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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ
АКАДЕМИЯСЫ» РҚБ

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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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Universitas Negeri Gorontalo, Gorontalo, Indonesia.
E-mail: aang@ung.ac.id*

TECTONIC GEOHISTORY OF THE GORONTALO REGION BASED ON FORAMINIFERA FOSSIL

Aang Panji Permana — PhD, Researcher and Associate Professor in Geological Engineering Study Program, Earth Science and Technology Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Gorontalo, Indonesia, E-mail: aang@ung.ac.id, https://orcid.org/0000-0002-6865-3564;
Dewi Wahyuni K. Baderan — Researcher and Professor in Environmental Science Doctoral Study Program, Postgraduate, Universitas Negeri Gorontalo, Indonesia, https://orcid.org/0000-0003-3014-0832;
Ronal Hutagalung — Researcher and Lecturer in Geological Engineering Study Program, Earth Science and Technology Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Gorontalo, Indonesia, https://orcid.org/0000-0001-8142-8903;
Fadhil Abdillah Ahmad — Researcher in Geological Engineering Study Program, Earth Science and Technology Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Gorontalo, Indonesia, https://orcid.org/0009-0009-6728-3192.

Abstract. The tectonic geohistory of the Gorontalo region, situated at the convergent boundary of the Pacific and Eurasian plates and influenced by microplate interactions, remains inadequately understood despite its high seismic vulnerability. This study reconstructs the Cenozoic tectonic evolution of Gorontalo using benthonic foraminifera fossils to address critical gaps in regional geological knowledge and support disaster mitigation efforts. Field stratigraphy was conducted in Ombulo Village, where limestone bed thicknesses (up to 25 m) and facies distributions were measured. Sixteen benthonic foraminifera species were identified using Olympus SZ61 microscopy, enabling detailed paleobathymetric reconstructions. Bathymetric corrections were applied using (van Hinte's) midpoint-range method, and local depth changes were compared to global sea-level data using (Miller et al) to distinguish between eustatic and tectonic influences. The results indicate a progressive deepening from middle shelf (178.4 m) to upper slope (500 m) environments between 6.4–5.8 Ma, corresponding to a ~321.5 m increase in depth that is not explained by global sea-level changes. The study concludes that tectonic subsidence is the dominant process shaping the Gorontalo basin, with foraminifera

distributions serving as reliable proxies for reconstructing paleodepths. These findings have practical applications in disaster mitigation (by providing baseline data for subsidence modeling), conservation planning (through the identification of geological protected areas), and energy exploration (by characterizing carbonate reservoirs relevant to hydrocarbon prospecting).

Keywords: Foraminifera Fossil, Geohistory, Gorontalo, Tectonics.

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Негери Горонтало университеті, Горонтало, Индонезия.
E-mail: aang@ung.ac.id*

ФОРАМИНИФЕРА ҚАЗЫҒЫНЫҢ НЕГІЗІНДЕГІ ГОРОНТАЛО АЙМАҒЫНЫҢ ТЕКТОНИКАЛЫҚ ГЕОТАРИХЫ

Аанг Панджи Пермана — PhD, зерттеуші және Геологиялық инженерияны зерттеу бағдарламасының доценті, Жер Туралы ғылымдар және технологиялар кафедрасы, Математика және жаратылыстану ғылымдары факультеті, Негери Горонтало Университеті, Индонезия, E-mail: aang@ung.ac.id, https://orcid.org/0000-0002-6865-3564;

Дьюи Вахюни К. Бадеран — зерттеуші және қоршаған ортаны қорғау ғылымдарының докторантурасын зерттеу бағдарламасының профессоры, аспирантура, Негери Горонтало университеттері, Индонезия, https://orcid.org/0000-0003-3014-0832;

Ронал Хутагалунг — Индонезиядағы Негери Горонтало университетінің Математика және жаратылыстану ғылымдары факультеті, Жер туралы ғылымдар және технологиялар кафедрасының Геологиялық инженерияны зерттеу бағдарламасының зерттеушісі және оқытушысы, https://orcid.org/0000-0001-8142-8903;

Фадхил Абдилла Ахмад — Геологиялық инженерияны зерттеу бағдарламасының ғылыми қызметкері, Жер туралы ғылымдар және технологиялар кафедрасы, Математика және жаратылыстану факультеті, Негери Горонтало университеті, Индонезия, https://orcid.org/0009-0009-6728-3192.

Аннотация. Тынық мұхиты мен Еуразиялық плиталардың конвергентті шекарасында орналасқан және микропластиналық өзара әрекеттесулердің әсерінен Горонтало аймағының тектоникалық геотарихы оның жоғары сейсмикалық осалдығына қарамастан жеткілікті түрде зерттелмеген. Бұл зерттеу аймақтық геологиялық білімдегі маңызды олқылықтарды жою және апаттардың салдарын азайту жөніндегі күш-жігерді қолдау үшін бентондық фораминифера қазбаларын пайдалана отырып, Гороналоның кайнозойлық тектоникалық эволюциясын қалпына келтіреді. Омбуло ауылында дала стратиграфиясы жүргізілді, онда эктас қабатының қалыңдығы (25 м дейін) және фациялық таралу өлшенді. Толық палеобатиметриялық реконструкцияларды

жүргізуге мүмкіндік беретін Olympus SZ61 микроскопиясының көмегімен он алты бентондық фораминифера түрі анықталды. Батиметриялық түзетулер (ван Хинтенің) ортаңғы диапазон әдісі арқылы қолданылды, ал жергілікті тереңдік өзгерістері эвстатикалық және тектоникалық әсерлерді ажырату үшін (Миллер және т.б.) теңіз деңгейіндегі жаһандық деректермен салыстырылды. Нәтижелер теңіз деңгейінің жаһандық өзгерістерімен түсіндірілмейтін тереңдіктің ~321,5 м ұлғаюына сәйкес келетін орта қайраңнан (178,4 м) жоғарғы еңіске (500 м) дейін 6,4–5,8 млн аралығында біртіндеп тереңдеуді көрсетеді. Бұл аймақтағы ерте плиоцендегі теңіз деңгейінің көтерілуі эвстатикалық факторларға емес, тектоникалық шөгулерге байланысты болды деген гипотезаны қолдайды. Зерттеу нәтижесінде тектоникалық шөгу Горонтало бассейнін қалыптастыратын басым процесс болып табылады, фораминифера таралулары палеотереңдіктерді қалпына келтіру үшін сенімді прокси ретінде қызмет етеді. Бұл нәтижелер апаттардың салдарын азайтуда (шөгуді модельдеу үшін бастапқы деректерді беру арқылы), консервацияны жоспарлауда (геологиялық қорғалатын аумақтарды анықтау арқылы) және энергетикалық барлауда (көмірсутектерді іздеуге қатысты карбонатты қабаттарды сипаттау арқылы) практикалық қолданбаларға ие.

Түйін сөздер: фораминифераның қазба қалдықтары, геотарих, Горонтало, тектоника

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Университет Негери Горонтало, Горонтало, Индонезия.
E-mail: aang@ung.ac.id*

ТЕКТОНИЧЕСКАЯ ГЕОИСТОРИЯ РЕГИОНА ГОРОНТАЛЛО НА ОСНОВАНИИ ИСКОПАЕМЫХ ФОРАМИНИФЕР

Ааанг Панджи Пермана — PhD, исследователь и доцент кафедры инженерно-геологических исследований факультета Наук о Земле факультета Математики и естественных наук университета Негери Горонтало, Индонезия, E-mail: aang@ung.ac.id, https://orcid.org/0000-0002-6865-3564;
Дьюи Вахьюни К. Бадеран — исследователь и профессор докторантуры по экологическим наукам, аспирант Университета Негери Горонтало, Индонезия, https://orcid.org/0000-0003-3014-0832;
Ронал Хутагалунг — исследователь и преподаватель программы инженерно-геологических исследований, факультет Наук о Земле и технологий, факультет Математики и естественных наук, Университет Негери Горонтало, Индонезия, https://orcid.org/0000-0001-8142-8903;
Фадхил Абдиллах Ахмад — исследователь программы инженерно-геологических исследований, факультет Наук о Земле и технологий, факультет математики и естественных наук, Университет Негери Горонтало, Индонезия, https://orcid.org/0009-0009-6728-3192.

Аннотация. Тектоническая геоистория региона Горонтало, расположенного на конвергентной границе Тихоокеанской и Евразийской плит и находящегося под влиянием микроплитных взаимодействий,

остается недостаточно изученной, несмотря на его высокую сейсмическую уязвимость. Это исследование реконструирует кайнозойскую тектоническую эволюцию Горонтало с использованием ископаемых бентосных фораминифер для устранения критических пробелов в региональных геологических знаниях и поддержки усилий по смягчению последствий стихийных бедствий. Полевая стратиграфия была проведена в деревне Омбуло, где были измерены толщина известняковых слоев (до 25 м) и распределение фаций. Шестнадцать видов бентосных фораминифер были идентифицированы с помощью микроскопии Olympus SZ61, что позволило провести подробные палеобатиметрические реконструкции. Батиметрические поправки были применены с использованием метода средней точки диапазона (van Hinte), а локальные изменения глубины были сопоставлены с глобальными данными об уровне моря с использованием (Miller et al) для различения эвстатических и тектонических влияний. Результаты указывают на постепенное углубление от среднего шельфа (178,4 м) до верхней части склона (500 м) в период 6,4–5,8 млн лет назад, что соответствует увеличению глубины примерно на 321,5 м, что не объясняется глобальными изменениями уровня моря. Исследование приходит к выводу, что тектоническое опускание является доминирующим процессом, формирующим бассейн Горонтало, а распределение фораминифер служит надежными прокси для реконструкции палеоглубин. Эти результаты имеют практическое применение в смягчении последствий стихийных бедствий (путем предоставления исходных данных для моделирования опускания), планировании охраны природы (путем определения геологических охраняемых территорий) и разведке энергоносителей (путем характеристики карбонатных резервуаров, имеющих отношение к разведке углеводородов).

Ключевые слова: ископаемые фораминиферы, геоистория, Горонтало, тектоника.

Introduction. Gorontalo is one of the areas prone to earthquake disasters; this condition is due to Gorontalo's tectonic position, which is influenced by the activities of the meeting of two large plates, namely the Pacific plate and the Eurasian plate. In addition, three microplates also contribute to the seismicity in Gorontalo, namely the Sulawesi, Banggai-Sula, and Sangihe sea plates. Evidence in the field is the uplifted limestone of the Gorontalo region, originally under the sea but now exposed above the land into hills. The presence of limestone at high elevations is evidence of a powerful tectonic influence (Jablonski, 2007; Pasari, et al., 2021; Efendi, et al., 2021; Handyarso, et al., 2023; Meidji, et al., 2023). The tectonic evolution of the Gorontalo area is a challenge in this study in providing new geological information. This new information on tectonic geohistory is related to the importance and originality of this research, which lies in the research methods and objectives to be achieved. The existence of rocks and foraminifera fossil species

as objects of geological study is beneficial in reconstructing tectonic geohistory. Unfortunately, research on tectonic geohistory analysis of the Gorontalo region has never been done. For this reason, research is needed on the tectonic geohistory that occurred in Gorontalo not only thousands of years ago but millions of years ago until now. One way to do this is to utilize the content of foraminifera fossil species in Gorontalo rocks. This reconstruction is very important to provide geological information for the government, researchers, academics, and the public. The main target is to develop a model of geological conservation area and geological natural disaster mitigation based on local wisdom in the future.

Foraminifera is a unicellular organism from the phylum Protozoa, class Sarcodina, and sub-class Rhizopod. They are characterized by the ability to form an outer shell. Some species may have a length of more than 100 mm or more but generally have a size of less than 1mm (Jones, 1969; Hanagata & Nobuhara, 2015).

Applying benthonic foraminifera fossils for paleo bathymetry is closely related to the distribution of characteristic species based on bathymetry or depth. This distribution is associated with the ability of benthonic foraminifera to live at specific depths so that environments with different depths will have different characteristic species (Jones, 1994; Herkat & Ladjal, 2013; Milker et al., 2014). The distribution of benthonic foraminifera fossils will be used as a determinant of paleo bathymetry using two classifications, namely the classification of Jones (1994) and Tipsword et al. (1966), which divide paleo bathymetry based on the depth of habitat of each benthonic foraminifera species. In fact, Tipsword et al. (1996) divided bathymetric zones for marine environments based on microfossil association data and planktonic/benthonic (P/B) ratio from the Gulf of Mexico. This classification combines the data associated with lithology, sedimentology, and tectonics. Based on this background, this research aims to analyze the Tectonic Geohistory of Gorontalo Region based on Benthonic Foraminifera Fossil.

Materials and Methods.

The research location is in Ombulo Village at coordinates 00° 39′ 7.08" East Longitude and 00° 39′ 7.08" North Latitude, precisely in the highland morphology. The research material is limestone outcrops scattered along the Gorontalo Outer Ring Road. The stratigraphic position of the study area can be seen on the geological map of the Ombulo Region, Gorontalo Regency (Figure 1).

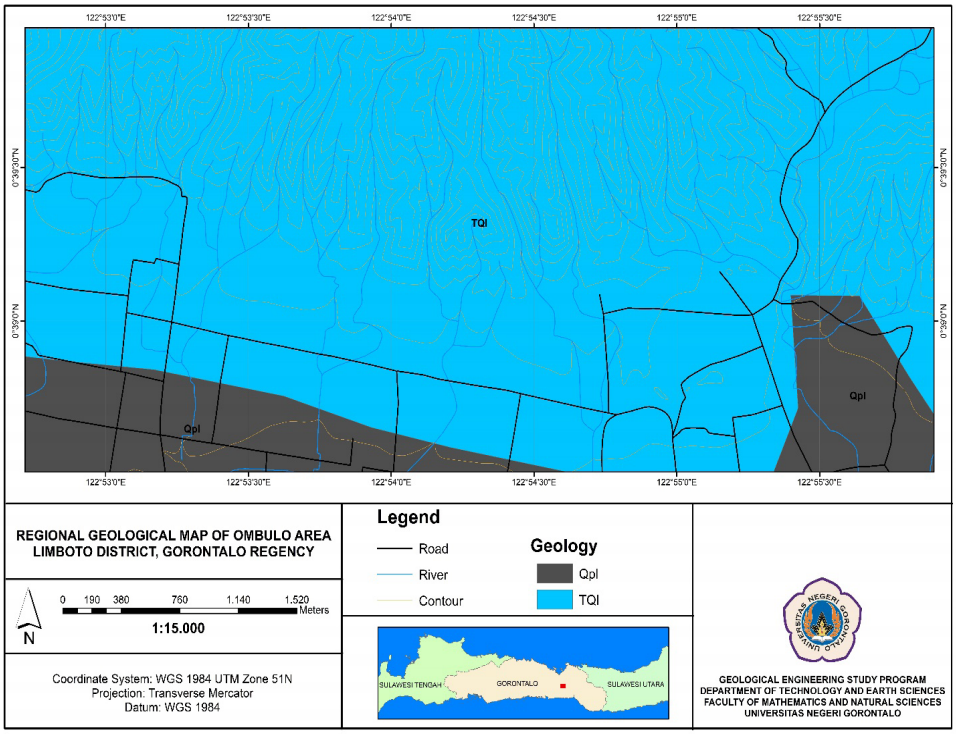

Figure 1. Distribution of limestone outcrops (TQl) with other rocks on the geological map of the Ombulo area, Gorontalo Regency.

The material or object of research is limestone outcrops with a thickness of up to 25 meters. The types of research used in this study are qualitative and quantitative. Qualitative analysis in the form of field surveys in the form of stratigraphic measurements is known as the measured section (MS) method and sampling. Sampling for biostratigraphic analysis to be taken to the laboratory is a fine-sized limestone sample, namely mud. Quantitative analysis is based on microscopic observations from the samples taken in the field for biostratigraphic analysis (Kadar, 1986; Armstrong & Brasier, 2005). The MS method measures the details of stratigraphic sediment layers using Jacob's stick, which has a length of 1.5 meters with sequential and systematic sampling. The 1.5-meter Jacob's stick has an interval of 10 cm marked by a striking color difference between black and white. This MS method aims to obtain the stratigraphy of the study area based on the different characteristics of each facies (Compton, 1985; Permana, et al., 2019; 2021; 2024).

Biostratigraphic analysis was conducted at the Paleontology and Micropaleontology Laboratory of Universitas Negeri Gorontalo using an Olympus SZ61 binocular microscope connected to a computer to facilitate the observation and documentation of photos or images of very small (micro) foraminifera fossils.

This biostratigraphic analysis helps identify the type of benthonic foraminifera fossils so that the main purpose of ancient environments and ancient salinity content can be known (Jones, 1994; Nichlos, 2009; Permana, et al., 2020; 2021; Refalta, et al., 2022).

Paleo bathymetry data obtained from the analysis of benthonic small foraminifera must first be corrected to create a bathymetry change curve from the oldest to the youngest rock, where the connected point is generally the midpoint of the paleo bathymetry range (van Hinte, 1978) (Figure 2). The final analysis step is to make eustasy corrections by correlating regional eustasy data with age. After that, the main cause of the change in paleo bathymetry will be known, whether it is tectonic or eustasy.

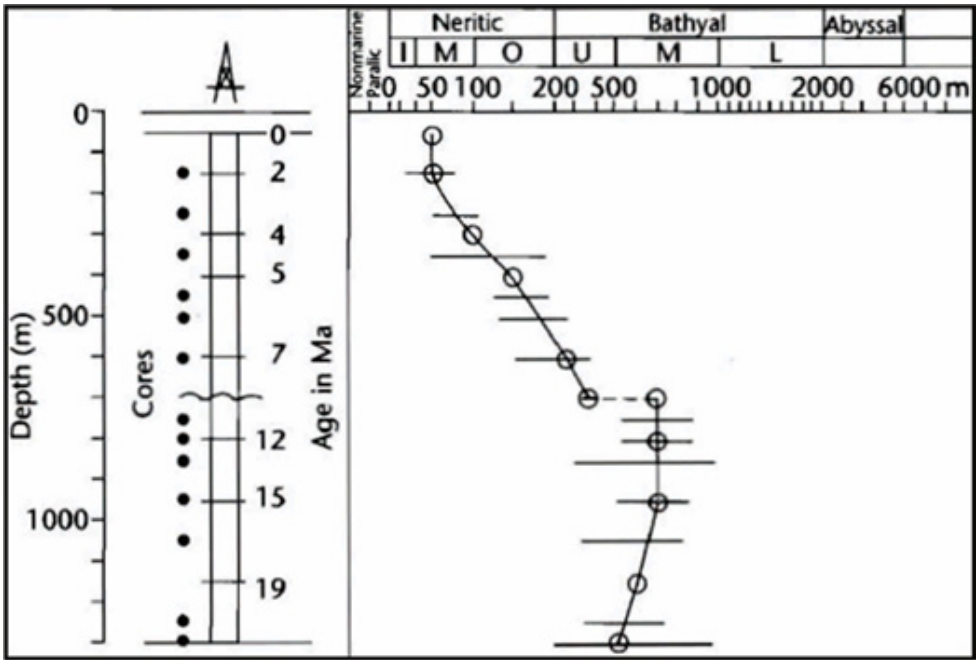

Figure 2. Paleo bathymetry correction curve (Van Hinte., 1978)

Results.

Geological survey in the study area based on measured section (MS) results shows that the main constituent is limestone. Based on the facies analysis in the field, there is only one facies, namely coralline rudstone interbedded with mudstone. Full petrological description: the limestone is white, poorly sorted, open-fabric, matrix-supported grains with dominant grain abundance >2 mm. The bedding structure is thinning upward. The composition is mollusk fragments, coral fragments, quartz, and opaque minerals as fragments with a matrix of micrites. Based on the petrological description, the rock's name is coralline rudstone, which refers to the classification (Embry & Klovan, 1971; Permana et al., 2019a). The insertion

based on petrological analysis is fine brown limestone (grain size <1/256 mm), mud-supported, well-sorted, closed fabric with micrite and quartz composition. According to the results of the petrological analysis, the rock's name is mudstone, referring to the classification (Embry & Klovan, 1971; Permana, et al., 2019a). The age of the rock based on the biozonation of planktonic foraminifera in the study area with LO *Globoquadrina dehiscens* biodatum (5.80 MA) is equivalent to Early Pliocene (Permana, et al., 2019b).

Micropaleontological observations in the study area using the measuring section (MS) method on ten samples sorted stratigraphically from oldest (bottom) to youngest (top), there are 16 species of benthonic foraminifera fossils. Sixteen species of benthonic foraminifera fossils, namely *Bolivinita quadrilatera* (Schwager, 1866), *Cornuspira foliacea* (Phillippi,1844), *Fijinonion fijiense* (Cushman & Edwards,1937), *Gyrodinoides broeckhiana* (Karrer, 1878), *Gyrodinoides soldanii* (d'Orbigny,1825), *Lenticulina denticulifera* (Cushman,1913), *Mellonis Affinis* (Reuss, 1851), *Nautilus craticulatus* (Fichtell & Moll, 1798), *Nonion fabum* (Fichtel & Moll,1798), *Pararotalia venusta* (Brady, 1884), *Praeglobobulimina ovata* (d'Orbigny,1839), *Pyrgoella sphaera* (d'Orbigny,1839), *Rhabdammina discreata* (Brady,1881*), Saccorhiza ramosa* (Brady,1879), *Spiroplectinella wrightii* (Silvestri,1903), and *Uvigerina hollicki* (Thalmann,1950).

Paleo bathymetry analysis on the MS Daenaa line on samples 3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H, 3I and 3J. The paleo bathymetry zone on the MS Danaa line is divided into several zones. The paleo bathymetry zone for sample 3A is the middle shelf-upper slope (72.5-283.65 meters). The paleo bathymetry zone for sample 3B is the outer shelf-upper slope (183-283.65 meters). The paleo bathymetric zone for sample 3C is the upper slope (283.65-366 meters). The paleo bathymetry zone for sample 3D is the upper slope-lower slope (283.65-1830 meters). The paleo bathymetry zone for sample 3E is the upper slope-lower slope (283.65-1830 meters). The paleo bathymetry zone for sample 3F is the upper slope (283.65-466.65 meters). The paleo bathymetry zone for sample 3G is the upper slope (283.65-366 meters). The paleo bathymetry zone for sample 3G is the upper slope (283.65-366 meters). The paleo bathymetry zone for sample 3H is the upper slope (283.65-466.65 meters). The paleo bathymetric zone for sample 3I is middle shelf-abyssal (54.9-1830 meters). The paleo bathymetric zone for sample 3J is the upper slope (283.65-549 meters). The benthonic fossil content association can be seen in Table 1.

Table 1. Benthonic foraminifera distribution chart and paleo bathymetry of the study area

SAMPLE CODE	Bentonic Foraminifera																NUMBER OF SPECIMENS	Paleobathymetry									Paleobathymetry (Jones., 1994)
	Bolivinita quadrilatera (Schwager,1866)	*Cornuspira foliacea (Phillippi,1844)*	*Fijinonion fijiense (Cushman & Edwards,1937)*	*Gyrodinoides broeckhiana (Karrer)*	*Gyrodinoides soldanii (d'Orbigny,1825)*	*Lenticulina denticulifera (Cushman,1913)*	*Mellonis Affinis (Reuss)*	*Nautilus craticulatus (Fichtell & Moll)*	*Nonion fabum (Fichtel & Moll,1798)*	*Pararotalia venusta (Brady)*	*Praeglobobulimina ovata (d'Orbigny,1839)*	*Pyrgoella sphaera (d'Orbigny,1839)*	*Rhabdammina discreata (Brady,1881)*	*Saccorhiza ramosa (Brady,1879)*	*Spiroplectinella wrighti (Silvestri,1903)*	*Uvigerina hollicki (Thalmann,1950)*		*Terrestrial*	*Littoral*	*Shelf*			*Slope*			*Abyssal*	
																				Inner	*Middle*	*Outer*	*Upper*	*Middle*	*Lower*		
3J			12	2									1				15										283,65-549 m
3I							1						4				5										54.9-1830 m
3H			7			1							4		1		13										283,65-466.65 m
3G			2						1				12				15										283.65-366 m
3F			1										1				2										283,65-466,65 m
3E													2	1			3										283.65-1830 m
3D													1	1			2										283.65-1830 m
3C			2						2				2				6										283,65-366 m
3B					1				1		2		3				7										183-283.65 m
3A		2	1				1		2				2				8										72.5-283.65 m

Discussion.

Paleobathymetry data obtained from the analysis of benthonic small foraminifera must be corrected first because the paleo bathymetry results obtained are in the form of a range, while what is needed in the study of sea level change is paleo bathymetry in the form of absolute numbers. Therefore, correcting by making a paleo bathymetry change curve from the oldest to the youngest stratigraphic layer is necessary. The step taken is that the connected point is generally the midpoint of the paleo bathymetry range. The resulting curve is made as smooth as possible so that it will be corrected for some depths by not plotting at the center of the depth range.

After completing the benthonic foraminifera distribution chart, the paleo bathymetry correction curve should be made. The paleo bathymetry correction curve is created by smoothly connecting the depth points from each sample's paleo bathymetry range, then sorted stratigraphically from bottom to top (van Hinte., 1978). The paleo bathymetry correction curve aims to determine the pattern of sea level change to be compared to the global sea level change curve. The sea level will be known whether it drops or rises so that if it is related to global sea level changes, it is clear that the tectonic influence is very strong in the study area.

Paleobathymetry correction curve analysis based on plotting ten samples from

the oldest sample, 3A (bottom), to the youngest sample, 3J (top), shows a striking or significant sea level change in the study area during the Early Pliocene (6.4 MA - 5.8 MA). Changes in sea level tend to increase (getting deeper) because initially, the depth of the sea level was 178.425 meters and then changed drastically to be deeper to 500 meters. The difference in sea level change from the oldest to the youngest stratigraphic layer is 500-178.425 meters = 321.575 meters (Figure 3).

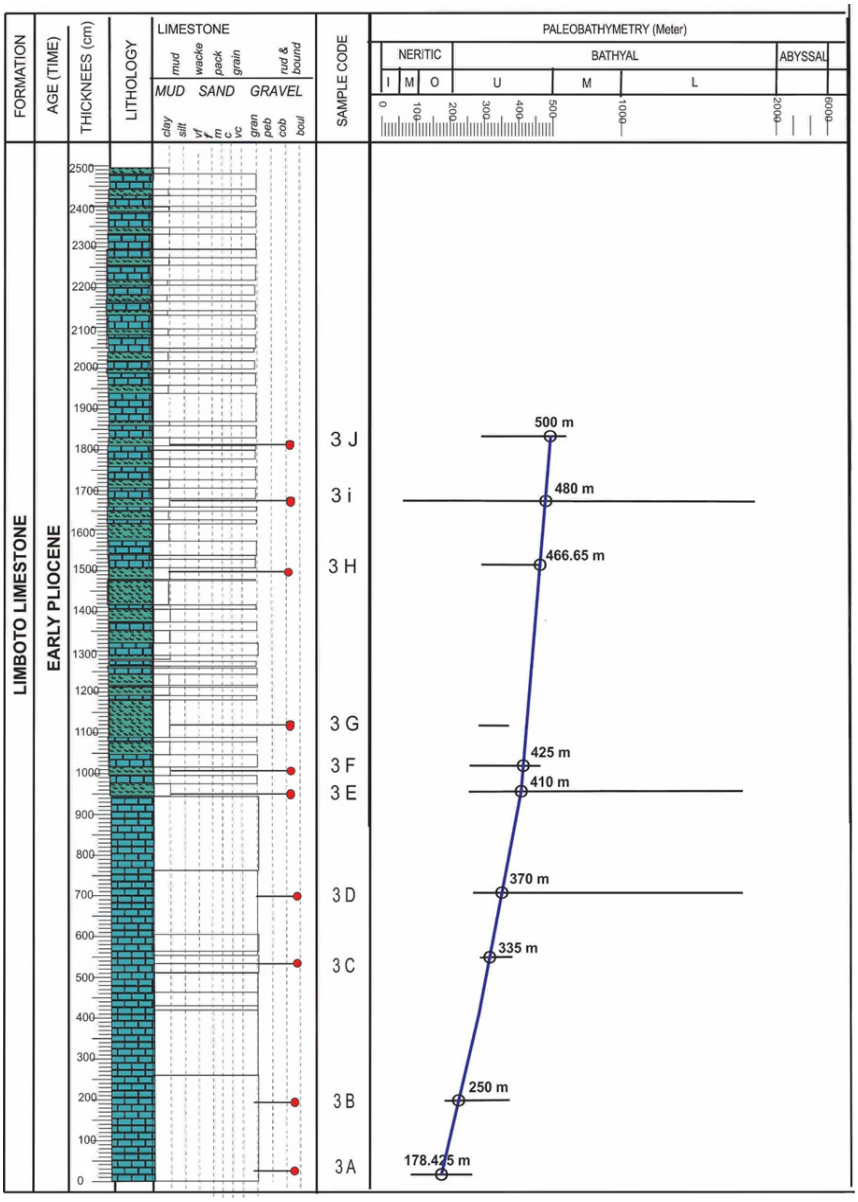

Figure 3. The paleo bathymetry correction curve of the study area shows a deepening sea level change from the oldest to the youngest stratigraphic layer.

The results of the paleo bathymetry curve analysis in the study area are the key to answering the mystery of the Early Pliocene period (6.4-5.8 MA) whether the sea level rise of 321.575 meters was due to global sea level rise or tectonic influences in the form of subsidence. The step that needs to be done is to make an eustasy correction. Eustasy correction is done by correlating regional eustasy data with age. After that, the leading cause of paleo bathymetry changes will be known, whether due to tectonic influence or eustasy.

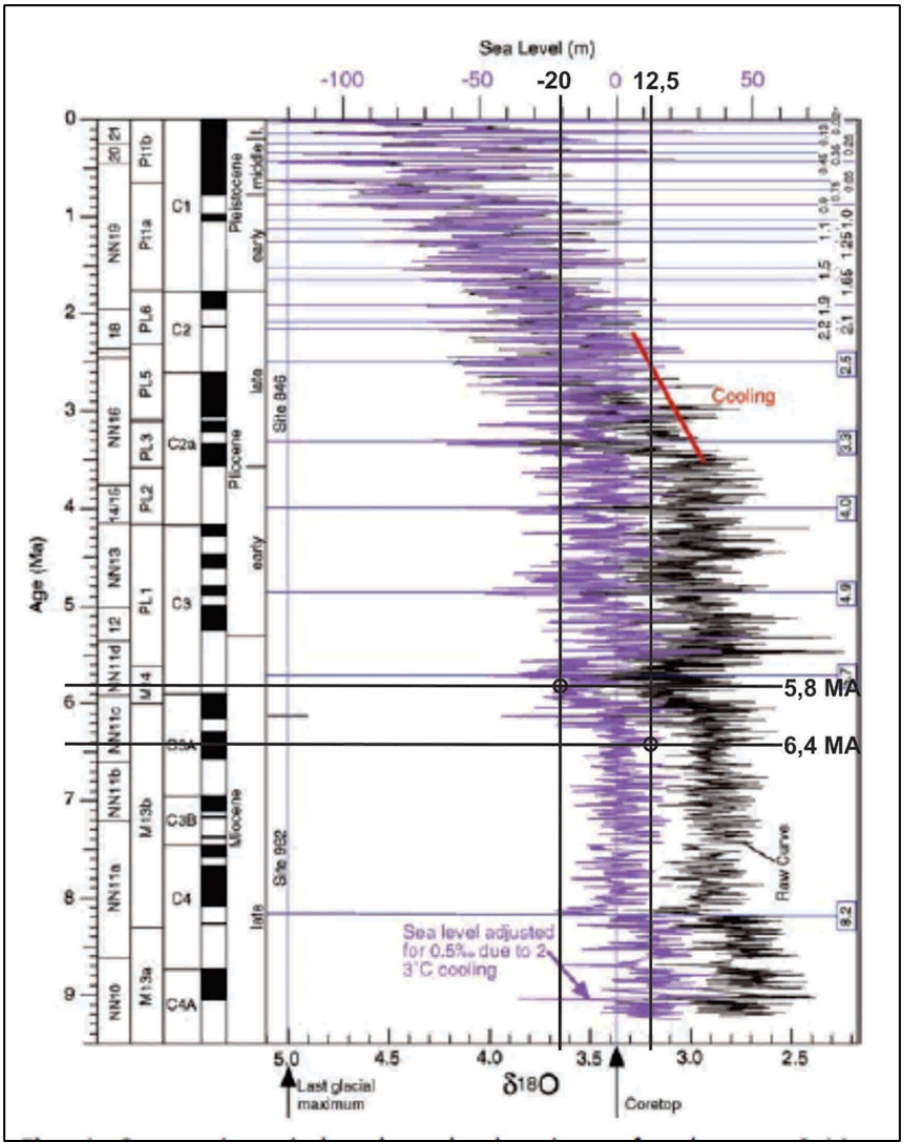

Figure 4. The position of the sea level of the study area (Early Pliocene 6.4-5.8 MA) in the global sea level curve tends to be stable, with no changes in either rising or falling sea level, referring to the model Miller et al. (2005).

Analysis of the geohistory of the study area refers to changes in sea level that rose drastically due to tectonic subsidence because, according to the model Miller et al. (2005) (Figure 4) in the Early Pliocene (6.4-5.8 MA), no global water level changes occurred. Based on (Figure 4), it shows that in the Early Pliocene, sea level tends to be stable. For this reason, if there is an increase in water level in the research area based on the analysis of the paleo bathymetry curve, the tectonic influence in the form of subsidence is dominant because this subsidence causes a change in the depth of the rock deposition basin which was initially at a depth of about 178.425 meters to 500 meters.

Conclusion.

Referring to the results of research on the Tectonic Geohistory of the Gorontalo Region Based on Benthonic Foraminifera Fossils, the primary lithology of the research area is limestone, which contains 16 benthonic foraminifera fossil species. Those fossils indicate that paleo bathymetry ranges from the middle shelf to the abyssal, which facilitates making paleo bathymetry curves after correction. This curve becomes data to develop the eustasy curve, which shows that the decrease in sea level in the study area is due to tectonic influences, namely subsidence.

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