Tectonic Control to Geothermal System of Way Panas, Lampung, Indonesia

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ABSTRACT

Way Panas is part of Ulubelu geothermal field, which is situated at the southern end of Sumatera Island, Indonesia. This geothermal field is built along the active Sumatera Fault Zone, which also had acted as the main control on the development of geothermal system on the area. Abundant surface thermal manifestation were observed in the Way Panas, such as hot springs, fumaroles, gas discharges, mud pots, steaming grounds, and altered rocks. Several geologic and geophysic studies have been conducted, and some geothermal system model were proposed. However, since this area were strongly controlled by tectonic processes, it is noticed that the role of geologic structures have never been put in considerable study.

This paper presents recent findings on tectonic and structural geology based on geologic mapping and remote sensing interpretation. A number of 1938 lineaments were extracted from digital elevation model, which were analyzed according to their respective rock ages. A number of 220 tectonic joints and fault kinematic were analyzed from field data. It is observed that those surface manifestations were associated with major NW-SE normal fault, which acting as boundary fault of Early Pliocene structural graben that filled by Plio-Pleistocene volcanic complex. This NW-SE structural trend was part of the Sumatran Fault system, and its reactivation produced extensional faults and joints controlled the outflow of geothermal system. Another significance finding was arcuate geologic structures produced by volcanic load that influenced the existing geothermal system.

1. INTRODUCTION

Way Panas is situated in the southern part of Ulubelu Geothermal Field, which was also known as Rindingan-Ulubelu-Way Panas (RUW) geothermal system (Suharno, 2003). It is located in the Lampung Province, at the south-eastern end of Sumatera Island, adjoining to Semangko Bay (Figure 1). Its development is closely controlled by tectonic history of the Sumatera Fault. Geophysic study indicates the RUW system was developed in a concealed structural graben (Daud, 2000). Abundant surface thermal manifestation were observed in the Way Panas, such as hot springs, fumaroles, gas discharges, mud pots, steaming grounds, and altered rocks. It was interpreted that Way Panas acted as outflow zone of RUW system (Daud, 2000; Yorinaldi, 2000). However, since this area were strongly controlled by tectonic processes, it is noticed that the role of geologic structures have never been put in considerable study.

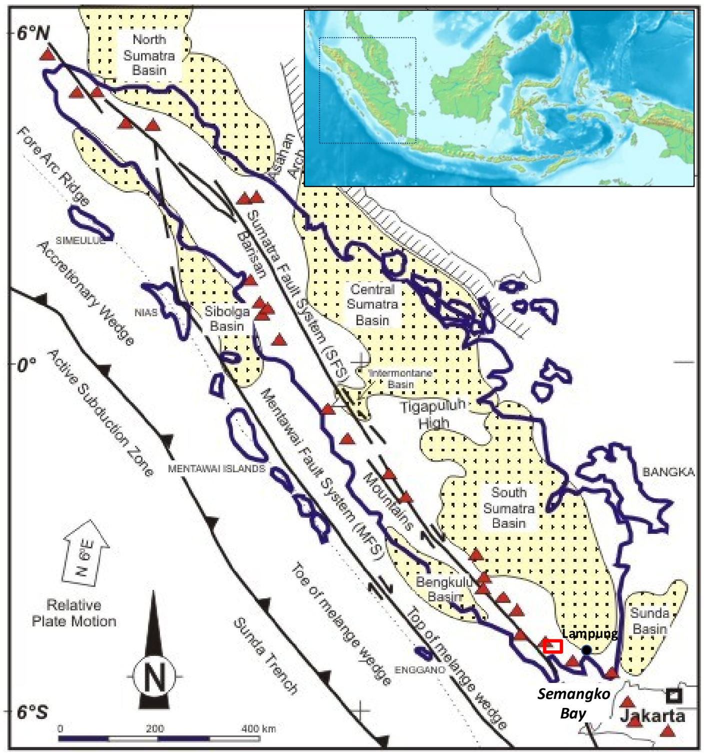

Figure 1: Location of study area refers to physiography of Sumatera (Darman and Sidi, 2000), shown by red-line rectangle.

This study utilized geologic mapping to establish the role of geologic structures in tentative geothermal model of Way Panas. Research output also includes distribution of volcanostratigraphic units and their depositional sequences, as well as thermal manifestation and hydrothermal alteration.

2. GEOLOGIC SETTING

2.1 Tectonic and Geologic Structures

Tectonically, Sumatera Island can be divided into 5 areas, i.e. outer-arc ridges, fore-arc basins, back-arc basins, Barisan mountain range that occurred along the Sumatera Fault, and intra-arc basins that developed along Barisan Range (Figure 1; Darman and Sidi, 2000). Quaternary volcanism dominates the Barisan Range, represented by 50 volcanic centers along the Sumatera Fault zone (Sieh and Natawidjaja, 2000). Relationship between volcanism and tectonic activity of the Sumatera Fault was poorly understood, as only few volcanism that lies on the active fault zone, whilst majority of them distributed in a distance of 20 to 40 km from the fault zone. It was interpreted that the presence of Quaternary volcanism, which is getting more established to the southeast, reduced the slip rate of Sumatera Fault through their ductile magma chambers.

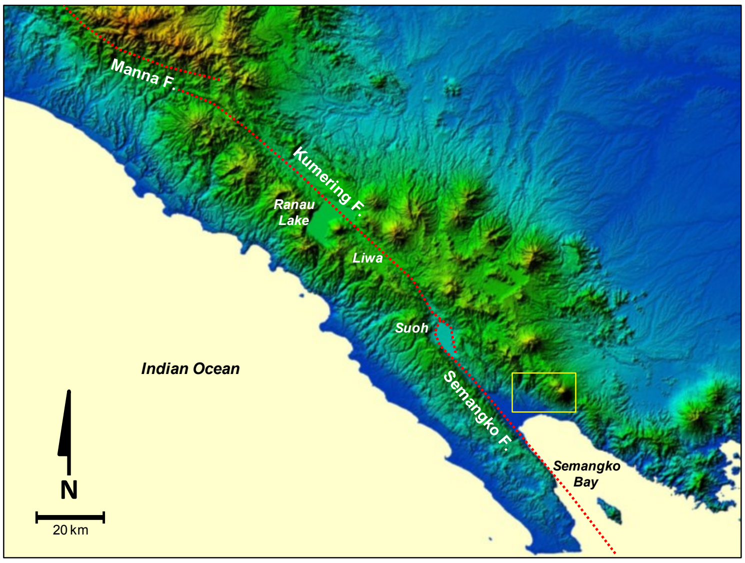

Figure 2: Segmentation of southern section of Sumatera Fault (modifed after Sieh and Natawidjaja, 2000). Red-line rectangle is the study area.

Way Panas, Lampung, is located in the southern end of Barisan Range. This area formed as embayment area along the Sumatera Fault terminus, known as Semangko rift zone (van Bemmelen, 1949) or Semangko Fault segment (Figure 2; Sieh and Natawidjaja, 2000). It was rifted in a rate of 6-7 mm/year (Bellier *et al*., 1999; Pramumijoyo, 2008). The Semangko segment extends 65 km, from the pull-apart basin of Suoh in the northwest, to the Semangko Bay at the southeast (Sieh and Natawidjaja, 2000). The northeast-facing escarpment of Semangko segment suggests that this fault is normal fault, with the northeast block as downthrown part. Based on microstructure study, Pramumijoyo (2008) proposed that this segment had evolved by a N-S compression before 5 Ma ago, subsequently replaced by NE-SW extension to 1 Ma ago, before extended in E-W direction up to present-day. Seismicity of Semangko segment is lower than other segments in the Sumatera Fault, as only a notable 7.0 Mw earthquake recorded in 26 July 1908 (Sieh and Natawidjaja, 2000).

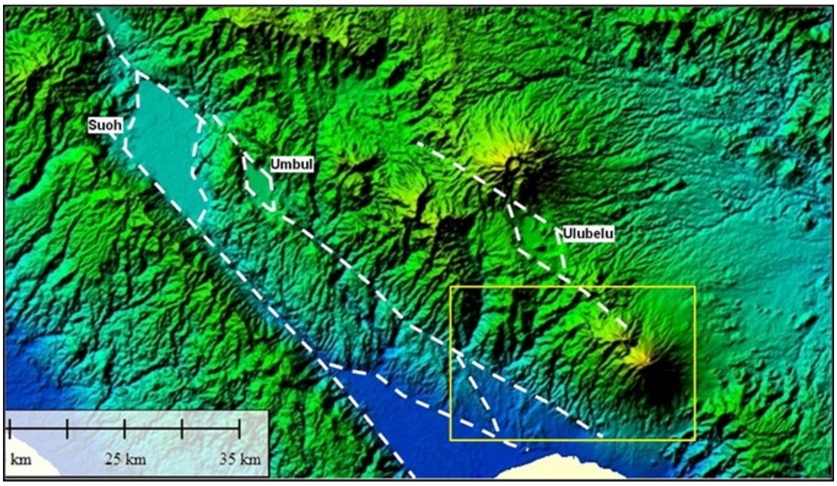

Figure 3: Distribution of pull-apart basins along the Semangko fault zone. Bounded faults are right-lateral strike-slip trending NW-SE and normal dip-slip trending N-S. Red-line rectangle is the study area.

Semangko segment is punctuated by several pull-apart basins, resulted from overstepping of smaller fault segments (Figure 3). The smallest pull-apart basin is Umbul Depression with diameter of 3 km, located 7 km to the east of Semangko segment. Pramumijoyo (2008) assummed that this basin formed along the preceding Semangko segment. The recent Semangko segment is responsible to create Suoh Depression (Sieh and Natawidjaja, 2000; Pramumijoyo, 2008) as the largest pull-apart basin with diameter of 7 km, although van Bemmelen (1949) proposed this basin as a remnant of a large caldera and had spread its tuff deposit to surrounding area. Ulubelu Depression is situated far east, 30 km from Semangko segment, and escorted by two Quaternay volcanoes of Rindingan and Tanggamus. With a diameter of 4 km, Ulubelu Depression is filled by numerous smaller young monogenic volcanism, such as Duduk Volcano. It was interpreted that this Ulubelu Depression is linked to Ranau Depression located 80 km to northwest by an ancient (Early Pliocene) Semangko segment.

2.1 Stratigraphy

Stratigraphy of Lampung refers to Barisan Range zone (van Bemmelen, 1949; Amin *et al*., 1993) as follow:

a. Menanga Formation (Early – Middle Cretaceous): intercalation of calcareous shales and sandstones, with lenses of chert and limestones.
b. Kikim Formation (Paleocene – Early Oligocene): volcanic breccias, andesitic tuff, and welded tuff.
c. Gading Formation (Oligocene – Early Miocene): sandstones, siltstones, and claystones, intercalated with limestones and lignite.
d. Hulusimpang Formation (Oligocene – Early Miocene): volcanic breccias, lava, basaltic-andesitic tuff, some were altered as well as cut by quartz and sulfide veins.
e. Bal Formation (Late Miocene): volcanic breccias intercalated with dacitic tuff and sandstones.
f. Igneous intrusions: granodiorite batholites and dacitic dikes (intra-Miocene); volcanic feeding channels such as necks, dikes, and fissure eruption, intercalated with dacitic tuff (Plio-Pleistocene).
g. Lakitan Formation (Late Miocene – Pliocene): basaltic-andesitic volcanic breccias, tuff and tuffaceous sandstones, some were prophyllitic altered and cut by Au-Ag veins.
h. Lampung Formation (Pliocene – Pleistocene): pumiceous tuff, tuffaceous sandstones, tuff.
i. Ranau Formation (Pliocene – Pleistocene): pumiceous breccias, micaceous tuff, pumiceous tuff, silicified woods; few possible sources, i.e. Ranau, Suoh, and Gedung Surian (van Bemmelen, 1949).
j. Semung Formation (Pliocene – Pleistocene): conglomeratic sandstones, sandstones, claystones.
k. Old Quaternary Volcanics (Pleistocene – Early Holocene): basaltic-andesitic lava, tuff, volcanic breccias.
l. Young Quaternary Volcanics (Holocene): volcanic breccias, lava, basaltic-andesitic tuff.
m. Alluvial (Holocene): boulders, gravels, sands, silts, clays.

3. METHODS

This research covers geologic surface mapping procedures. Initiated with literature reviews of existing publication and interpretation on remote sensing imagery analysis as well as on digital elevation model to derive tentative geologic and structural maps. Field works was conducted to obtain lithologic distribution, structural data, alteration type, surface thermal manifestation, and rock sampling. Output from this step was geologic map and volcanism history controlled by tectonic development. Further analysis on rock samples focused on petrogenetic and alteration processes. Specific methods for tectonic study were developed for geomorphologic analysis, volcanostratigraphic analysis, and structural analysis.

Geomorphology is a basic approach for interpreting geologic structures. Three geomorphic aspects were taken into account in geomorphic analysis, i.e. shapes, processes, and history (Huggett, 2007), and was extensively exploiting digital elevation model (DEM) from Shuttle Radar Topographic Mission (SRTM) that had developed by Jet Propulsion Laboratory (JPL) National Aeronautics and Space Administration (NASA) in 2000. Spatial resolution of SRTM DEM is one arcsecond or 30 m. Field data required were collected as lithologic types, confirmed geologic structures, factual morphologic shapes, degree of valley formation, and level of weathering.

As geothermal manifestation commonly associated with volcanic edifices, then a successful geologic mapping requires good identification on volcanic stratigraphic facies (Wohletz *et al*., 1992), that often changes lateral and vertical in a short distance (Fisher and Smith, 1991). This volcanistratigraphy analysis provides a basis for other analysis, such as petrogenetic, geochemistry, geothermal, and geologic structures. Standard procedures for this analysis were lithologic facies mapping, cross-section reconstruction, and absolute or relative age-dating (Wohletz *et al*., 1992).

Identification of geologic structures and undertanding tectonic development of geothermal area are extremely important in geothermal exploration, as the occurrence of certain geologic structures, such as extensional fractures and faults, enhanced permeability. Therefore, this step is divided into two works, i.e. regional study based on DEM interpretation to obtain tectonic setting and development, and local study based on field data and satellite imagery interpretation to attain responsible structures in the geothermal system.

In DEM interpretation for geologic structural purpose, morphologic lineament was the primary spatial data. The identified object was elongate river valleys, with an argument that they were location of concentrated erosion that controlled by the presence of structural deformation. The DEM was prepared following procedure given in Husein *et al*. (2012) as follow: (i) hillshade analysis to enhance morphologic relief, (ii) manual extraction where the repetitive lengthen river valleys picked as major structures, and (iii) digital extraction where the smaller river valleys picked as minor structures, using GIS softwares with certain parameters such as pixel radius, edge gradient, curve length, linear fit, angular differentiation, and connecting distance.

Field data collected for geologic structural purpose include bedding attitude, joint orientation, and fault kinematics. Joint data were statistically analyzed to obtain principal domains and spatial trends. Fault data composed of fault planes and fault striation, which then were analyzed kinematically to define relative block movement in response to the prevailing tectonic regimes. All these structural data put into a coherence synthesis to understand deformation processes and tectonic development of the study area.

4. RESULTS

4.1 Geomorphology

There are 4 geomorphic unit that could be identified in the research area (Figure 4): (i) young volcanoes, (ii) faulted old volcanoes, (iii) eroded structural hills, and (iv) Kotaagung alluvial plain. The following explanation is given according to each unit.

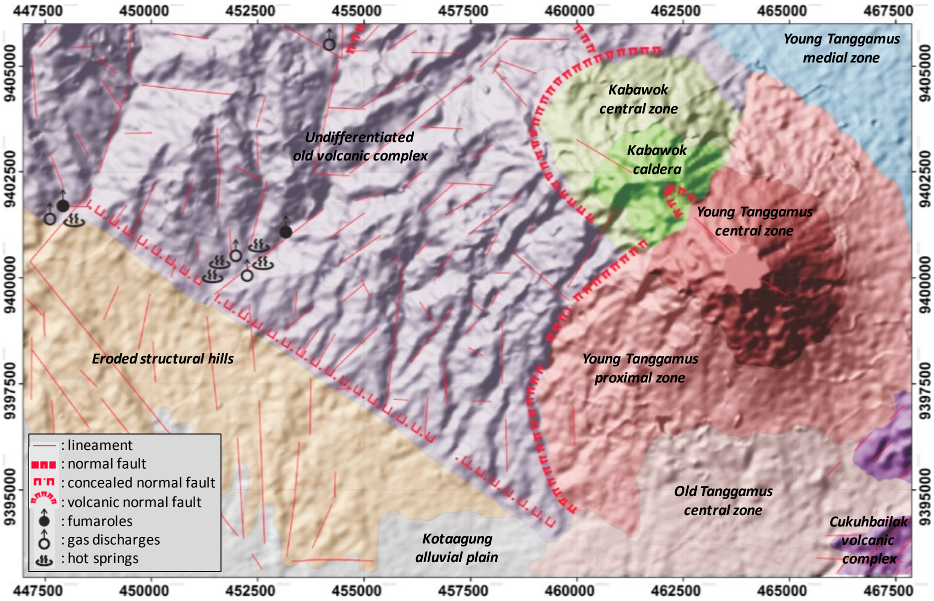

Figure 4: Geomorphologic map of study area.

a. Young volcanoes

Landscapes influenced by recent volcanic activities were distributed in the north-central-east of study area. Landforms belong to this unit were examined following Bogie and Mackenzie (1998), that based on volcanic facies could be expanded into 6 units:

- Kabawok caldera rim: located in the north-east of study area, a remnant of western caldera rim of Kabawok Volcano was identified in associated with pyroclastic breccias.
- Kabawok central zone: located in the north-east of study area, a truncated volcanic cone formed a circular escarpment in associated with lava flow.
- Old Tanggamus proximal zone: located in the southern part of study area, formed by steep slopes and dense drainage pattern, and associated with pyroclastic breccias.
- Young Tanggamus central zone: located in the eastern part of study area, characterized by undissected cone and associated with andesitic lavas.
- Young Tanggamus proximal zone: located in the eastern part of study area, occupied steep slopes formed by pyroclastic breccias and ignimbrites.
- Young Tanggamus medial zone: located in the northeastern part of study area, occupied gentle slopes formed by laharic breccias.

b. Faulted old volcanoes

- Cukuhbailak volcanic complex: located in the southeastern part of study area, formed by Tertiary volcanism of Cukuhbailak that produced pyroclastic breccias and andesitic lavas, and characterized by strongly dissected hills.
- Undifferentiated old volcanic complex: located in the northwestern part of study area, characterized by severely dissected and eroded volcanic hills, formed by pyroclastic breccias and andesitic lavas that collectively produced by Tertiary volcanism of Sula, Way Panas, Tiga, and Old Kabawok. Numerous geothermal surface manifestation were observed in this unit.

c. Eroded structural hills

Located in the southwestern part of study area, this unit was characterized by highly-dissected low-lying hills that bounded by a normal fault at its northern boundary.

d. Kotaagung Alluvial plain

This geomorphic unit occupies the southwestern part of study area, partially formed by flood plain of Ngarip and Belu rivers.

4.2 Stratigraphy

The study area is situated in a Quaternary active volcanoes overlying Tertiary volcanic products. Rock distribution is depicted in Figure 5, and their vertical relationship were interpreted in geologic cross-section (Figure 6). Lithologic units are divided according to physical characters and their volcanic origin.

a. Lava and pyroclastic breccias of Cukuhbailak (CLB)

This unit occupies the southeastern part of study area. Andesitic lava was grayish, columnar structure, porphyrtic texture with plagioclase and pyroxene as phenocrysts. It was slightly altered as some clay minerals and chlorite were observed. Masdjuk (1989) named this unit as Old Andesite and radiometric dating indicates 14.6 Ma. However, this unit might be younger in age, as field observation revealed uncompacted rocks in a moderately dissected morphology.

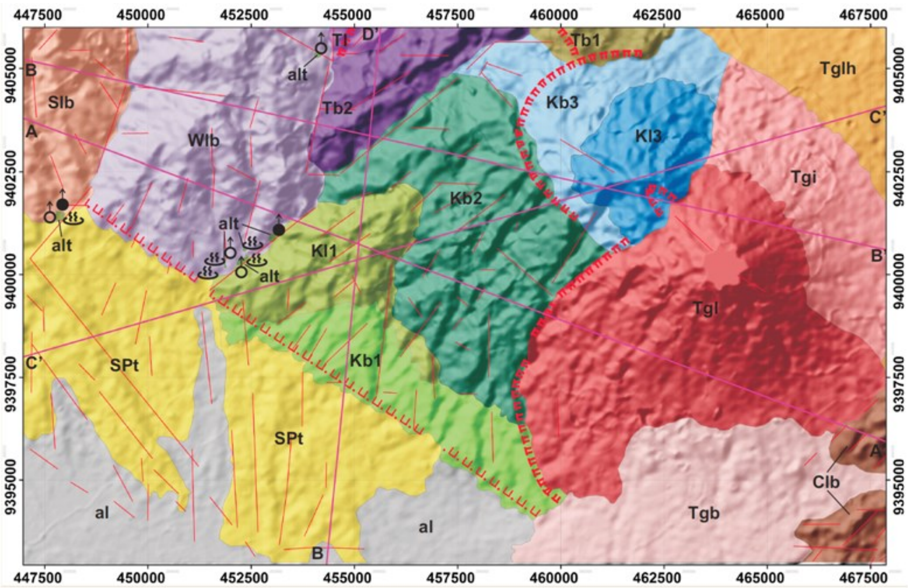

Figure 5: Geological map of the study area. Please refer to text for letter abbreviation.

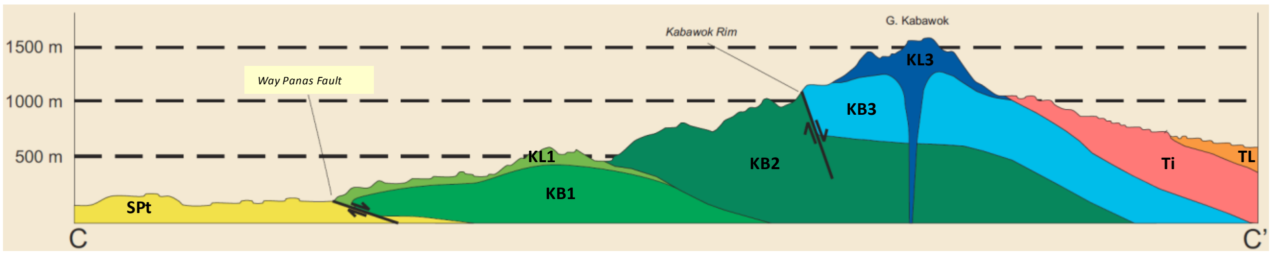

Figure 6: Geologic cross-section CC' of the study area, location refers to Figure 5.

b. Tuff of Sumurpitu (SPt)

This unit located in the southwestern part of study area. Tuff were moderately weathered, colour of white, grain size of medium sand, and well sorted. Some andesitic fragments were found as bomb sags. Pumiceous tuff were also noticed, grain-supported, composed of lithics, quartz, plagioclase, hornblende, and pyroxene. Some pumice were altered to be sericite. Amin et al. (1993) put this unit into the Quaternary Young Volcanic Formation as product of Tanggamus eruption. However, van Bemmelen (1949) and Masdjuk (1989) proposed Plio-Pelistocene age. Field observation indicates a morphology of peneplain occurred on this unit. suggests an old age, that cut by the Late Pliocene Way Panas normal fault. Field observation also indicates that this unit was deposited before lava and pyroclastic breccias of Sula and pyroclastic breccias of Way Panas.

c. Lava and pyroclastic breccias of Sula (SLB)

This unit located in the western part of study area. The pyroclastic breccias were fairly weathered, colour of brownish gray, poorly-sorted, matrix-supported, calcite-filled fractures, fragments were angular and consist of porphyritic andesite, aphyric andesite, and scoria, with groundmass of crystalline tuff. The andesitic lava were gray, texture of porphyritic, phenocrysts of plagioclase and pyroxene, slightly altered to clay, chlorite, and epidote. Based in radiometric dating, Masdjuk (1989) put this unit in age of 4.5 Ma. Based on paleomagnetic polarity, Suharno et al. (2005) indicates this unit must be older than 0.7 Ma. Remote sensing analysis suggests that this unit unconformably overlying the tuff of Sumurpitu (SPt).

d. Lava and pyroclastic breccias of Way Panas (WLB)

This unit distributed in the central-east of study area. The pyroclastic breccias were polymict, poorly sorted, fragments consist of pumice, andesite, and basaltic andesite, with groundmass of volcanic glass that strongly altered to sericite and calcite. The andesitic lava were brown, textures of aphanitic and porphyritic, fragments consist of plagioclase, quartz, and pyroxene, which some were slightly altered to iddingsite, epidote and iron oxides. Based in radiometric dating, Masdjuk (1989) put this unit in age of 3.9 Ma. Based on paleomagnetic polarity, Suharno et al. (2005) indicates this unit must be older than 0.7 Ma. Remote sensing analysis suggests that this unit was younger than the lava and pyroclastic breccias of Sula (SLB).

e. 1st Pyroclastic breccias of Tiga (TB1)
This unit located in the northern part of study area. The pyroclastic breccias were highly weathered, colour of brown, normal graded of pumice, lithic, and tuff. Lower part of this unit was pyroclastic flow deposits, while the upper part was pyroclastic fall deposits. Field observation suggests this unit was younger than lava and pyroclastic breccias of Way Panas (WLB).

f. 2nd Pyroclastic breccias of Tiga (TB2)
This unit found in the northern part of study area. It was highly weathered, colour of brown, poorly sorted, rounded fragments of porphyritic andesite, groundmass of pumice, crystal, and volcanic glass. Field observation suggests this unit was younger than the 1st pyroclastic breccias of Tiga (TB1).

g. Lava of Tiga (TL2)
This unit distributed in the north-northeast of study area. It was grayish black, porphiritic with phenocrysts of plagioclase, biotite, and pyroxene, that slightly altered to chlorite and epidote. Field observation suggests this unit was younger than the 2nd pyroclastic breccias of Tiga (TB2).

h. 1st Pyroclastic breccias of Kabawok (KB1)
This unit distributed in the central-south of study area. It was highly weathered, grayish brown, poorly sorted, angular fragments of porphiritic andesite with phenocrysts of plagioclase and pyroxene, groundmass of lapilli tuff that strongly altered to sericite. Satellite imagery analysis suggests this unit overlying the tuff of Sumurpitu (SPt) and lava and pyroclastic breccias of Way Panas (WLB).

i. 1st Lava of Kabawok (KL1)
This unit found in the central-south of study area. It was gray, porphyritic, phenocrysts of plagioclase and pyroxene that partially altered to epidote. Quartz vein were observed in thin section. Field observation suggests this unit was younger than the 1st pyroclastic breccias of Kabawok (KB1).

j. 2nd Pyroclastic breccias of Kabawok (KB2)
This unit located in the central-north of study area. It was highly weathered, brown, poorly sorted, rounded fragments of porphyritic andesite with phenocrysts of plagioclase and biotite, groundmass of pumice, plagioclase and volcanic glass. Field observation suggests this unit overlying the lava of Kabawok (KL1).

k. 3rd Pyroclastic breccias of Kabawok (KB3)
This unit located in the central-west of study area. It was highly weathered, grayish brown, poorly sorted, angular fragment of basaltic andesite. Field observation suggests this unit was younger than the 2nd pyroclastic breccias of Kabawok (KB2).

l. 3rd Lava of Kabawok (KL3)
This unit occupied the central-east of study area, on the center of Kabawok Volcano. It showed flow structures with aligned plagioclase, colour of dark gray, texture of porphyritic, phenocrysts composed of plagioclase and pyroxene. Field observation suggests this unit was younger than the 3rd pyroclastic breccias of Kabawok (KB3). All of Kabawok products were assigned to the age of 1.7 Ma (Masdjuk, 1989).

m. Pyroclastic breccias of Tanggamus (TB)
This unit found in the centre-southeast of study area. It was composed of angular-subrounded fragments of porphyritic andesite with phenocrysts of plagioclase, pyroxene, and hornblende, embedded in groundmass of lapilli tuff. Minor alteration occurred as volcanic glass changed to clay and chlorite. Satellite imagery analysis suggests this unit was younger than the 3rd lava of Kabawok (KL3).

n. Ignimbrite of Tanggamus (Ti)
This unit located in the east-northeast of study area. It was white, angular, and composed of biotite, plagioclase, hornblende, volcanic glass (partially altered to clay), and lithic fragments. Satellite imagery analysis suggests this unit was younger than the pyroclastic breccias of Tanggamus (TB).

o. Lava of Tanggamus (TL)
This unit occupied the central-east of study area. It was bright gray, vesicule, porphyritic with phenocrysts of plagioclase that partially altered to chlorite. According to Masdjuk (1989), radiometric age of this unit was 1.4 Ma, younger than units of pyroclastic breccias (TB) and ignimbrite (Ti) of Tanggamus.

p. Laharic breccias of Tanggamus (Tlh)
This unit found in the northeastern part of study area. It was composed of weathered lahar deposits, poorly sorted, angular to rounded fragments of porphyritic andesite (phenocrysts of plagioclase and pyroxene) and pumice. Radiometric age of this unit was 1.5 Ma (Masdjuk, 1989). However, that number perhaps too older, as field observation suggests this unit was younger than units of lava (TL) and ignimbrite (Ti) of Tanggamus.

q. Alluvial (al)
This unit distributed in the south-southwestern part of study area. Deposited in Holocene, it was the youngest stratigraphic unit of study area. It was composed of gravel, sand, and mud, that being deposited as flood plain by fluvial processes.

4.3. Geologic structures

4.3.1. Morphologic Lineament

As mentioned in section Methods, morphologic lineament as presented by linear valley and escarpments indicates the existance of tectonic deformation. Lineament extraction were done in manual as well as digital (computerized). Manual extraction was based on significant length and only consists of tens of lineaments (Figure 7). At the other hand, digital extraction produced thousands of lineaments (Figure 8).

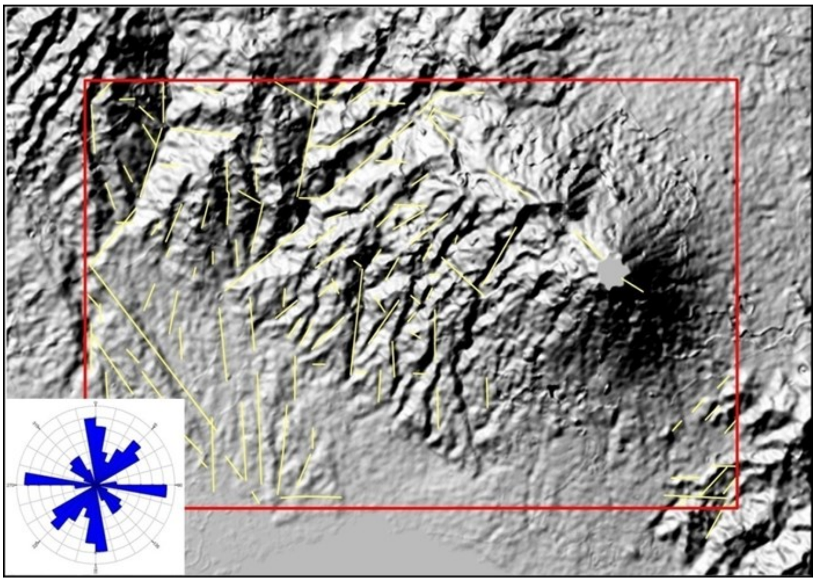

Figure 7: DEM manual extraction of lineament (indicates by thin yellow lines). Study area is shown by thick red-line rectangle.

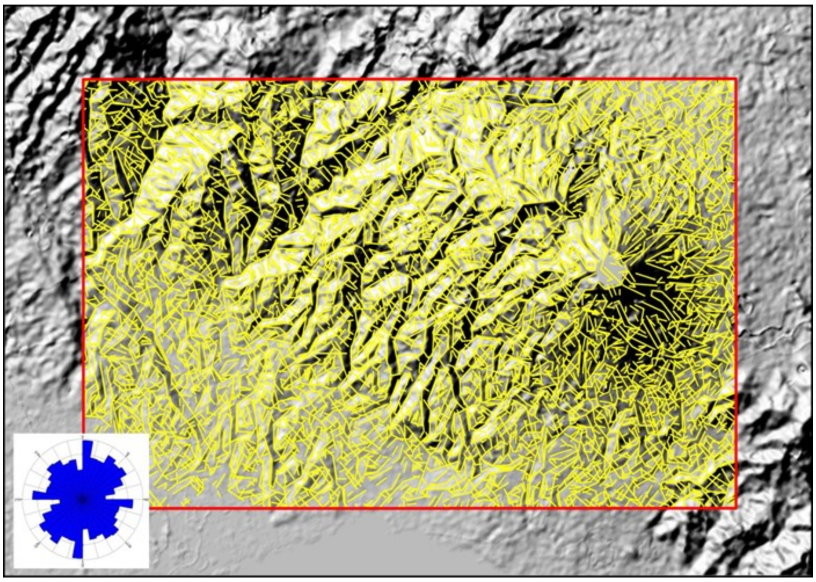

Figure 8: DEM digital extraction of lineament (indicates by thin yellow lines). Study area is shown by thick red-line rectangle. From total 1938 data, statistic analysis suggests dominant lineament aligned northeast-southwest following its major faults.

Manual extraction indicates two principal trends, i.e. N-S and NE-SW (Figure 7). Those two trends were mostly occurred in old volcanic rocks and interpreted to represent shear fractures which developed by NNE-SSW compressive stress. Related to the NW-SE regional trend of Sumateran Fault as the primary structure, those two principal trends were formed as secondary structures. Other than the secondary structures, a small portion of manual extracted lineament occupied NW-SE trend (Figure 76), in parallel with primary structure. This trend mainly found in the Sumurpitu Tuff (SPt), which is older than rock units cut by the N-S and NE-SW shear fractures.

Digital extraction indicates two principal trends of NE-SW and NW-SE (Figure 8). Differences in result between digital extraction and manual extraction were mainly caused by number of resulted lineaments, where a larger number of data in digital extraction allows appearance of tectonic lineament in more objective approach. Although visually dissimilar, both lineament extraction support each other. The principal trend of NE-SW is probably resulted as secondary structures formed by movement of the primary structure. The principal trend of NW-SE is interpreted to be aligned and formed by the primary structure.

Analysis on digital-extracted lineaments according to their respective lithologic unit (Figure 9) suggests development of tectonic deformation working in the study area. Old volcanic rocks commonly have one principal trend, either in NE-SW (in northwest section) as resulted from secondary compressional stress, or in NW-SE (in central and north sections) as part of activation of primary structure. Younger volcanic rocks tend to have radiated principal trends, suggesting volcanic radial fractures were the most dominant tectonic factor.

4.3.2. Field Measurement

Field data were composed of joints (both extension joints and shear joints) and faults.

Joints: statistical analysis on 220 data suggests a NNE-SSE compressional stress that responsible for the NNE-SSW extension joint formation, and a ENE-WSW compressional stress that generated shear joints of N-S and NE-SW direction (Figure 10). Differences in those trends of compressive stress could be explained in different tectonic origin. The occurrence of NNE-SSW extension fractures in the central part probably triggered by two NW-SE fault segments with right-lateral wrench movement. Later, when new volcanic complex emerged in the extended central part, aligned in NW-SE direction, their enormous weight had exerted outward compressional forces to ENE-WSW direction, produced the N-S and NE-SW shear joints.

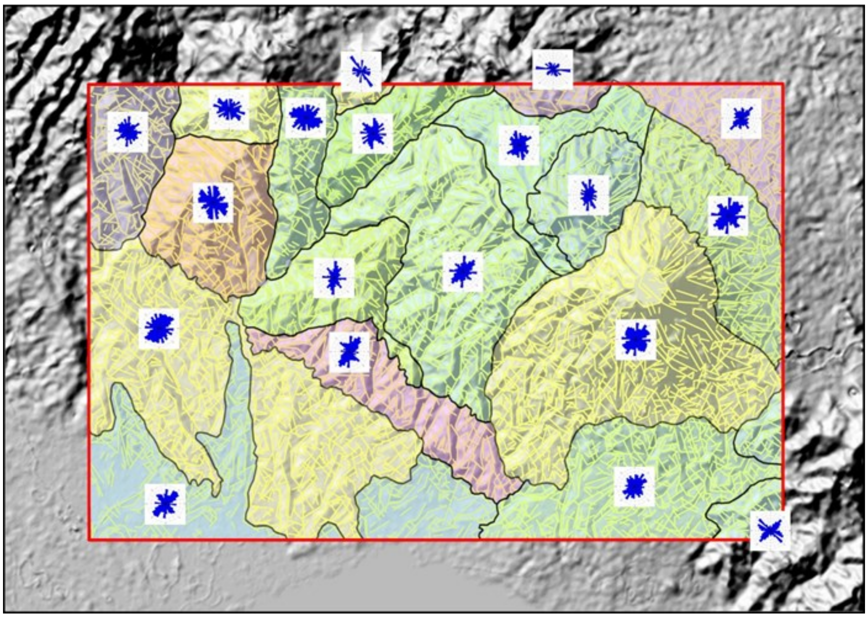

Figure 9: Statistic analysis on digital-extracted lineaments in each rock unit (colour symbols refer to Figure 5).

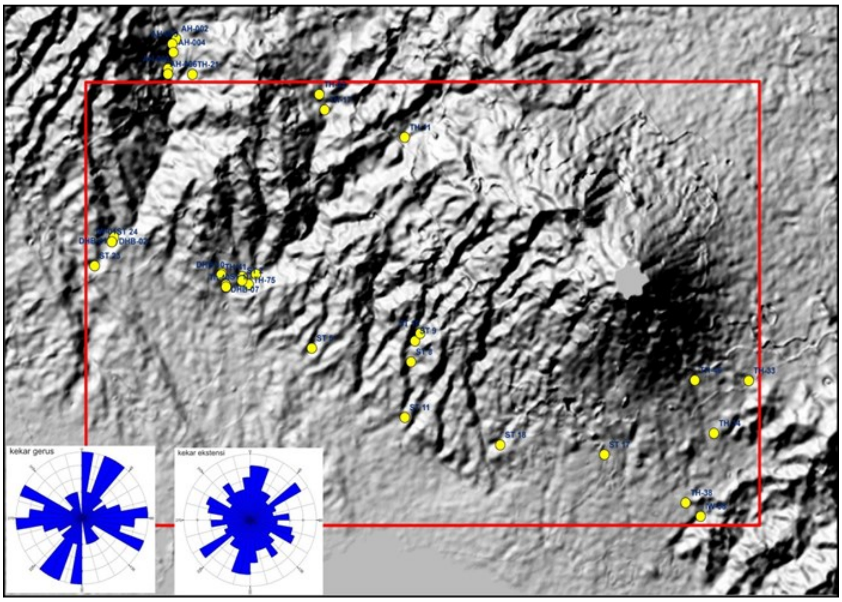

Figure 10: Statistical analysis on surface fractures (joints and veins), data of 170 extension joints and 50 shear joints.

Faults: analysis on fault movement was done with kinematic analysis, to determine extended region and slipped region (Figure 11). The NE-SW extension dominates the southern part of study area, particularly along Way Panas Fault and eastern part of Sula Volcano, that associated with extension joints. Some NE-SW extension also occurred in the eastern part of Way Panas Fault which associated with shear joints resulted from volcanic load gravitational force.

Volcanic faults: circular, horse-shoes shaped, normal faults were common in volcanic edifices, as shown by DEM interpretation of the study area (Figure 4). In Kabawok Volcano those faults opened to SE direction with diameter of 3.5 km. In the southern slope of Tanggamus Volcano another fault opened to the east. Tanggamus Fault probably associated with Way Panas Fault reactivation, or probably it just exploited Way Panas fault plane to slide down.

4.4. Surface thermal manifestation

Based on the area of occurrence, surface thermal manifestation were grouped into three clusters, i.e. Tiga cluster, Pangpete cluster, and Way Panas cluster. Tha Pangpete and Way Panas manifestation were spatially closed to Way Panas Fault.

- Tiga manifestation: it was located in the western slope of Tiga Volcano, occurred as gas discharges (temperature ranges from 75 °C to 82 °C) and mud pots.
- Pangpete manifestation: located in the southern slope of Sula Volcano, occurred as hot springs (aligned ENE-WSW, temperature ranges 97 °C – 100 °C), fumaroles (99,8 °C), gas discharges (73 °C), steaming grounds (38 – 40 °C), altered rocks (to quartz, halloysite, smectite, kaolinite, and calcite), and hydrothermal mineral deposits (quartz).
- Way Panas manifestation: located in the eastern slope of Way Panas Volcano, occurred as hot springs (aligned E-W, temperature ranges 66.4 °C – 100 °C), seepages (46.7 °C – 99.6 °C), fumaroles (aligned NW-SE, tempearture ranges 81.4 °C – 99.5 °C), gas discharges (56.3 °C – 100.5 °C), geysers (occurred in E-W trending fault plane, regular outburst every 3 seconds, temperature 99.6 °C), altered rocks (halloysite, illite, chlorite, and quartz), and hydrothermal mineral deposits (quartz and travertine).

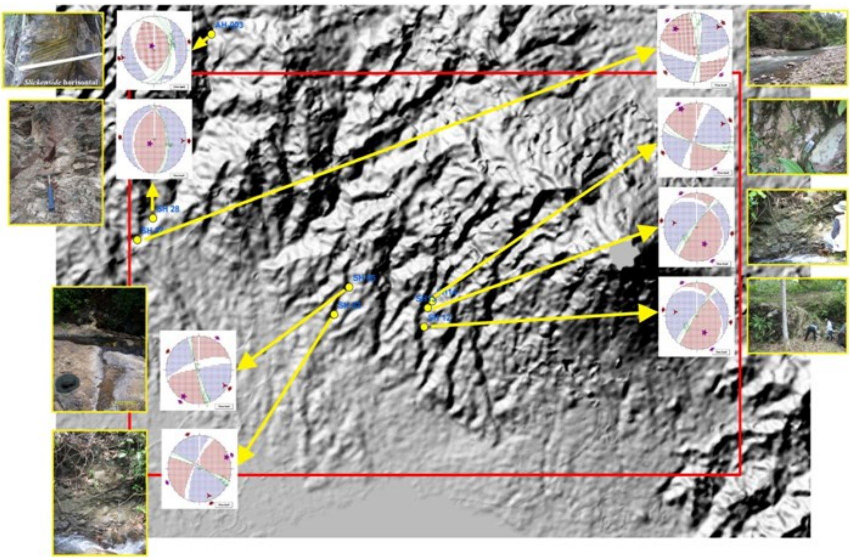

Figure 11: Kinematic analysis on minor fault using dihedra (spherical ball) stereographic method. Each dihedra net was divided into 3 or 4 kinematic domains, red dihedra suggests contractional, whilst blue dihedra suggests extensional. Position of red dihedra in net center and blue dihedra in net margin suggests extensional tectonic domain.

5. DISCUSSION

5.1. Structural Development

The study area is located in between two fault segments, i.e. Ulubelu Fault to the north, and Umbul Fault to the south. The Umbul Fault was named as Way Panas Fault in the study area (Figure 5). Those two fault segments were interpreted to be active in Pliocene (Pramumijoyo, 2008), as part of Semangko Fault establishment at that time. The Ulubelu Fault created a pull-apart basin to the north of study area, which later developed into Ulubelu geothermal system. The Way Panas Fault was active as extensional fault.

Structural development of the study area resulted from interaction between those two faults. They are aligned in NW-SE direction, following the primary structure of Sumatera Fault. A relatively north-south compressional stress was generated by right-lateral movement of those two faults, producing extension joints and extension faults that distributed in the study area.

In addition to tectonic compression, weight-load exerted by volcanic edifices also plays important role in creating geologic structures. In the older volcanic complex that aligned in WNW-ESE direction, gravitational stress from the volcanic weight produced NNE-SSW extension joints, as well as N-S and NE-SW shear joints. In the younger volcanoes, gravitational force produced horse-shoes shaped extensional faults opening to ESE direction. Direction of the extensional fault opening in these younger volcanoes could be understood as only to ESE direction that those gravitational sliding were not obstructed by older volcanic edifices.

5.2. Volcanism History

Volcanism in Way Panas have been occurred since Tertiary and being incessant up to present-day. Tertiaty volcanism was marked by development of Hulusimpang Formation in Late Oligocene to Early Miocene (Barber *et al*., 2005), that was represented in the study area by the lava and pyroclastic breccias of Cukuhbailak (CLB). This unit was formed as pyroclastic flow deposits that ended by lava flow. Its role as basement for Quaternary volcanic deposits was accompanied by the occurrence of late Tertiary Sumurpitu tuff (SPt). The latter unit was deposited as pyroclastic falls from an explosive eruption with unknown source, probably beyond the study area. The nearest possible candidate for the source of Sumurpitu tuff was Suoh Caldera (Bemmelen, 1949), that was located 30 km to the northwest.

Quaternary volcanism was marked by regular shifting of volcanic activities from west to east. It was initiated by Sula deposits that composed of pyroclastic breccias, lava, and tuff (SLB). They were formed as explosive eruption of Sula Volcano that concluded by lava flow. Subsequent volcanic activities of Way Panas, located to the east of Sula Volcano, produced pyroclastic breccias from its eruption that followed by lava flow (WLB).

Further volcanism occurred to the east of Way Panas Volcano as Tiga Volcano was active in two phases. The first phase produced by Tiga Caldera with pyroclastic flow deposits that followed by fall deposits (TB1). The second phase marked by intra-caldera eruption that produced pyroclastic flow deposits (TB2) and concluded by lava flow (TL2) along the ring fracture. Only the north-west section of Tiga Caldera that can be recognized from satellite imagery analysis, as its east-south part buried by Kabawok deposits.

Kabawok Volcano that located to the east of Tiga Volcano was active in three phases. The first phase resulted by explosive eruption that produced pyroclastic breccias (KB1) and terminated by lava flow (KL1). The second phase was marked by development of Kabawok Caldera and deposition of pyroclastic breccias (KB2) at its outer rim. Estimated from geometry of caldera and distribution of deposits, it was assummed that this second phase had involved the largest energy among the life-long activity of Kabawok Volcano. The third phase was marked by pyroclastic flow deposits (KB3) that filled the inner part of Kabawok Caldera, concluded by lava flows (KL3) in the central cone. Satellite imagery analysis indicates that observable caldera rim only left at the northwest to northeast section, the rest were destroyed and buried by deposits of Tanggamus.

The youngest volcanic activity in the study area was associated with Tanggamus Volcano that located to the east of Kabawok Volcano. Its activity could be separated into four phases. The first phase was occupied by explosive eruption that produced pyroclastic breccias (TB). The next phase was done by further devastating eruption that produced ignimbrite (Ti). The third phase was marked by lava flows (TL) that covered the cone and southeastern slopes. The last phase was built by lahar deposits (Tlh) that reworked older materials and distributed to the north-east.

5.3. Implication to Geothermal Model

Way Panas prospect is considered as part of greater geothermal system of Rindingan-Ulubelu-Way Panas (Suharno, 2003), whereas Way Panas is situated in the southern part of the system. This study offers a tentative geothermal model as follow (Figures 12, 13):

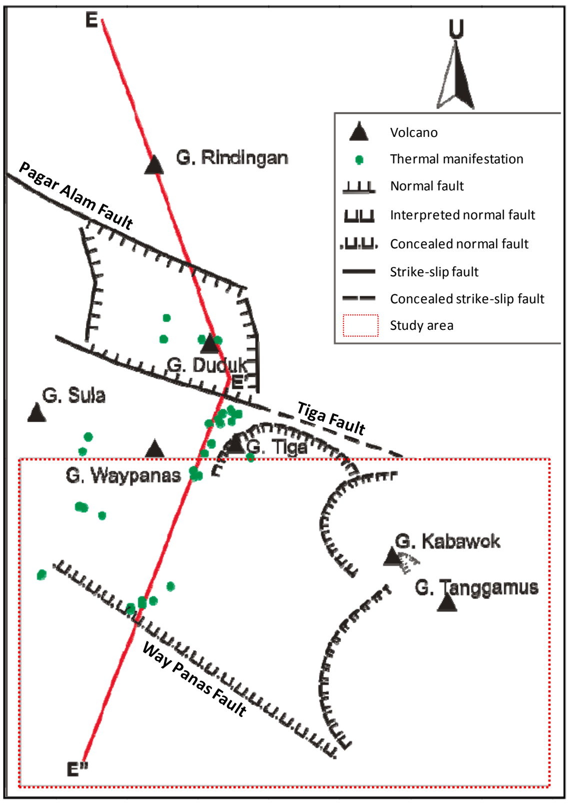

Figure 12: Sketchmap of tentative geothermal model of Rindingan-Ulubelu-Way Panas.

a. Heat source: close association between surface thermal manifestation with volcanic centers suggests the heat source for geothermal system of Rindingan-Ulubelu-Way Panas (RUW) is of magmatic origin. Two possible location of heat source were deduced from magnetotelluric survey that indicated conductive area beneath the southern slope of Rindingan Volcano and another beneath Kukusan Volcano, both with undefined depth (Yorinaldi *et al*., 2000)

b. Permeability:
- Potential rock units that exhibit good primary permeability in the study area are:
  (i) lava and pyroclastic breccias of Way Panas (WLB), permeability mainly constructed by its cooling fractures and autoclastic brecciation,
  (ii) lava and pyroclastic breccias of Sula (SLB), permeability given by autoclastic brecciation.
- Potential structures that acting as fluid migration pathways are:
  (i) the NW-SE trending Way Panas Fault that is most likely to act as out flow zone; in Pangpete this fault was associated with fumarolic manifestation (fumaroles, steaming grounds, and springs), whereas in Way Panas it was associated with bicarbonate fluids and travertine deposits,
  (ii) horse-shoes shaped structures of Tiga, which was associated with acid fluids manifestation and altered rocks.

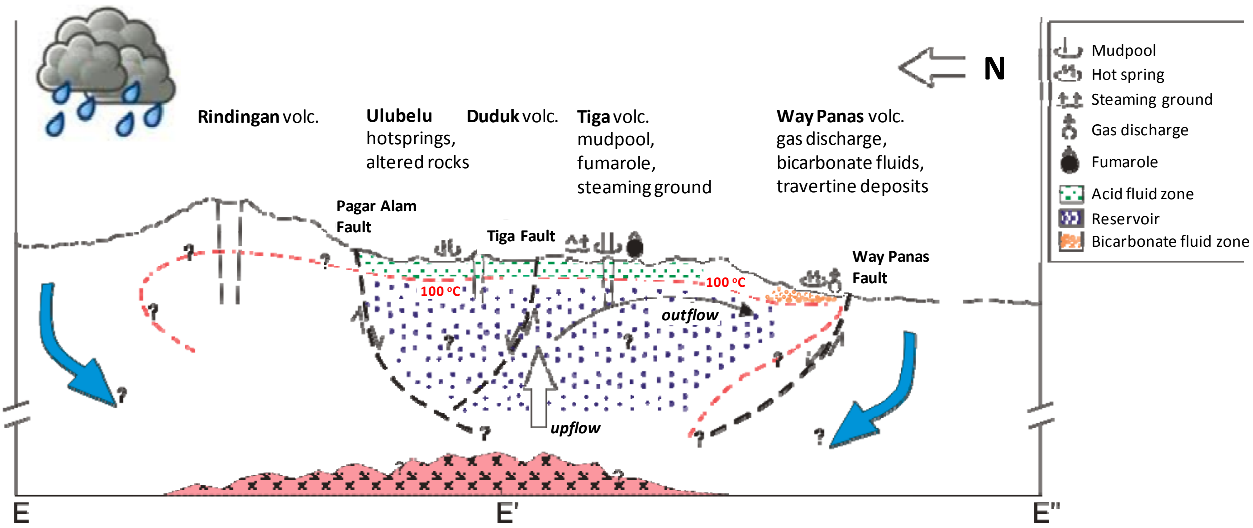

Figure 13: Conceptual model of Rindingan-Ulubelu-Way Panas geothermal system. Location refers to Figure 12.

c. Hydrothermal fluids: it was deduced that the hydrothermal fluids in the RUW system were meteoric origin, which is common in Indonesia and West Pacific regions.

d. Hydrologic structures:
- Way Panas is an outflow that controlled by the Pliocene Way Panas Fault. Boundary of the RUW system was marked by the occurrence of bicarbonate hotsprings with travertine deposits. It was supported by low resistivity value of DC-resistivity and MT that showing "opening tongue" to the south (Yorinaldi *et al*., 2000).
- Upflow area is assummed to be located beneath the pull-apart basin of Ulubelu that formed at Early Pliocene. Large permeability due to pull-apart extension made the heat transfer from underlying younger source possible. Indication of active hydrothermal reservoir in this area is also supported by microseismic analysis (Suharno, 2003) and rock-magnetization analysis (Suharno *et al*., 2005). The existence of concealed structural graben in Ulubelu was also supported by gravity data (Daud *et al*., 2000).
- The absence of thermal manifestation in the east – southeast part of study area was probably related with undeformed young products of Tanggamus Volcano (<1.4 Ma) that lack of secondary vertical permeability.

6. CONCLUSION

- Three geomorphic units established in the study area, i.e. (i) young volcanoes, (ii) faulted old volcanoes, (iii) eroded structural hills, and (iv) Kotaagung alluvial plain.
- Seventeen (17) rock units established referring to its nature of deposition that distributed into 7 origin as follow: (1) Cukuhbailak Volcano, (2) Sumurpitu Tuff of uncertain origin, (3) Sula Volcano, (4) Way Panas Volcano, (5) Tiga Volcano, (6) Kabawok Volcano, and (7) Tanggamus Volcano.
- Those volcanic edifices above were built sequentially from older to younger in WNW to ESE direction, thus constructing the volcanism history of the study area.
- Structurally, the study area is located in between two fault segments, i.e. Ulubelu Fault and Umbul Fault (Way Panas Fault), both were active since Pliocene, as part of Semangko Fault movement.

- The Ulubelu Fault created a pull-apart basin that developed to Ulubelu geothermal system (upflow zone), while the Way Panas Fault was active as extensional fault (outflow zone).
- A relatively north-south compressional stress was generated by dextral movement of those Ulubelu and Way Panas faults, producing extension joints and extension faults that distributed in the study area, producing good permeability.
- Lateral load-weight from older volcanic edifices creates NNE-SSW compressional force, producing corresponding extension and shear fractures, which also generated good permeability.
- Younger volcanic edifices creates a ESE extensional force from its weight and their undeformed deposits reduced permeability.

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