**Carbonate Sedimentology of Coral Reefs in Sumba Island, Indonesia**

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**Abstract:** The Island of Sumba, Indonesia, comprises several reef terraces formed by changing global sea levels and episodic tectonic activity. Volcanic-derived sediment has been found to have been incorporated into reef fabrics without impacting coral growth. The uninterrupted reef growth shows a conflicting theory that coral reefs do not survive under significant clastic input. Continuous reef growth has been documented in this region known as the Coral Triangle. However, it is unclear whether intervals of increased clastic content affect coral growth strategies or whether the immature nature of the volcaniclastic sediment (larger and angular grain) explains why clastic input does not choke corals. This study employs various thin sections from fossil reefs (late-Pleistocene) to document and characterize the sediment's size and circularity, which is a measure of sediment maturity. The study involves imaging analysis by taking images of each thin section. The thin sections have all been stained with Alizarin red, a stain that only turns calcite or aragonite grains a shade of red, and all other minerals remain unstained. Then, the images were colour indexed to black and white, with clastic grain appearing as white. The images underwent thresholding to isolate the white grains to measure their circularity and sizes. It was found that the grains of the sediments are sand size and angular, which means that the grains only have some transported involved, but they did not deposit far away from their source. A range of grain sizes in these sections have revealed that some of the grains detected are small enough to enter corallites and pores in the coral skeleton, while others are much larger and would not impact the coral growth.

**Introduction:**

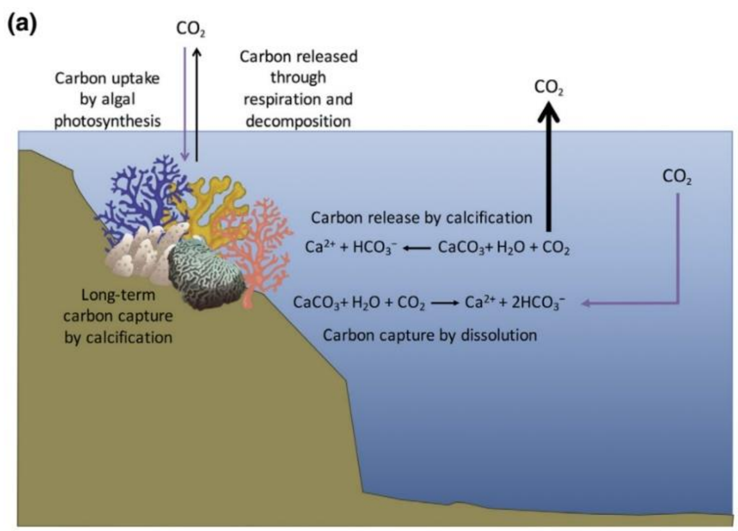



**Figure 1:** Coral reefs mechanism as carbon sources and sink. Figure courtesy: Howard et al. (2017)

The world's coral reefs cover about 2,284,300 km$^2$, which only accounts for 0.09% of the total area of the world's oceans, and are found within twenty-five degrees north and south latitude in the tropical and subtropical areas (Majumdar et al., 2018). The Indo-pacific region consists of about 90.6% of the world's reef area, and Indonesia and Australia account for most of that portion (Majumdar et al., 2018). Indonesia has 77 percent of the world's coral reef species, more than 500 coral species and half of the world's reef fish species (Dunning, 2018). Indonesia lies within the coral triangle, a region home to diverse species of corals. The corals provides an essential habitat for many sedimentary organisms and fish as they encourage growth to the reefs (Cole et al, 2008). There are several arguments whether coral reefs act as carbon sources or sinks. Oceans, in general, are considered as carbon sinks, absorbing 20-35 percent of anthropogenic $CO_2$ emissions (Howard et al., 2017). However, according to Howard et al. (2017), coral reefs can be either a source or sink of carbon dioxide (Fig. 1). They can be a carbon source by releasing carbon through respiration and calcification; they can also act as a carbon sink by taking carbon through photosynthesis (Howard et al., 2017). Regardless, coral reefs are under threat from climate change. As the sea temperature continues to rise from climate change, the coral reefs begin to break down their single-celled algae (zooxanthellae), which results in bleaching (Spalding and Brown, 2015). The event of mass bleaching started to become recognized during 1983 and was linked to a rise in sea temperatures (Spalding and Brown, 2015).

Siltation is another threat to the coral reefs caused by anthropogenic activities and natural catastrophes. Siltation is an environmental threat or issue that is not often discussed, but moreover, faced by the coastal areas where rivers meet the ocean basins. The main factor that causes siltation is the subsequent deforestation and development of dams and agricultural activities that encourage soil erosion (Cortes and Risk, 1985).

To gain a better understanding of how corals may or may not be affected by siliciclastic input, this study will examine several thin sections from Pleistocene coral reef terraces on the Island of Sumba, located in the southern part of Indonesia. Coral reefs living in this area are thriving, despite being at the base of the river that delivers a significant amount of sediment load (Zonneveld et al., 2021). The sediments have been incorporated into the reef fabrics. The reasons why some coral reefs can under intense sediment load are not well understood. The study area is mainly dominated by siliciclastic/volcaniclastic mixed sediments sourced from Late Cretaceous volcanics of the Wangametti Volcano. This study will determine the grain size of the particles and compare them to the diameter of corallites present in the samples to ascertain why the sediments sourced from the local Kambaniru River not adversely affected coral reef growth. Usually, coral reefs do not survive in an environment where there is a lot of siliciclastic sediment accumulation, such as a delta.

**Literature Review:**

*Sumba Island Geologic History and Features*

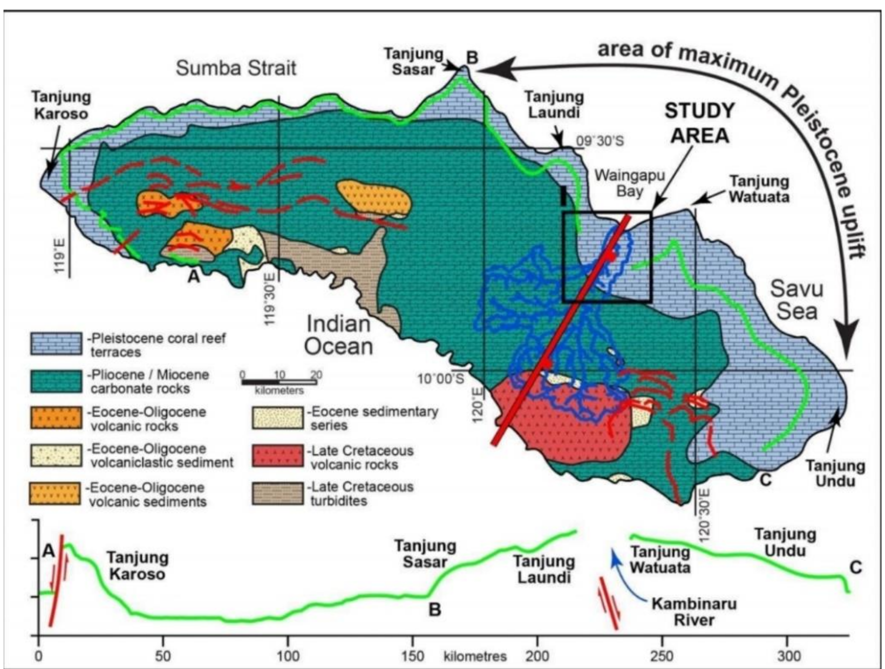


**Figure 2:** the map of the Island of Sumba with the study area. Figure courtesy: Zonneveld et al. (2021).

The Island of Sumba is a 220 km-long and 65 km-wide island in Indonesia, specifically located close to the transition between the Java trench and the Indian-Australian plate (Chauveau et al., 2021). Based on the geochemical evidence of the Late Cretaceous to Early Oligocene igneous rocks, the Island of Sumba formed in an oceanic island-arc environment (Rutherford et al., 2001). The island was part of the Great Indonesia Volcanic arc system until the island rifted away from the volcanic arc in Miocene (Rutherford et al., 2001). The island of Sumba has a displacement rate of approximately 50 mm $yr^{-1}$ over a distance of 450 km before reaching its current position (Rutherford et al., 2001). Most of the rocks in the island range from the Cretaceous Tanadaro pluton to reefal limestone from the Quaternary, which is shown in figure 2 (Rutherford et al., 2001).

There are six sequences of raised coral-reef terraces located near Cape Laundi (Pirazzoli et al., 1991). Sumba Island remains an active rising island, creating a staircase geometry (Chauveau et al., 2021). The coral reef terraces form when a coral reef dies and fossilizes due to rapid global sea level decline, and/or the reef is lifted by the tectonic activity (Chauveau et al., 2021). The series of uplift terraces began during the mid-Pleistocene, the oldest formed of coral reef terraces and dated around one million years (Pirazzoli et al., 1991). The average denudation rate of Sumba Island is 14.7 ± 8.3 mm/ka (Chauveau et al., 2021).

The river on the island known as the Kambaniru River (Fig. 2) is a 118 km long river with a high gradient and steep-side profile (Zonneveld et al., 2021). The river's source is Mount Wanggameti (1225 m), then the river empties into Waingapu Bay. The river carries volcanic sediment from the main source of the river basin, and carbonate rocks as the river flow down to the island, then deposited in the delta (Zonneveld et al., 2021).

*Coral reef siltation and sedimentation*

Coral reef threats occurred both naturally and anthropogenically. Coral reefs can be damaged by catastrophic natural disasters such as typhoons, earthquakes, tsunamis, etc. Siltation and sedimentation contribute to a major problem of coral reefs. In Cortes and Risk, (1985), coral growth rates diminished in areas with high sediment resuspension rates. The availability of light is crucial for the survival of coral reefs due to photosynthesis, and sediments can reduce the light available for photosynthesis (Rogers, 1990). Siltation has been known as deleterious to the coral reefs because it decreases the corals' light availability (Cortes and Risk, 1985). Human activities promote the risk of coral reef sedimentation. For instance, mangrove trees are known to entrap sediments. However, cutting these mangrove trees has resulted in excessive siltation from the heavy run-off (Rogers, 1990). Heavy run-off of eroded soils increases turbidity, reducing the available light for photosynthesis. Sedimentation has also negatively impacted the complex food web on the reef by killing the corals, sponges and other organisms important for food to the commercial shellfish and fish (Rogers, 1980). Human activities such as sand mining for construction materials have led to the destruction of coral reefs (Majumdar et al., 2018).

**Methods:**

There are eight thin sections analyzed for this project provided by Dr. J.P. Zonneveld from the Earth and Atmospheric Science Department at the University of Alberta. This project will analyze the thin section’s mineral composition, siliciclastic grain size and circularity. The pore sizes of the corallites will also be measured to determine if the siliciclastic grains can enter through the pores. The thin sections were stained with Alizarin Red, which turns calcite and aragonite red without affecting the siliciclastic and volcanoclastic grains (Fig. 3).

**Figure 3.** Thin section stained in Alizarin red

The thin sections were analyzed using a petrographic microscope (Zeiss Axio Scope.A1), with a camera (Zeiss Axiocam 105) attached to the microscope. The petrographic microscope is used to examine the mineralogy, grain sorting, porosity, and allochems of the thin sections.

Zen 2.3 lite software was used to capture the image of the thin sections from the microscope (Fig. 4a). The captured images were indexed in Adobe Photoshop to colour template associated with an Image J macro called JPor (Grove and Jerram, 2011). The images were converted to black and white to appear the siliciclastic grains as white. (Fig. 4b). Each image was analyzed in ImageJ by thresholding the images to highlight the siliciclastic material (Fig. 4c). Then, the grains' sizes and circularity were measured using the analyze particles function.

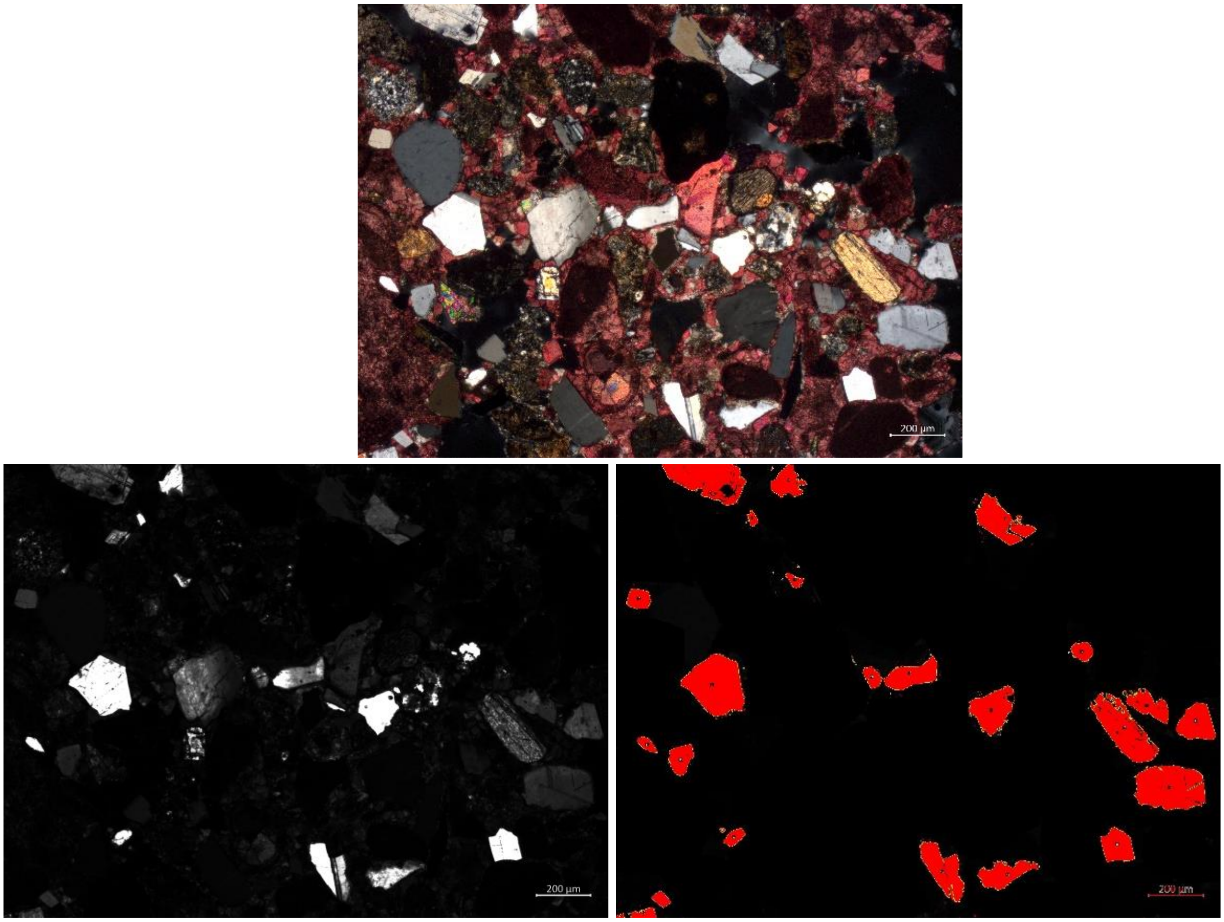



**Figure 4:** The process of Image process analysis (a) image capture using Zen 2.3, (2.5x) (b) colour indexed by Adobe Photoshop (c) ImageJ grain threshold

The particles' size will be determined by their ferret, which is the longest diameter of the grains, and the minimum ferret, the shortest diameter of the grain. The grain sizes of the siliciclastic particles were determined by the Udden-Wentworth scale values (Fig. 5). The ferret and minimum ferret were measured in millimetres. The circularity of the grains was measured from 0 (the least circular) to 1.0 (the most circular). ImageJ's grain size data were analyzed using Microsoft excel by creating an x- and y-axis graph. A histogram maker software was used to create a histogram to analyze the grain circularity. The diameter of the corallite's pores are manually measured using the Zen 2.3 lite software.

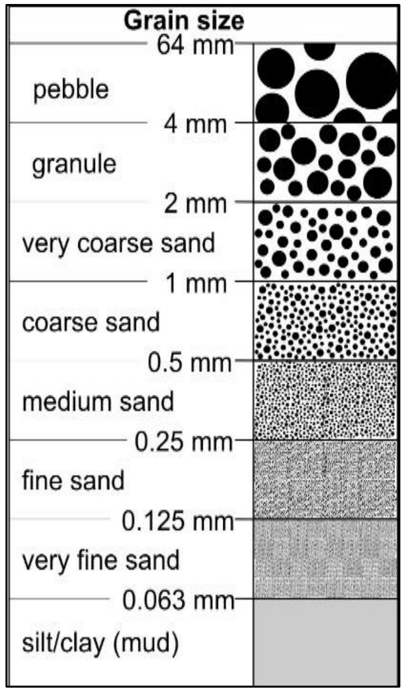



**Figure 5:** Udden-Wentworth Scale. Figure link: https://geologyistheway.com/sedimentary/grain-size/

**Results**

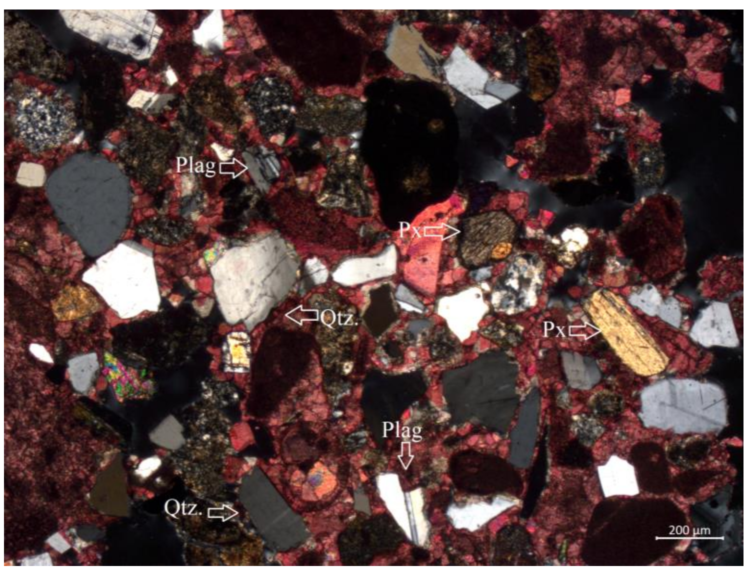
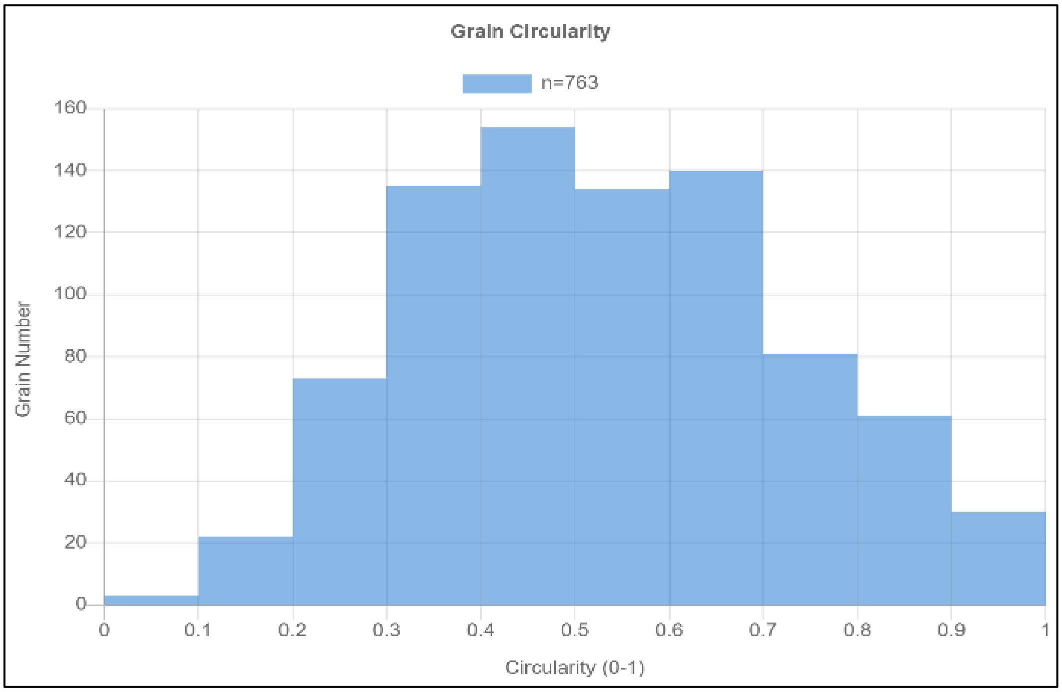



**Figure 6 :** The mineral composition of the carbonate rocks on a thin section, XPL (2.5x)

The rocks in the thin section are classified as volcanoclastic-siliciclastic mixed carbonate sedimentary rock. Quartz, plagioclase feldspar and pyroxene are the top three minerals in thin sections (Fig. 6). Also, the thin sections have bioclastic material consisting of different species of corals (mostly Scleractinia), foraminifera (benthic and planktic), ooids, and echinoderms. Calcite and aragonite cement is the cement that consists within thin sections.

a) 

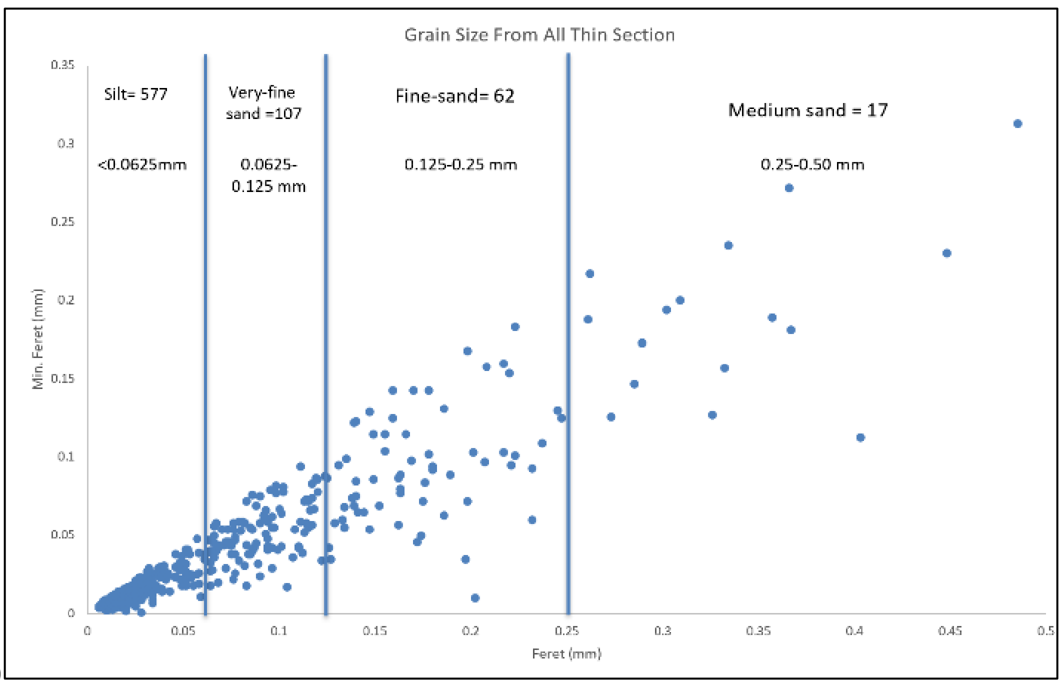

b) 


**Figure 7: (a)**Histogram of the grain circularity **(b)**Grain Size Graph

The recorded data for the grain circularity measured by ImageJ is shown in figure 7a. ImageJ measures 763 grains from the images based on the black-and-white image pixels. A total of 563 grains have a circularity value between 0.3 to 0.7, with 0.4-0.5 having the highest amount of grains (154 grains). The grain circularity is identified as angular to moderately rounded grains (Szmańda and Witkowski, 2021). A total of 172 grains have a circularity value between 0.7 to 1 which is almost completely circular. In terms of the grain sizes, figure 8a contains the most coarse grains and figure 8b contains the finest grain. According to figure 7b, the grain sizes range from silt to medium sand grains.

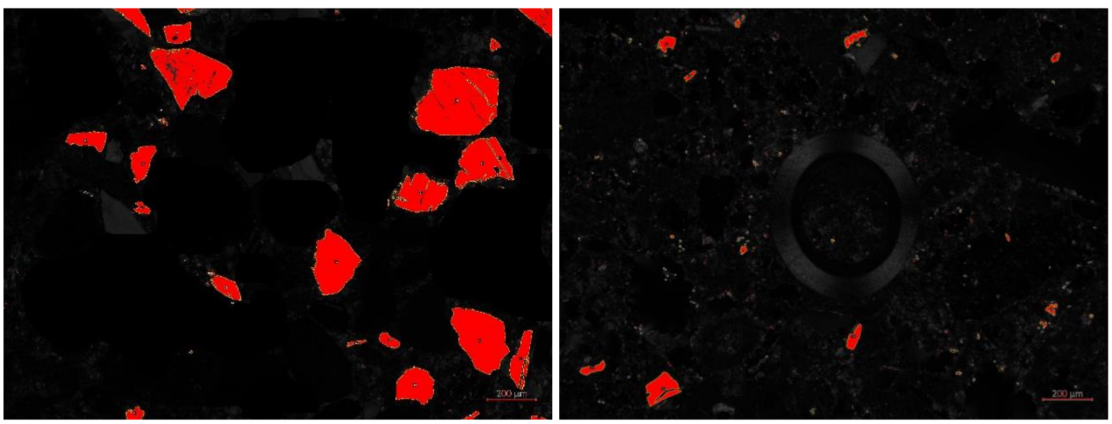


**Figure 8:** Samples with (a) the most coarse grain, and (b) fine grain

The grain circularity and mineralogy are considered immature in grain texture (Klein & Philpotts, 2017). Figure 9 shows a poorly sorted angular grain, and there are a considerable amount of fine-sized particles mixed with sand-size particles (Boggs, 2012). The stability of the minerals accounts for the immaturity of the grains. Quartz is the most abundant in all thin sections. Quartz has high stability, which means that it is highly resistant to weathering (Boggs, 2012). Finally, the corallites' measured pores range from 0.057-0.215 mm (Fig. 10). The average pore size is 0.174 mm, within the range of fine sand grains (0.125-0.25mm).

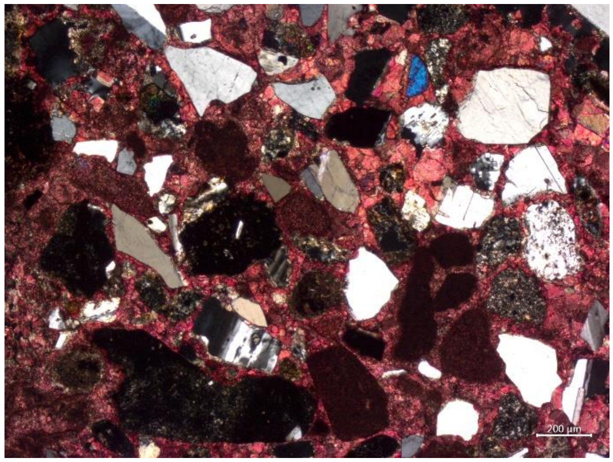



**Figure 9:** Grains that are immature in texture and composition, XPL (2.5x)

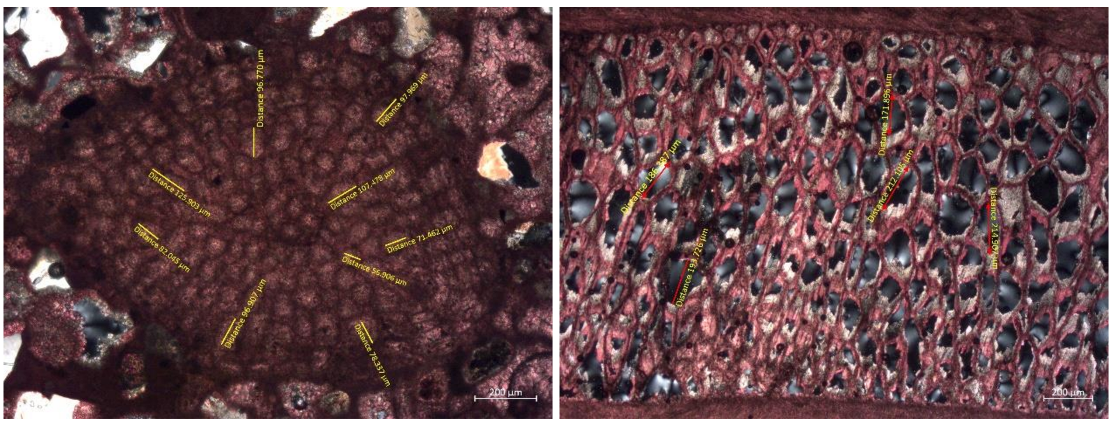



**Figure 10:** estimated measurements of the pore sizes of the corallites, left: XPL (5x), right: XPL (2.5x)

Unfortunately, there are some sources of error when working with the image analysis of the grains, especially when using ImageJ. The first problem encountered is that the thin sections do not have a blue epoxy. The epoxy highlights the pores of the thin section, so it will differentiate from the grains when looking at the thin section under a cross-polar light on a microscope (Grove & Jerram, 2011). It is difficult to differentiate the grains and the pores with our thin sections when looking at the plane polar light because some grains have a low relief, such as quartz (Klein & Philpotts, 2017). The thin section has to be investigated under crossed polar light to see the grains and pores under the microscope. The pores of the samples look black under crossed polar light, but there is some light able to get through, and ImageJ counts it as a small fine grain which skewed our data. The corrective methods to fix the problem will be to get a new thin section with blue epoxy resin or dissolve the rock sample with hydrochloric acid or nitric acid. These acids will dissolve any carbonate materials on the rock, leaving the siliciclastic grains. Although hydrochloric acid can dissolve siliciclastic grains, nitric acid would be a better option.

**Discussion**

Considering rock-forming minerals (quartz, plagioclase feldspar, and pyroxene) means that the rocks are more likely to come from the igneous source. Mount Wanggameti is the source of the Kambaniru River, which contains volcanic rocks dating from the Late Cretaceous, intruding by andesitic and dacitic dikes (Rutherford et al., 2001). Thus, the grain's mineralogy is expected to be carried by the river. The presence of other minerals than quartz, such as feldspars, and unstable rock fragments indicates that the sediment is compositionally immature (Boggs Jr, 2012). According to Klein and Philpotts (2017), the more detritus is subjected to abrasion, the more quartz it contains, as the less resistant minerals are sifted away.

The rocks' carbonate materials could come from Pliocene/Miocene carbonate rocks, which make up most of the island (Fig. 2) (Zonneveld et al., 2021). Specifically, the Pliocene/Miocene carbonate rocks near the Kambaniru river are part of the Kananggar Formation, where there is evidence of resedimentation of volcaniclastic and sedimentary rocks from shallow water (Rutherford et al., 2001).

Any grains finer than fine sand, such as silt, can still enter the pores of the corals. However, corals can survive and thrive for millions of years, looking at the carbonate rock records. Their survival is that the natural episodic monsoon drives siltation in the river. Perhaps, the river does not experience siltation during the dry season. The river's source experiences rainfall from November to April, with 2000-4000 mm of rain (Zonneveld et al., 2021). The Kambaniru delta only receives heavy rain between December and March with 800-600 mm (Zonneveld et al., 2021).

**Conclusion and Impact:**

The research project aims to investigate coral reef survival under siltation. Usually, coral reefs do not favour heavily sedimented areas due to reducing light and clogging of their pores. Looking at the ancient reef records, they were able to thrive when there was siltation. It was concluded that the siltation is driven by the episodically by monsoon. The siliciclastic grains are texture and compositionally immature and are locally sourced from the island. The importance of this research project is that it will open up more possibilities for tackling the problems regarding coral reefs. Siltation is not often focused on when it comes to talking about the adversities of coral reefs. Unfortunately, humans are the main driving force of siltation. Reaching this issue to the people, especially the scientific community, people can re-think ways to reduce this problem. Re-think when infrastructure is being built near the coastal areas to ensure that siltation is not possible for the coral reefs. Also, this study shows us that the coral in this region can deal with some episodic sedimentation, so it can help us to understand what acceptable levels of sedimentation are near coral reefs.

**Acknowledgement:**

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