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## Geological Evaluation of Structural Deformation of the Tawar Formation, Aceh Tengah, Indonesia

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### Abstract

Lake Lut Tawar, which is situated in Aceh Tengah, has a unique geological landscape, with the presence of rock formations of the Pre-Tertiary age (Tawar Formation) and its geological connection with the Sumatran fault and the Bukit Barisan mountains. Even though the geological condition of the Lut Tawar Lake has attracted the attention of many geologists to carry out various kinds of research, there is still a lot of geological understanding that is not yet known, especially regarding the Tawar Formation. Tawar Formation is of Pre-Tertiary age and can be found around Lut Tawar Lake, Aceh Tengah. This research targeted the Tawar Formation with two main objectives: (1) to evaluate structural deformation and geologic structures developed within the Tawar Formation and (2) to understand better the main factors influencing the evolution of the Tawar Formation. Integrated geological analyses, including structural geology analysis, scanline method, and stereo net method, were used to achieve the objectives of this research. Results from this study show that the Tawar Formation has experienced a complex structural deformation, evidenced by the presence of various geological structures such as multi-size and multi-episode fracture systems and numerous folds and faults. Furthermore, we interpret the evolution of the Tawar Formation to be strongly influenced by tectonic activity, possibly related to the movement of the Sibumasu plate, the Sumatran fault system, and plate subduction in the southwest part of Sumatra. It is expected that the results of this research will provide a new understanding of the history and evolution of the Tawar Formation and a better understanding of the deformation of rock structures that occurred in the Lut Tawar area, Aceh Tengah.

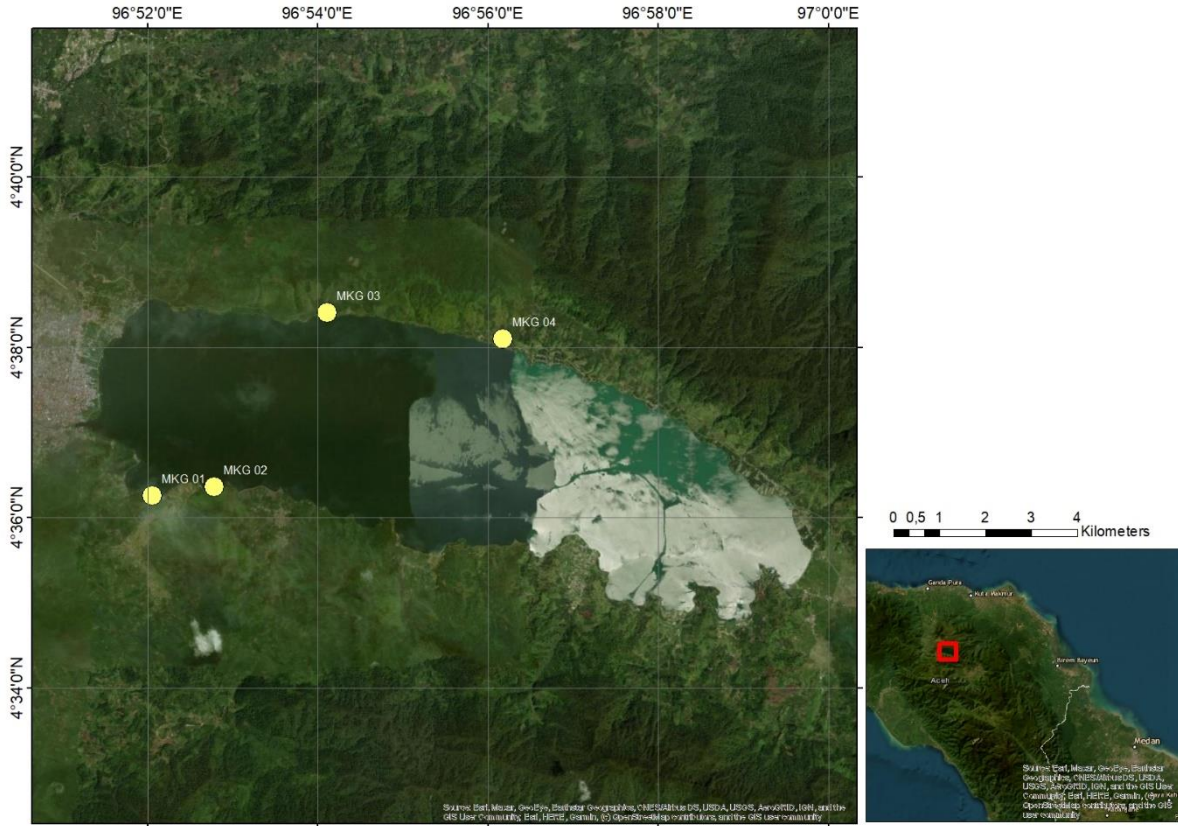
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### Introduction

Lut Tawar Lake (~57 km<sup>2</sup>) and its vicinity, located in Aceh Tengah regency, province of Aceh, Sumatra, Indonesia, provided a good location for structural deformation study due to the presence of various rock outcrops with strong deformation and its accessible location. The geological study of the Tawar Formation, located around Lut Tawar Lake (Figure 1), is rare in the literature, and much is not known about the geological history of this formation. Research on the geological condition of the Tawar Formation was previously carried out by [1], [2], and

[3], and there are limited available published articles about the Tawar Formation within the last 20 years. Moreover, this earlier research on the Tawar Formation was conducted over 20 years ago. Therefore, this research is expected to provide some new insights into the deformation of the Tawar Formation using current data and knowledge.



**Figure 1.** The study area is in Aceh Tengah, Province Aceh, Sumatra, Indonesia. This study collected data from four locations around Lut Tawar Lake (MKG-01 to MKG-04). Modified from Google Earth.

This research was carried out to achieve two objectives: (1) to evaluate structural deformation and geologic structures developed within the Tawar Formation and (2) to understand better the main factors influencing the evolution of the Tawar Formation. Tawar Formation plays an essential role in the geological history of Sumatra due to its Pre-Tertiary age (Jurassic-Cretaceous) [2], and this formation is also strongly related to the movement of the great Sumatran Fault Systems [4]. A better understanding of the Tawar Formation may also provide new insights into the formation and development of Lut Tawar Lake of Sumatra, Indonesia. It will offer new geological data for future regional natural resources management and development planning.

### **Geological Setting**

The island of Sumatra is the product of convergent interactions between the Indo-Australian and Asian plates, and its tectonic patterns and variations are influenced by the magnitude of the interaction angle and the speed of the plates colliding [1]. The formation of Sumatra Island started at the beginning of the Permian period, with the eastern and western positions of

Sumatra on the edges, namely, the seas, which were still separate. On the seashore, carbonates are formed. As we entered the mid-Permian, east and west Sumatra positions became closer together. This is due to the movement of the paleo-pacific plate. Then, it entered the late Permian phase, where the Sibumasu plate (Siam, Burma, Malaya, Sumatra) and the Indochina plate had united. Then, into the Triassic era, western Sumatra and eastern Sumatra merged. Likewise, carbonates on the seashore resulted in the formation of the Bukit Barisan mountains.

The research area is around Lut Tawar Lake, and Figure 2 clearly shows that the study area targeting the Tawar Formation is influenced by the presence of numerous rock formations and various structural deformations. Tawar Formation is classified as being of Jurassic to Cretaceous age, possibly having the character of the Woyla limestone group, which is also of Jurassic and Cretaceous age [2]. On the map of Figure 2, the Tawar Formation appears as thrust wedges implicating shales and phyllites of the Carboniferous-Permian Kluet Formation, Jurassic-Cretaceous Woyla Group, and Tertiary sediments. The phyllites and volcanoes in the Toweren Member may belong to the Woyla Group. Current study of the limestone member of the Woyla group by [5], [6], and [7] showed that this Pre-Tertiary formation was strongly affected by tectonic activities, and this may also seem to be the case with the Tawar Formation, where tectonic activities strongly influence the evolution of the Tawar Formation. Moreover, the Tawar Formation is also considered a potential site of landslides around the Lut Tawar Formation, mainly due to its geological characteristics. [8].

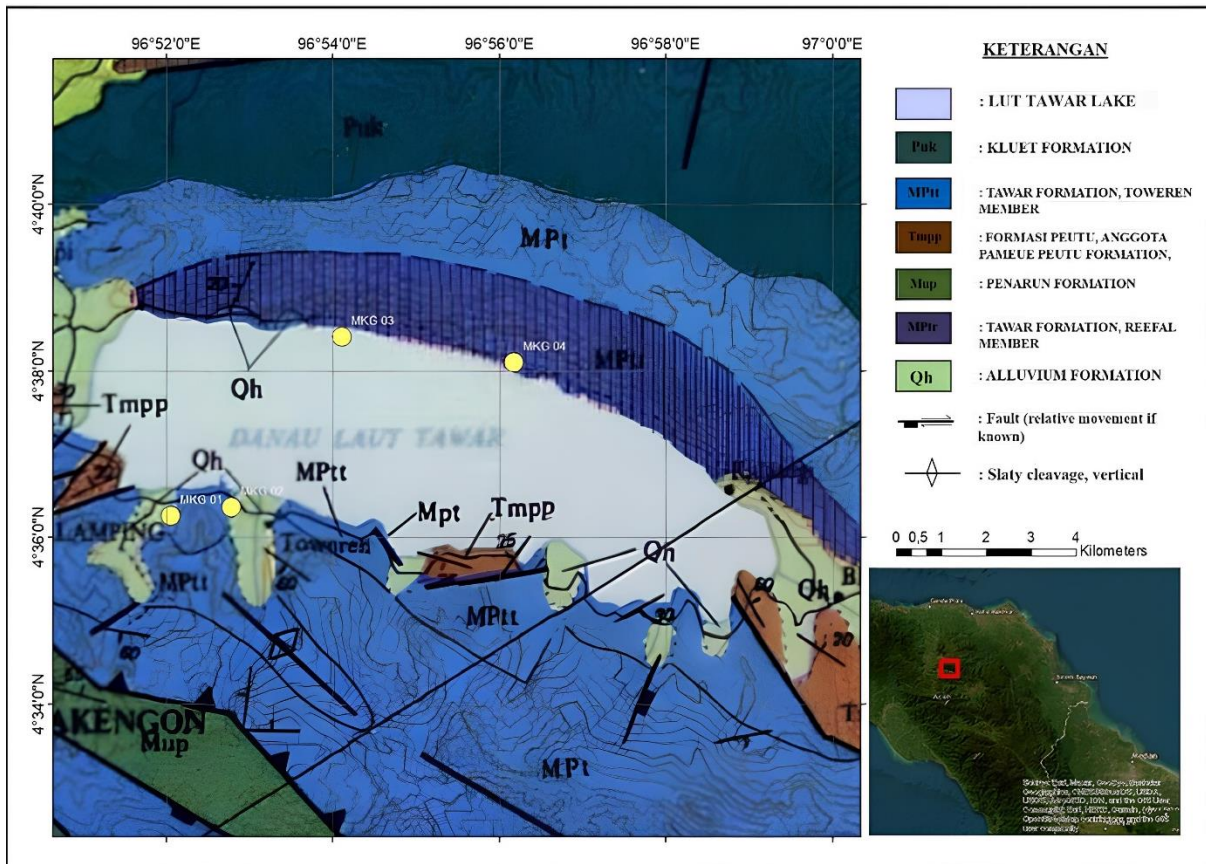


Figure 2. Regional geology map of Aceh Tengah, scale 1:250000, showing numerous rock formations and various structural features [3].



## Methods

This research was conducted using structural data from four locations around Lut Tawar Lake (Figure 1), and 148 structural data were successfully collected. Details of the locations of the data collections are provided in Table 1. Structural analysis, scanline, and stereonet methods were used to process and analyze the data.

**Table 1.** General information about the study area and the number of structural data collected

No	Station	Northing	Easting	No. of structural data
1	MKG-01	509270	263410	18
2	MKG-02	509474	264774	80
3	MKG-03	513237	267233	30
4	MKG-04	512652	271065	20

Structural Geological Analysis is a field concerned with understanding and interpreting how specific rock layers and geological formations interact and experience deformation under scientific pressure and forces. [9]. This is an essential aspect of geology because it helps understand geological history, earth crust movements, and geological processes occurring over millions of years. There are several important things regarding structural geological analysis: basic geological structure, understanding rock deformation, interpretation of folds and faults, geological mapping, research, and discoveries.

The Scanline method is a line on the rock surface that measures all fracture records that intersect with that line [10]. This scanline is a method commonly used to observe and measure fractures on a surface. Still, this method has several limitations, one of which is the difficulty of sampling in extreme areas, such as cliffs or areas prone to landslides, so that it can endanger observers.

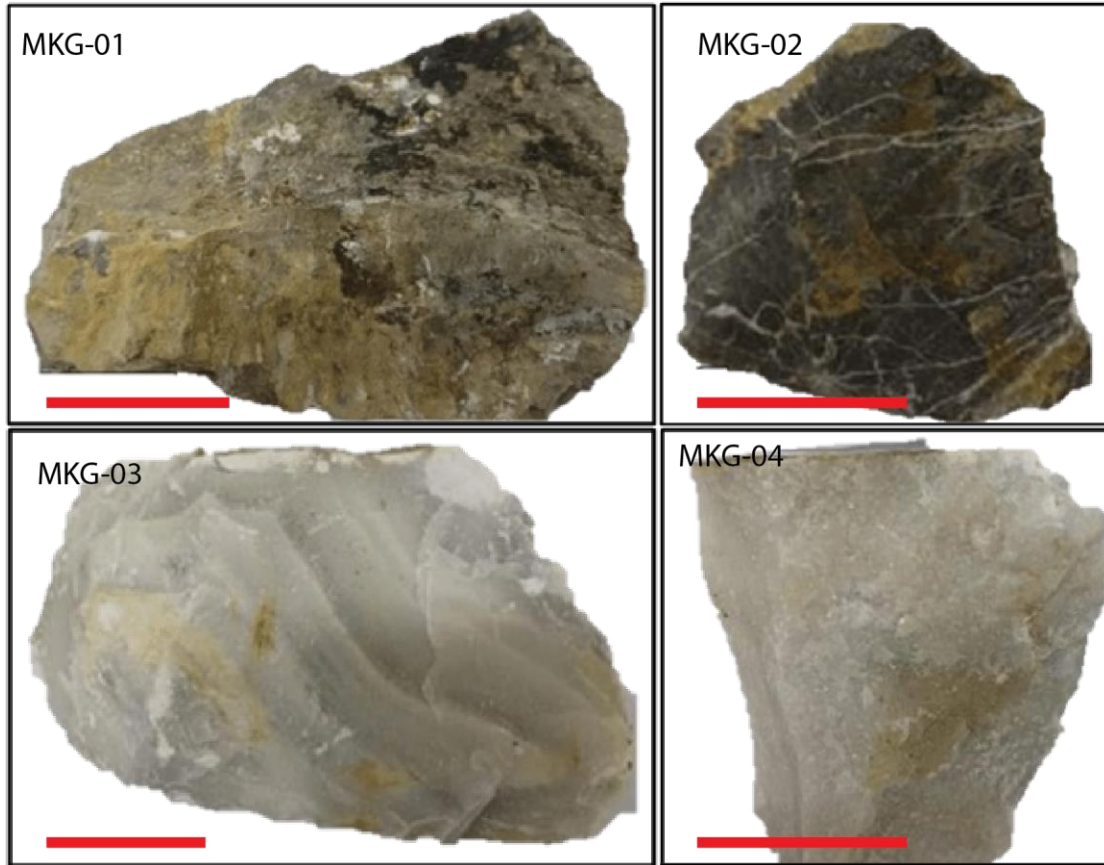
The Stereonet method is an analysis technique used in structural geology to visualize and analyze the orientation or direction of rock planes and fold planes in the earth's crust [9]. This method is very useful in understanding the geometry of the Earth's crust and the relationships between various geological features.

## Results and Discussion

The Tawar Formation of Sumatra mainly consists of limestone with characteristics of whitish-yellow to brownish-gray, soft to hard, and has a massive and layered structure (Figure 3). The sedimentological characteristics of the Tawar Formation are relatively uniform in almost all of the research locations. The outcrop size of the Tawar Formation also varies from a scale of 5 x 20 m<sup>2</sup> (width x height) to 15 x 50 m<sup>2</sup> (Figure 4). The Tawar Formation can be found outcropping around Lut Tawar Lake, Aceh Tengah.

The research results show that the Tawar Formation has experienced strong deformation characterized by various geological structures such as faults, joints, and folds (figure 4). The level of deformation that occurs in the Tawar Formation varies depending on its location. Fractures accompanied by normal faults were identified at locations MKG 1, 3, and 4, with the strongest degree of faulting found at MKG 4, then MKG 3, and the weakest at MKG 1. Meanwhile, deformation in the form of folding was most clearly identified at the MKG location

2, with a wing fold angle of around 30-50 degrees. The folding in MKG 2 was followed by fractures, both open and filled with minerals. The calcite mineral was identified as the main filler of fractures in the Tawar Formation in the research area. Meanwhile, at other locations (MKG 1,3,4), no large folding was found. The presence of multi-size and multi-episode fracture systems can be observed within the study area.



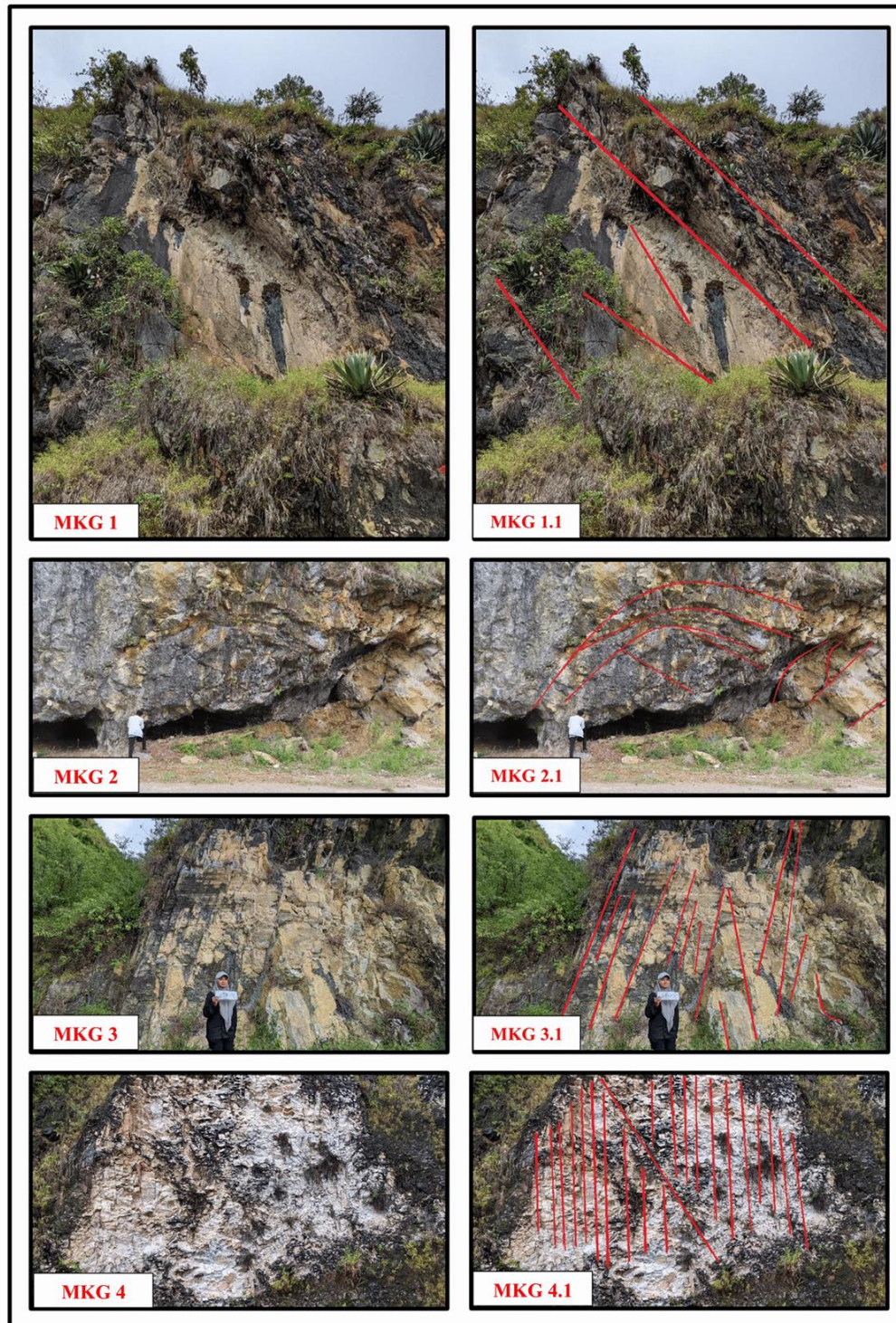
**Figure 3.** Photograph of the rock samples of the Tawar Formation from MKG-01 to MKG-04. The Tawar Formation consists of limestone. The scale bar is 5 cm.

Figure 4 shows field photographs of the Tawar Formation, un-interpreted on the left and interpreted on the right. The picture of MKG 1.1 shows an anticline fold that has been interrupted. While the image of MKG. 2.1 shows anticline folds, where the angle is greater on the right than on the left, and this is interpreted as the compression force greater on the right than on the left. Moreover, a photograph of MKG 3.1 shows several vertical joints within the Tawar Formation, and the picture of MKG 4.1 shows the presence of vertical joints to regular bedding and faults.

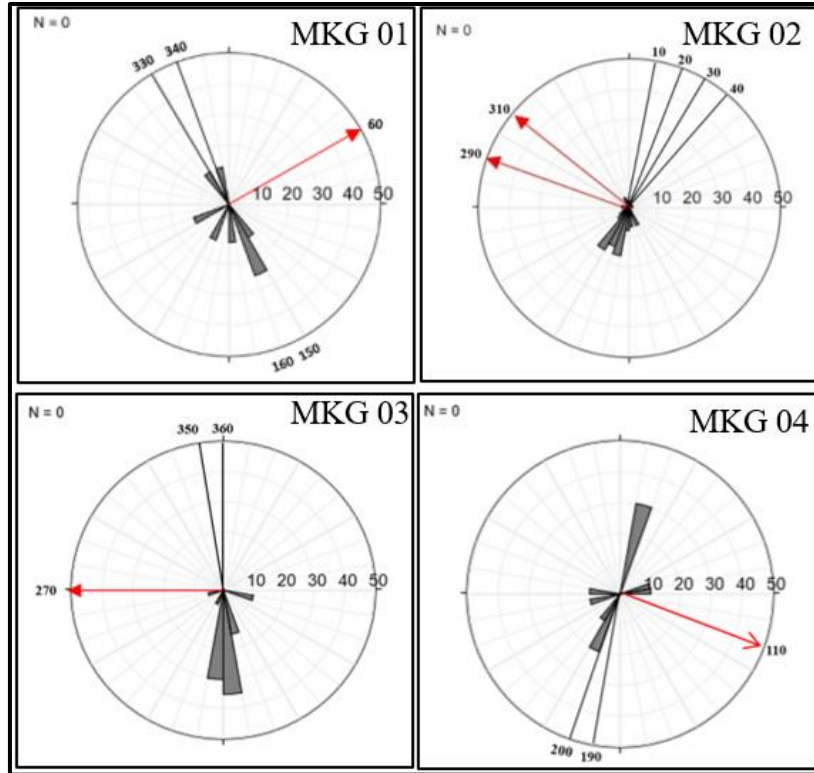
The results of strike-dip measurements (figure 5) show that at the MKG 1 location, the main strike direction is 150-160°, with the main force direction being 60°. Meanwhile, at the MKG 2 location, the main direction of the strike varies with an angle interval between 190-220°, with the direction of the main force indicated by an angle of 290-310°. The MKG 3 location's main strike direction is 170-180°, with the main force direction being 270°. Meanwhile, in MKG 4,



the main direction of strike is 20-30°, with the direction of the main force given by an angle of 110°.



**Figure 4.** Showing un-interpreted (left) versus interpreted (right) field photographs of the Tawar Formation from MKG-1 to MKG-4. A total of 148 structural data were collected (red line, some examples), and structural deformation identified in the field is marked with red line (right).



**Figure 5.** Summary of structural measurement of the Tawar Formation from the studied locations (MKG 01 = 18 data, MKG 02 = 80 data, MKG 03 = 30 data, MKG 04 = 20 data.) These collected structural data are presented in the rose diagrams to show their orientation.

Results from this study show that the Tawar Formation was strongly deformed, as evidenced by the presence of multi-size and multi-episode fracture systems, fault systems, and fold (figure 4-5). The presence of these structural features within the Tawar Formation is similar to the structural features of the Woyla Group of Sumatra [5-7]. Therefore, on this basis, we interpret that the development of the Tawar Formation may have been influenced by the same geological processes that affected the Woyla group.

Outcrops in the Tawar Formation are influenced by strong tectonic forces, indicating the influence of tectonic activity during the evolution of this formation. They may also be related to the Woyla group rocks [5, 11]. We propose that the Tawar Formation and the Woyla group of Sumatra may have undergone similar geological processes during their evolution. This tectonic activity is associated with the subduction of tectonic plates and faults that occurred during the evolution of the island of Sumatra [12]. The southwest-to-northwest Sumatra subduction zone is part of a long convergent area that accommodates plate movement northward [13]. Then, it was discovered that there were faults where these fault zones were formed due to oblique subduction of the subduction zone along the island of Sumatra. [14]. Apart from faults, there are also geological structures that have developed, including folds that have formed and faults with a primary direction of northwest (NW) - southeast (SE) [15].



## Conclusion

The Tawar Formation of Sumatra consists predominantly of limestone and was strongly deformed during its development. This is evidenced by the presence of numerous structural features, including multi-size and multi-episode fracture systems, folds, and faults. Fracture systems of the Tawar Formation are mainly infilled with calcite cements, which can be observed within the study area. These structural characteristics of the Tawar Formation are similar to those of the Limestone member of the Woyla group and, therefore, may share similar geological influences during their evolution. We propose that the Tawar Formation was strongly influenced by tectonic activities possibly related to the movement of the Sibumasu plate, the movement of the Sumatran fault system, and plate subduction in the southwest part of Sumatra. It is expected that the results of this research will provide some new insights into the development of pre-tertiary limestones of Sumatra and, hopefully, will benefit the government by facilitating better planning development in the study area.

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