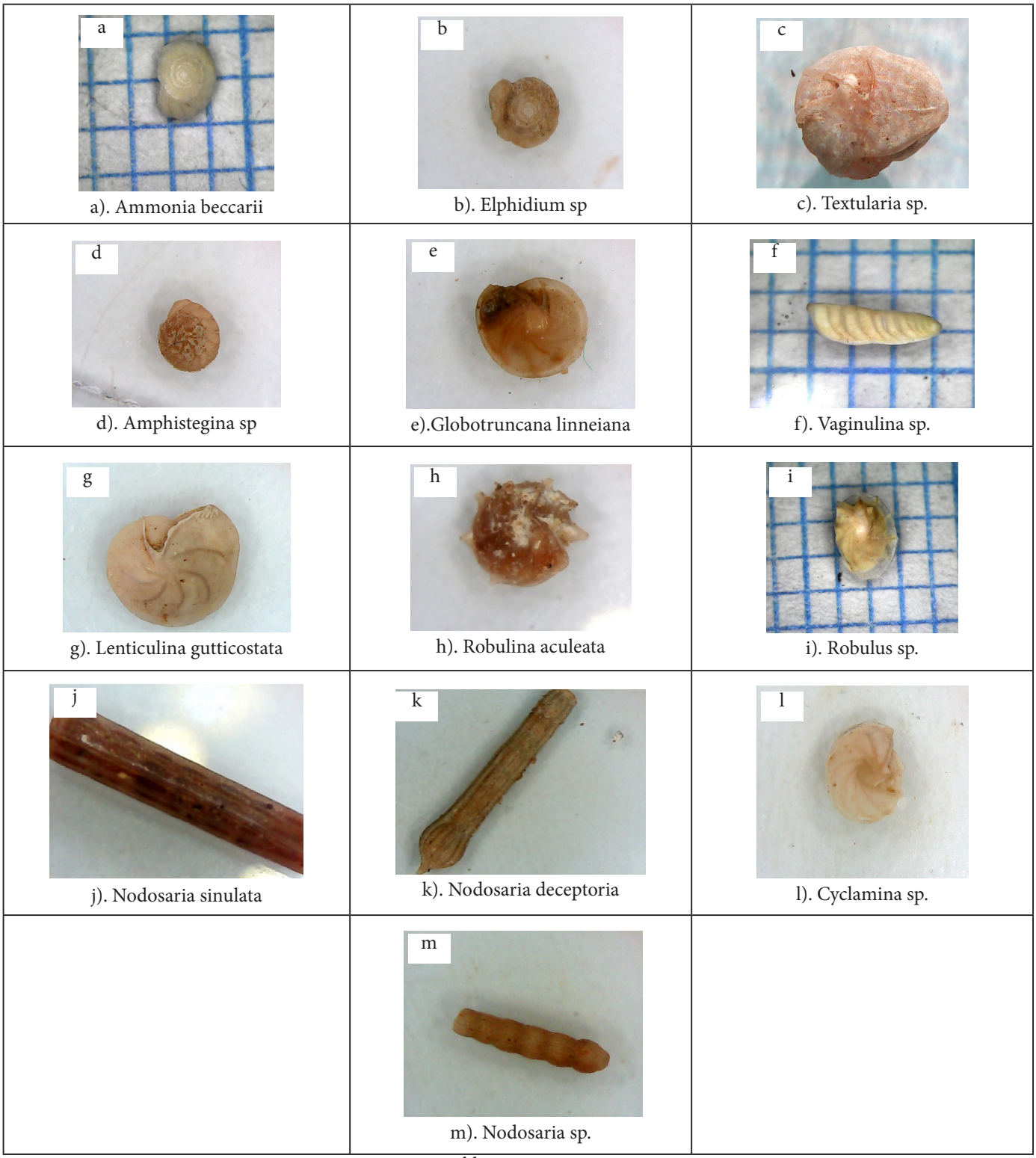
a). Dentallium sp. b). Dentalina amchitkaensis

note: 1 blue square = 1 mm^2

Figure 3. Mollusca fossils found in rRiver of Wonocolo Geosite

significant changes in climate, sea level, and disasters, thus helping scientists understand climate changes and the marine environment in the past (Dessandier, 2018; Fatela, 2016; Saraswati, 2021). Wonocolo Formation has a thickness of 9 – 600 m, composed of clay to sandstone rich in Foraminifera and plankton deposited in neritic to bathyal marine environments (Setiawan et al., 2021). In Wonocolo River, 289 fossil specimens found were *Foraminifera*. As for the species and number of fossils of each *Foraminifera* is presented in Table 1 and the picture shown on Figure 4.

The most abundant individual of *Foraminifera* fossils is the order Rotaliida, in which *Ammonia beccarii* and *Textularia sp* were dominant. *Ammonia beccarii* is a common species living in shallow marine environments (Subba & Ghosh, 2023) at a salinity of >33 ppt. This species plays an important role in environmental and geological studies because of its abundance, wide geographical distribution, the most stress tolerant (Sadanandan et al., 2023), and long duration since the Miocene (Debenay et al., 1998; Hayward, 2019). *Textularia sp.* is one of the Foraminifera groups, an agglutinated calcareous



note: 1 blue square = 1 mm2

Figure 4. *Foraminifera* fossils found in rRiver of Wonocolo Geosite

group with the most abundance record in marine environments (Parker & Gischler, 2021) especially in coarse-grained sediments (Capotondi et al., 2022). This particular species also plays an important role in ecological research as well as in bio-stratigraphic studies (Malek & Omar, 2014). In addition to Rotaliida is *Vaginulinida* with the most abundant individual *Lenticulina gutticostata.* Species *Lenticulina gutticostata* is characterized by a hyaline calcareous shell (Anan, 2022), lives sedentary attaching to the substrate at the bottom of the waters. This species inhabits areas such as beaches, coastal or tidal areas, marine coral reefs and the seabed (Thomsen et al., 2012; Wang, 2020).

Order *Allogromiida* represented by *Robulus sp*. It is a single-chambered foraminifer, mostly organic-walled; some produce agglutinated shells (Lagynacea). *Allogromiida* carved a relatively simple shell, usually with one chamber, similar to other protists such as *Gromia*. They are found both in the ocean and in freshwater and are the oldest known form of the fossil record (Henderson, 2023; Siemensma, 2021).

Foraminifera fossil of the Order *Loftusiida* was also found quite abundantly in Wonocolo River bed, with leading species *Cyclammina sp* which is almost evenly distributed around the world, especially in oceans that have cold waters below the depth of the continental shelf. This species is also widespread in Tertiary rocks, especially in the Miocene period rock. The presence of this species is one of the criteria that indicate the existence of an open sea deposition environment in the depths of the bathyal sea (Nomura, 2021). This species also has a high tolerance to seawater depth levels, ranging from 114 – 5800 MASL (Fadel, 2018).

Moreover, Foraminifera of the order *Nodosariida, i.e., Nodosaria sinulata* and *Nodosaria deceptoria*. They are characterized by their uniserial shell, fibrous walls consisting of collections of cones with a length of one to tens of micrometers, and a unique arrangement of spaces, thus distinguishing them from other Foraminifera shells. Many *Nodosariida* were found in marine habitats with estimated depths of 100-500 m and are easily recognized by their unique shell characteristics (Dessandier, 2018; Pacho et al., 2023).

The discovery of Foraminifera fossils as well as other marine macrobenthic in abundant and diverse quantities at the bottom of the Bungsu and Kragsaan Rivers at the Wonocolo Geosite can be important assets that have unique geological values to support the sustainability of the development of the Wonocolo Geosite Area later on, in particular for education and tourism.

4. Conclusion

At the bottom of river, Bungsu and Kragsaan at Wonocolo Geosite fossils of some marine benthic fauna were found, i.e., from the phyla *Cnidaria*, *Mollusca,* and *Foraminifera*. The discovery of azooxanthellate coral fossils of the phylum Cnidaria, Dentaliida fossils (Mollusca), and fossils of phylum Foraminifera served the allegation that in the old days Wonocolo was a deep sea. Thus, all the fossil evidence that lived some 500-7000 m below the water level may strengthen the theory regarding the origin of the Wonocolo Formation which was formed from the seabed uplifted by geological activity. The discovery of marine benthic fossils at the bottom of the Bungsu River and Kragsaan River in the Wonocolo Traditional Oil Mining Area in this study can be evidence that strengthens the theory of the formation of the Wonocolo Area.

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