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Geological structure of Flores Island, Indonesia: Relationship with volcanism and geothermal implications

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ABSTRACT

The Flores Island is located at the transition zone between Sunda and Banda Arc that is characterized by the change of tectonic regime from the subduction of the oceanic crust in the west, to the collision of the continental crust in the east. As a part of the volcanic arc, Flores Island has mostly been built by volcanic activities since Miocene. The volcanic arc in Flores Island, that has been migrating trenchward in the last 7 Ma, is in contrast with the general volcanism of the Sunda-Banda Arc that has migrated northward. Based on its tectonic regime, volcanism, and structural trend, the Flores Island is segmented into two segments; west, and east Flores. In the western half of Flores, the Oligocene-Late Miocene volcanism formed in an extensional regime due to the opening of the Flores and Savu basins, where the volcanism mainly occurs in the northern part of the island. The Pliocene to recent volcanism in the western half of the island, has been controlled by a compressional regime due to the Indo-Australian continental crust collision, which distributed to the south of the previous volcanism period. The dominant trend of the geological structure in the western half of Flores is mainly ENE-WSW direction; parallel with the trend of the Flores Basin opening. In the eastern half of the island, the volcanism has not been shifted. The distribution of the volcanoes in the east Flores is aligned progressively in series of en echelon segments eastward with the dominant trend of geological structures NNE-SSW. Fourteen geothermal prospects in the Flores Island have been identified by the Ministry of Energy and Mineral Resources (MEMR), through the Indonesian Government's Geothermal Development Acceleration Program in Eastern Indonesia. These geothermal prospects are mainly spatially associated with volcanic centres. In the western and central parts of the island, the geothermal prospects are associated with both Tertiary and Quaternary volcanic complexes, in contrast to those in the eastern part which are associated with the Quaternary single volcanic chain. This evidence shows that different assessment approach needs to be applied in developing the geothermal prospects in different parts of the island.

1. INTRODUCTION

The Flores Island is one of the largest islands in the Nusa Tenggara Timur (NTT) Province, in Eastern Indonesia. It has about 402,5 MW out of 633 MW of geothermal energy potential in the NTT province (MEMR, 2017). In the last few years, Flores Island has been chosen by the Indonesian government as a geothermal island model, as part of geothermal energy project acceleration in the Eastern Indonesia. However, Flores Island is still understudied both from the regional geology and its related geothermal systems. There are some previous studies which include Flores Island as part of their research area while others have specific locations along the island, and only few focused it.

Nevertheless, since Flores Island is located at the transition zone from subduction of the oceanic crust in the west to the collision of the continental crust in the east, it is noted that the geological structures' role should be studied extensively as it plays a vital role in providing ways for geothermal fluid flow. Thus, it is important to understand the geologic structure within the Flores Island, in order to enlighten the characteristics of known geothermal prospects in Flores Island in relation to their geological environments. Relationship between spatial association of geothermal prospect with geological structure and volcanic centre could be used as a classification in selecting exploration area of geothermal prospect.

2. TECTONIC FRAMEWORKS

2.1 Eastern Indonesia

The Eastern Indonesia formed as a result of a complex interaction between Pacific Plate, Eurasian plate, and Australian plate, also with microplate that may exist in a short period (Milsom, 2001; Charlton, 2000). This region has a history of various tectonic events and processes which include subduction, back-arc spreading, arc migration, collision, and crustal extension (Charlton, 2000; Hall & Smyth, 2008; Tate, et al, 2015; Pownall, et al, 2016).

The eastern Sunda-Banda Arc lies on the south of Eastern Indonesia as part of the segment of the arc, east of the Sundaland, which marked with the collision between Australian margin and the Banda Island Arc (Hall & Smyth, 2008). The west part of the arc is mainly built on a basement of Sundaland continental crust and progressively thinning eastward, and eventually changed into an oceanic crust on the east of Wetar Island (Figure 1; Syuhada, et al, 2016). The Proto Sunda-Banda Arc was formerly situated on the margin of Sundaland marked by the volcanic chain, which on the Cretaceous was stretch from Sumatra, Java, Sumba, to Western-arm of Sulawesi (Figure 1).

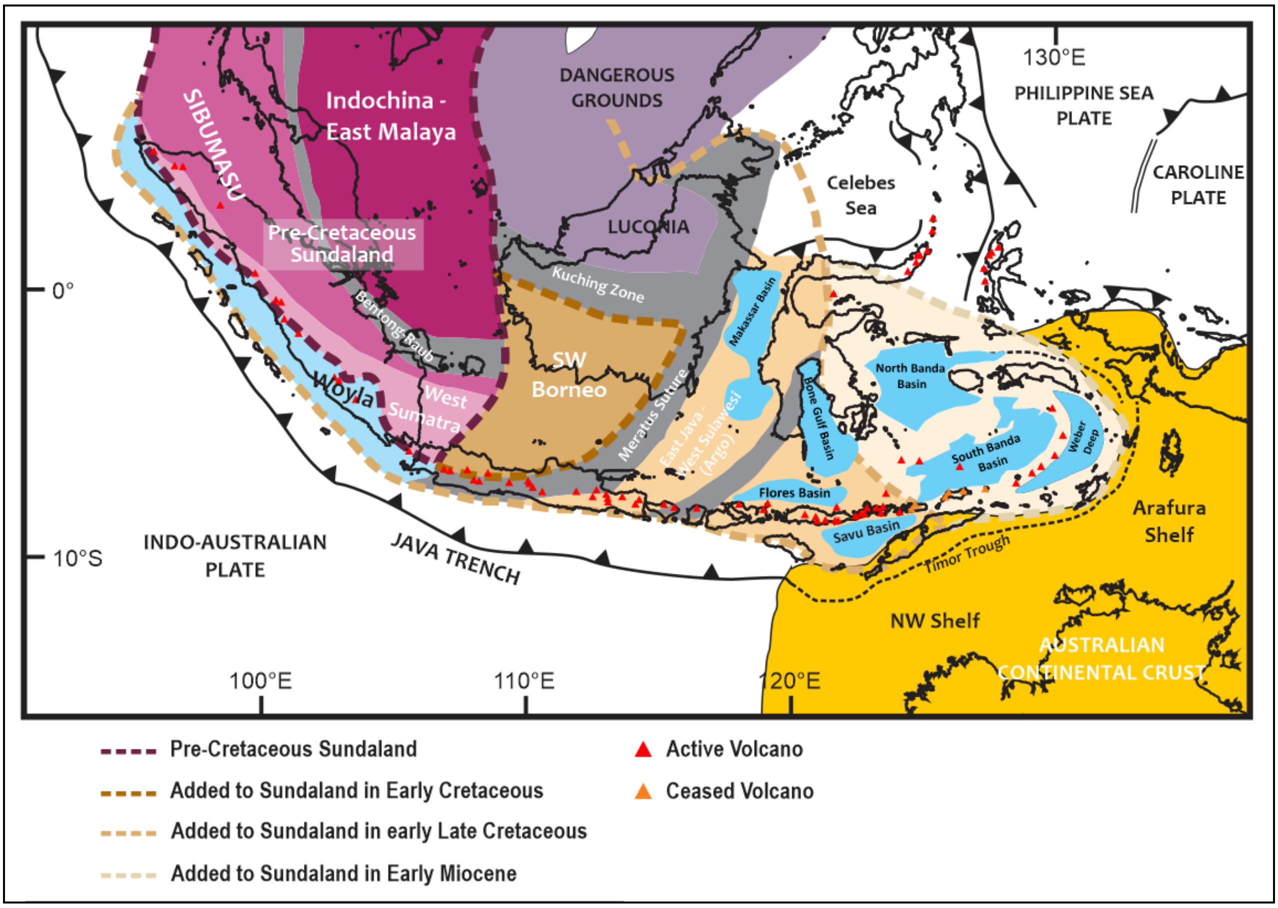

Figure 1: The Mesozoic to Cenozoic growth of Sundaland, (modified from Hall and Sevastjanova, 2012)

The extension of Eastern Indonesia is marked by the retreat of Proto Sunda-Banda Arc. It was started in the Paleogene to early Eocene by the opening of the Makassar Basin as an extension of the Celebes Sea with north-south orientation (Guntoro, 1999), followed by the opening of Flores basin in the Early Eocene (Pubellier & Morley, 2014; Figure 1) with east-west orientation has made the Proto Sunda-Banda Arc retreat to relatively southeast direction. This motion is also coherent with the southward drift of the Sumba Island in Late Cretaceous - Late Miocene (Wensink, 1997), an isolated continental crust, which is considered as part of east Sundaland. The latter opening of Bone Gulf, Savu basin, North and South Banda basin, and Weber Deep, accelerate the arc retreats forming the present Sunda-Banda Arc (Charlton, 2000; Hinschberger, et al, 2001; Hall & Smyth, 2008; Hall & Sevastjanova, 2012; Pubellier & Morley, 2014; Figure 1).

2.2 The Nusa Tenggara Timur (NTT)

The Nusa Tenggara Timur (NTT) Province consists of many islands, which are Sumba, Flores, Savu, Rote, Timor, Lembata, and Alor Island (Fig 2). Tectonically, these islands can be divided into two major tectonic elements, inner arc and outer arc. The northern islands (Flores, Lembata and Alor Island) belong to the inner arc, which dominantly built by the volcanism. The southern islands (Savu, Rote and Timor Island), are part of the outer arc, which are the product of accretionary wedge that uplifted as the result of the collision of Australian Continental Crust with the Sunda-Banda Arc (Tate, et al, 2015; Harris, 2011). An exception for Sumba Island, although it is located at the outer arc, it is an isolated microcontinent from proto Sunda Arc which is composed by Neogene volcanism (Abdullah, 1994; Wensink, 1997; Fleury, et al, 2009).

The overall morphology of the inner and outer arc varies along with the convergence as a result of variations in the thickness of overriding crust and ages of the subducted crust, the sediment flux, and the ages of the volcanism (Hendaryono, 1998; Hall, 2012; Hall & Spakman, 2015; Syuhada, et al, 2016). As the sediment flux on top of the oceanic crust decreases eastward, the outer wedge becomes narrower and thinner. This also coincides with the ages of the subducted crust which older eastward, which contribute to the opening of the Flores back-arc basin with slab roll-back mechanism. The inner arc developed on top of 29 km thick crust which becomes thinner eastward (Syuhada, et al, 2016), this also corresponds with its relative ages of the formation that become younger eastward. To the north of the inner arc, the Flores back-arc basin opened as a response of the slab rollback. The basin is characterized by ~14 km thick oceanic crust with E-W back-arc thrust in the middle of the back-arc basin (Guntoro, 1995).

The inner arc is also surrounded by the back-arc basin, Flores Basin, at the north, and forearc basin, Savu Basin, at the south (Figure 1). The outer arc is dominated by thrust and strike-slip fault as responses of the collision of Australian Continental which started at 8 Ma (Tate, et al, 2015). The ongoing collision is also marked by the exhumed accretionary wedge on northwest margin and uplifted microcontinental of Sumba Island on the west of Savu Basin.

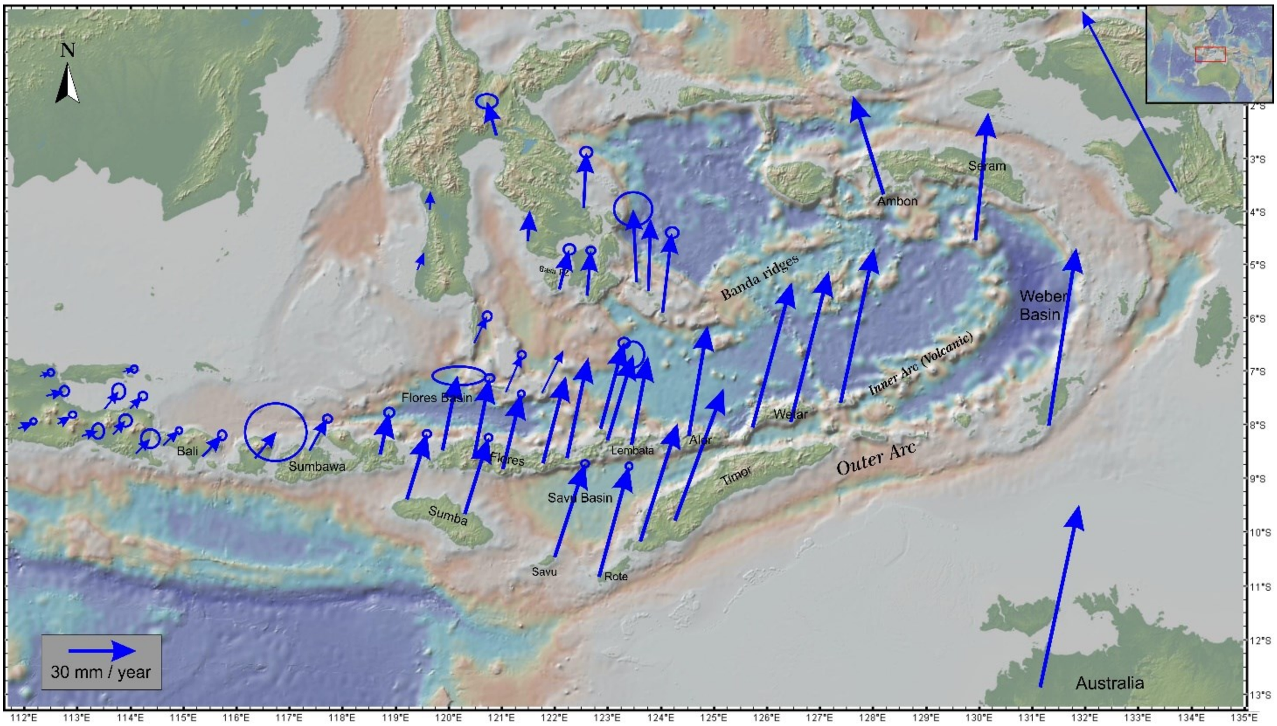

Figure 2: Kinematic framework of Lesser Sunda Island and eastern Indonesia with respect to Sunda Block (after Koulali, et al, 2016).

The present-day configuration coupled with the kinematic framework (Koulali, et al, 2016), shows the NTT province along with the entire arc has undergone a progressive counter-clockwise rotation, with increasing motion from 9 mm/yr at Bali Island to 82 mm/yr, toward the eastern end of Timor Trough, with respect to Sundaland (Koulali, et al, 2016). This motion is consistent with the oncoming Australian Plate that collides and pushing from the eastern end of the Sunda-Banda Arc. The increasing motion from west to east also implies that the convergence of Australian plate at the west were accommodated by the subduction of the oceanic crust at the Java Trench, while at the east, the continental crust has already collided and coupled with the outer arc with northeastward motion accommodated by back-arc thrust of Flores and Wetar (Koulali, et al, 2016; Figure 2). In this complex setting, the Flores Island is coexisted at the middle of the progressive counter-clockwise rotation, as a transition zone from subduction to collision setting. Hence, it is noteworthy to understand the geological structure of Flores Island in relation to its volcanism and geothermal prospect.

3. GEOLOGIC SETTING OF FLORES ISLAND

3.1 Regional Geology

The 360 km long of Flores Island with width, varies from 15 – 70 km, is an island arc with currently 14 active volcanoes. Most of the volcanic activity is extinct in the north part of the western half of the island (Figure 3). The morphology of Flores Island is dominated by mountainous areas, with very limited flat areas that may be found along the valley. The drainage pattern is consequent with the hilly and undulating form which develops a radial drainage pattern while elsewhere is dendritic.

The elongated shape of the Flores Island which stretch from west to east has two main trends of its geological structure (Ratman & Yasin, 1978; Suwarna, et al, 1989; Koesoemadinata, et al, 1994). The tectonic structures in Flores Island show a dominant NE-SW trend with some minor NW-SE trend. The geological structure mostly found as faults, folds, and lineament of escarpment and several alignments of volcanic edifices. The faults found in Flores Island are normal and oblique faults.

The Flores Island is underlain by Tertiary limestone, Tertiary volcanic, sedimentary rocks and Quaternary volcaniclastic (Ratman & Yasin, 1978; Suwarna, et al, 1989; Koesoemadinata, et al, 1994). The oldest rock belongs to the Walanae formation (Late Oligocene), which is composed of neritic limestone (Hendaryono, 1998). This formation is only exposed in West Flores. The Tertiary volcanic consists of many formations with rock types varying from basaltic to dacitic, which interfinger with sedimentary facies. The surface is dominated by the Quaternary volcaniclastic which lies on top of the Tertiary volcanic. The Quaternary volcaniclastic comprising mainly lava, breccia, tuff, and calcareous sediment. The shape of Flores Island appeared to have a distinct difference based on its width and length, and its stratigraphy which could be divided into three area groups, namely; West Flores, Central Flores, and East Flores (Figure 4). West Flores is dominated by the Quaternary volcanic in the southern part, while Central Flores is dominated by the Tertiary volcanic with only limited Quaternary volcanic appeared in the south and north part. East Flores has vastly covered by the Quaternary volcanic with some calcareous limestone. The appearance of the terrace along the south shore and coral reefs along the north shores indicate an uplifting process as a result of the compressional tectonic regime (Figure 3).

The presence of volcanoes is fairly distributed over the island, which is in favour for the formation of geothermal system in Flores Island. About 14 geothermal prospects are found on the Flores Island. Most of the geothermal prospects in Flores island are found in the proximity of Quaternary volcanoes, while few thermal springs are found on the Tertiary volcanic with low temperature (51°C; MEMR, 2017).

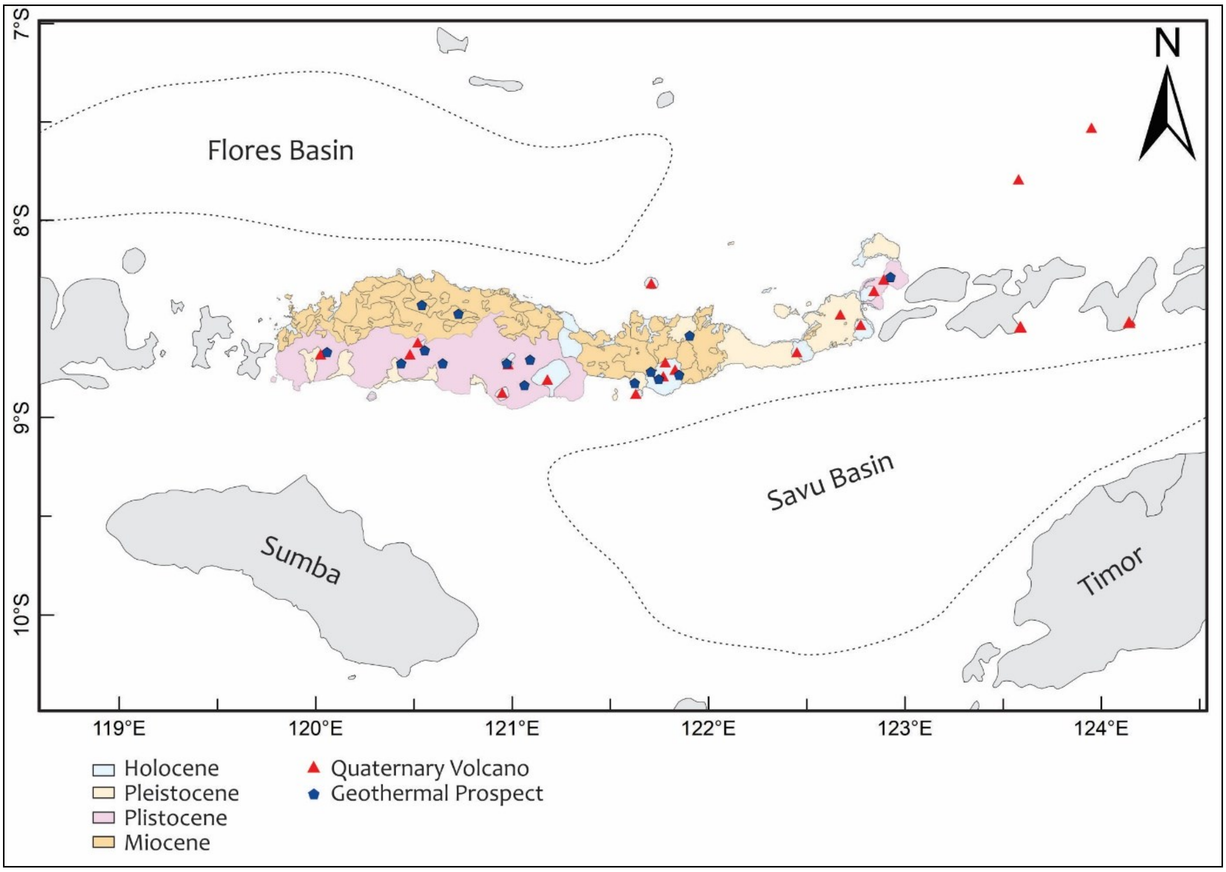

Figure 3: Regional Geology map of Flores Island (modified from Ratman & Yasin, 1978; Suwarna, et al, 1989; Koesoemadinata, et al, 1994)

3.2 Regional Lineament of Flores Island

Digital extraction of the lineaments on Flores Island was done based on the Digital Elevation Model (DEM). The dataset consists of 15 high-resolution (0.27-arcsecond) seamless DEM data that covers the Flores Island and they were provided by Badan Informasi Spasial (BIG) Indonesia. More than 150.000 lineaments were revealed based on this dataset. The length of the lineament varied from 50 m to 1500 m. The distribution of the lineament was evaluated and compared with the topographic features of the region. Most of the lineaments were found to be linear relief features in the form of ridges, valley, and subtle escarpments. These morphologic lineaments indicated the presence of tectonic deformation.

The lineaments were grouped into three areas based on the age of the volcanism and its stratigraphy, namely West Flores, Central Flores, and East Flores. The azimuth frequencies for the lineaments based on cumulative length indicate structural trends. The extracted lineament shows the orientation of east-west trend in the west Flores, N58°E and N72°E, for Tertiary and Quaternary volcaniclastic formation, respectively (Figure 4). While in the Central and East Flores, the extracted lineaments are oriented NNE – SSW (N21°E – N24°E; Figure 4). The trends present both in the Tertiary volcanic and Quaternary Volcanic.

4. DISCUSSION

4.1 Structural Development

The structural development of the Flores Island resulted from two different tectonic regimes, (i.e extensional and compressional). The extensional tectonic regime started with the opening of Flores Basin, north of Flores Island, which caused breakup at the eastern margin of Sundaland. This basin opening has trend relatively east-west. While the structural lineation on the tertiary volcanic in West Flores, south of Flores Basin, has a trend of relatively ENE-WSW. This lineament is interpreted to be inherited from the back-arc rifting. The Quaternary Volcaniclastic in West Flores has a slightly different trend, which is more to the east-west direction. This structure may exist as the secondary structure as result from the primary structure (ENE-WSW trend). The dominant trend of the lineament on the Tertiary Volcanoclastic formation is also consistent with the prominent structure which is a steep slope in Ruteng to Kepoh area that becomes the boundary between the Tertiary and Quaternary Volcaniclastic.

The collision of Australian Continental Crust with Eastern Indonesia in the Late Miocene (Tate, et al, 2015) change the tectonic regime of Flores Island from extensional to compressional tectonic regime. This change was expressed by the NNE-SSW structural lineation on the Central and East Flores. These lineaments were found mostly as ridges, escarpments, and faults. Based on the rose diagram, the lineament in the central and east Flores has the same Mean Value with some differences in the other trend distribution. The changes of the tectonic regime to compressional settings also may reactivate the existing faults in the Tertiary Volcaniclastic formation and formed the secondary structure on the Quaternary Volcaniclastic formation. This condition could be seen on West Flores where the ENE-WSW as the primary structure found on the Tertiary Volcaniclastic formation and the E-W trend act as the secondary structure as a response of the ENE-WSW structure's movements.

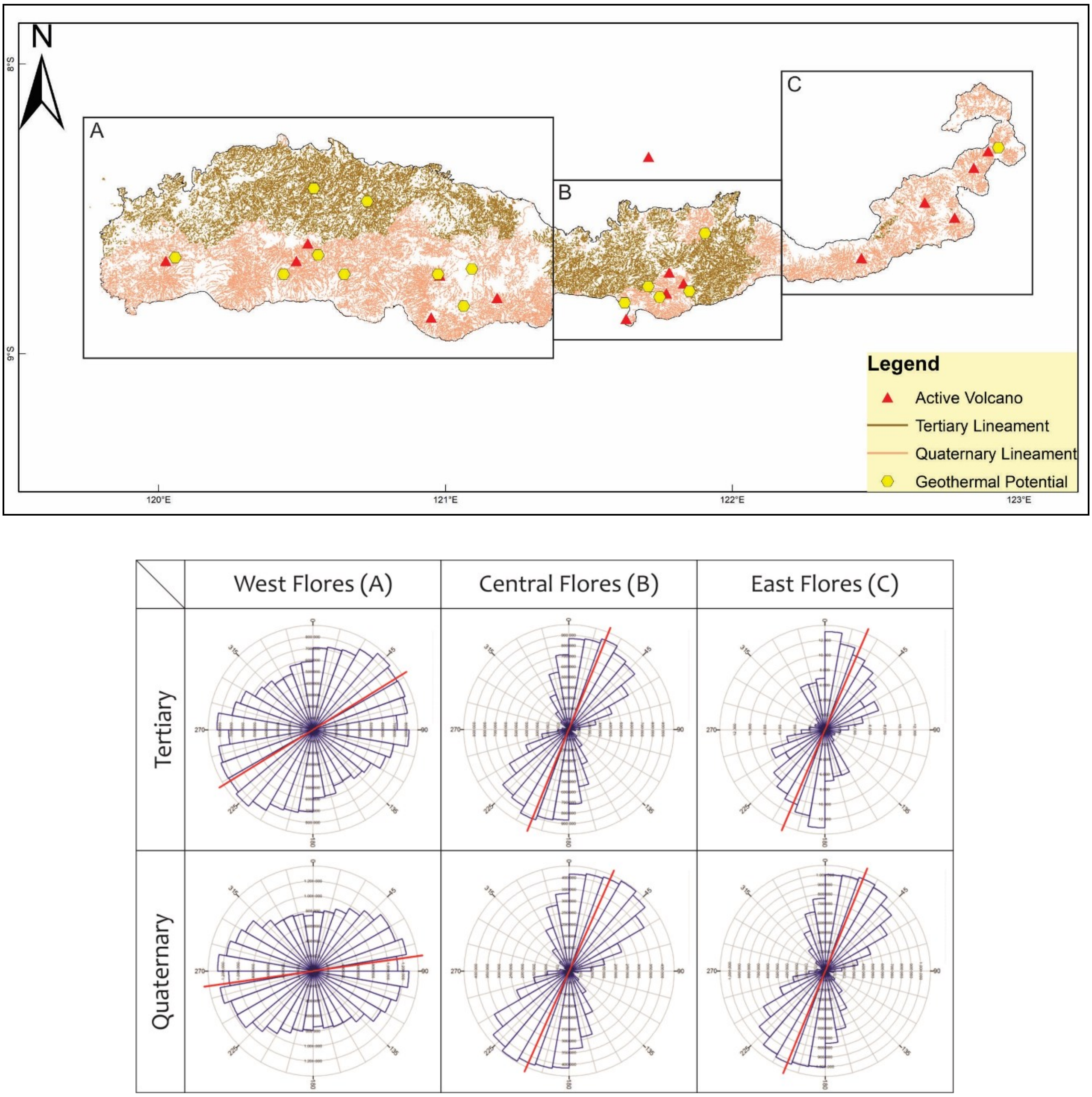

Figure 4: Extracted Lineament of Flores Island and its rose diagram (azimuth frequencies), the red line on the rose diagram is the mean value of the overall trend.

4.2 Volcanism and Geothermal Implication

The volcanism in Flores Island started in the Paleogene when the Flores Basin started to open. Based on the regional geology and existing radiometric data (Hendaryono, 1998), the volcanism started in West and Central Flores. During the Miocene, the volcanism is formed and concentrated in West and Central Flores. In the late Miocene, as the tectonic regime changed into the compressional setting, the volcanism on the West Flores started to migrate and localized along the southern part of the West Flores. The Quaternary volcanism in the West Flores formed as volcanic complex within a caldera structure from the Tertiary volcanoes. While in Central Flores, the Quaternary volcanism has significantly narrowed into two isolated areas (i.e. Kelimutu and Maurole). In the East Flores, the Quaternary volcanism formed as a single chain volcano and occurred in NE-SW alignment. This alignment of volcanoes may develop due to the compressional stress from the Australian Continental Crust collision.

The regional segmentation of Flores Island into three regions has differences in the geothermal prospectivity. The West Flores segment is the most prospective segment while the East Flores is the lowest. From the regional scale, the stress distribution of the colliding Australian Continental Crust has more effect on the eastern end of Flores compared to the western end. The anticlockwise rotation movement of the arc may be accommodated by the NE-SW lineament structure as an oblique strike-slip in Central and East Flores. This movement may potentially tighten or completely close the existing fluid path which may impact the formation of the geothermal system. Moreover, the spatial-temporal evolution of the Quaternary Volcanoes also plays an important role. The most favorable geothermal prospect formed in the West Flores which is dominated by volcanic complex and caldera structure, (e.g. Ulumbu, Waesano, and Mataloko). These types of volcanic structures may give favor in providing a fluid path for the geothermal system in the vicinity. In contrast with West Flores, these features have become less observable in East Flores due to the younger volcanism and single-chain volcanic feature. Thus, it makes the East Flores less prospective compared to Central and West Flores.

5. CONCLUSION

Based on the tectonic settings, Flores Island could be divided into three segments, namely West, Central, and East Flores. Each segment has a distinctive structural lineament trend that reflects the different stress distribution along the Flores Island. Due to the differences of its tectonic evolution, the three segments have variation in their volcanic evolution which directly affects the formation of the geothermal system. The prospectivity of the geothermal prospect decreases from the west to the east. According to each segment characteristic, different assessment approach needs to be applied in developing the geothermal prospects in different parts of the island.

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