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Evaluation of the productive geological structure in Ulubelu Geothermal System

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ABSTRACT

The Ulubelu geothermal field is within the Ulubelu geothermal working area or WKP, owned and operated by PT Pertamina Geothermal Energy (PGE). The WKP is in Lampung, South Sumatra. Ten production wells are currently supplying steam to the 2 x 55 MWe Units 1 and 2 turbines that were commissioned in October 2012.

The production borefield is situated inside a volcano-tectonic depression – a pull-apart basin tectonically-related to the dextral Semangko segment of the Sumatran Fault System (SFS). This structural study identified three sets of faults: the NW-SE striking Muara Dua and Talangmarsum faults, the ENE-WSW striking Sula and GunungTiga faults, and the other NW-SE striking Datarajan, Karangrejo, and Duduk faults. There are also three short strike-length faults, Rindingan 1 to 3. The Rindingan 3 fault is striking NNE-SSW. These shorter faults are geothermally-significant structures because they are believed to have provided the necessary fracture-permeability in the postulated upflow zone of the Ulubelu geothermal system.

Muaradua-Dataranjan and Talangmarsum are synthetic faults of the Semangko segment. These faults define the western and eastern boundaries of both the depression and the lateral extents of the geothermal resource area in these directions. The Sula and Gunung Tiga faults are antithetic of the same Semangko segment. Gunung Tiga fault roughly marks the southern edge of the geothermal resource.

Image logs of two prolific wells, UBL-3 and UBL-26, show that the productive faults and their associated fracture zones are striking NW-SE. These structures control fluid flow in the geothermal system and are excellent targets for make-up, production and reinjection wells.

1. INTRODUCTION

The high-temperature water-dominated Ulubelu geothermal system (UGS) within the Ulubelu geothermal working area (WKP) is located in Lampung, South Sumatra. The geothermal system is associated with the Pleistocene age Gunung (G) Rindingan andesite stratovolcano. Ten production wells supply steam to the 2 x 55 MWe Units 1 and 2 turbines since October 2012. Seven injectors dispose the separated hot brines and cold condensates. Drilling of additional production wells dedicated to the planned 2 x 55 MWe Units 3 and 4 is currently underway.

Well-fault intersection analyses show that high bulk permeabilities and production capacities of the production wells and high swallowing capacities of the injection wells can be attributed to some faults and their associated fracture zones. Presence of faults or open fractures correlates very well with both the depths partial (PLC) and total (TLC) circulation losses during drilling and feed zones recognized from temperature profiles taken during water-loss and subsequent heat-up pressure-temperature (PT) surveys.

The geological structures in the UGF consisting of faults, lineaments, and volcanic features such as sector-collapse structures and tuff-ring or maar were identified using a combination of these methods:

- Topographic map and satellite imagery (ASTER DEM) interpretations
- Geologic mapping and field verification
- Fault and fracture analyses on image logs (Formation Micro Imager or Scanner)
- Correlation between drilling parameters and temperature profiles (static and flowing)

The resulting structural map of the geothermal field and results of stress-strain modeling are discussed in the next sections.

2. REGIONAL TECTONIC SETTING

The UGF lies inside the NW-SE trending Ulubelu depression. This depression is one of the several pull-apart basins along the SFS that are hosting geothermal systems (e.g. Muraoka, et al., 2010). These basins were formed as a result of the dextral movement of the SFS to accommodate the oblique convergence between the Indo-Australian and the Eurasian plates along the Java Trench (see inset map of Fig.1). The other PGE-operated geothermal fields that are located in or near pull-apart basins are Hululais-Bukit Daun and Semurup-Sungai Penuh. These fields are ~ 350 km and ~ 480 km northwest of Ulubelu, respectively.

The Ulubelu depression is roughly bounded on the north and south by G. Rindingan (1.41 mya) and G. Tanggamus (<1.41 mya) andesite stratovolcanoes. These volcanoes are situated on the southern end of the NW-SE trending Barisan Mountain Range that stretches through the whole length of the Sumatra island. Barisan is the magmatic-volcanic belt that runs parallel to the SFS and the Java Trench.

G. Rindingan and its associated Ulubelu geothermal system also lie within the 65-km long Semangko segment of the SFS. This segment or fault is a tensional regime which is dominated by NW-SE trending transtensional faults (Sieh and Natawidjaja, 2000;

Pramuniwidjojo, 2008). Stress analysis on the dextral movement of the Semangko fault would show that the structural framework of the UGF is intimately related to the relative movements of this regional structure.

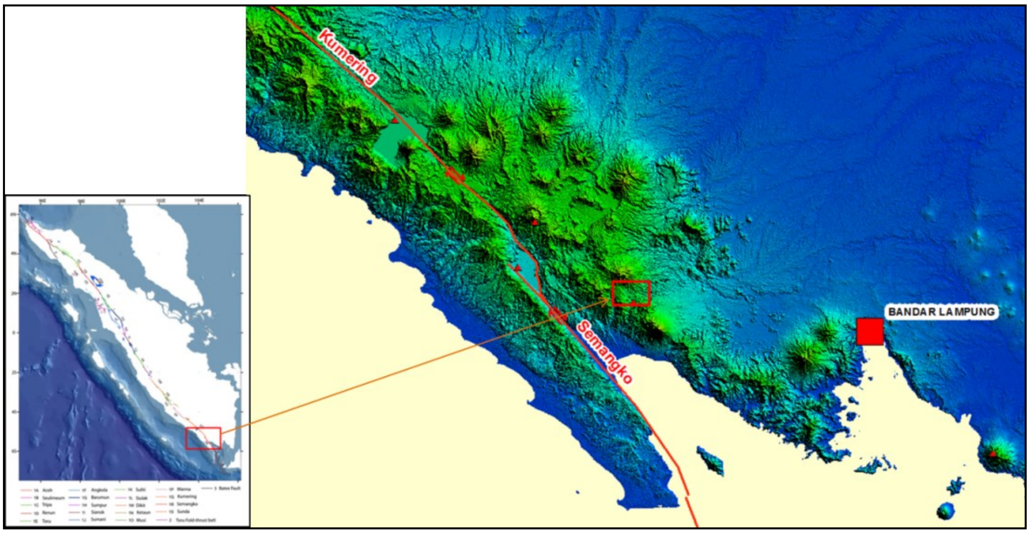

Figure 1: Location map of the Ulubelu geothermal working area (WKP) and the Ulubelu geothermal field (red open rectangle). The WKP and UGF are on the east of the dextral Semangko segment of the SFS.

3. LOCAL GEOLOGY

The Ulubelu volcano-tectonic depression or basin hosting the UGF is bounded on the north and south by G. Rindingan and G. Tanggamus andesite stratovolcanoes, respectively. The residual heat from cooling magma that is inferred to exist beneath G. Rindingan is the heat source that drives the geothermal system. Younger monogenetic dacitic domes G. Duduk (0.43 mya) and G. Tiga dominate the landscape of the southern part of the basin. The other andesite volcanoes outside the basin are G. Korupan (1.49 mya), G. Kabawok (1.75 mya), and G. Kukusan (3.94 mya).

The western- and eastern-boundaries of the Ulubelu depression are defined by the gravity faults Muaruadua-Datarajan and Talangmarsum, respectively. This ~ 3.5-km across and ~7-km long depression is filled with > 2.5 km-thick volcanic pile consisting of andesite lava, tuff, and pyroclastics mostly from G. Rindingan volcano, dacitic tuffs from nearby dacitic cones, and recent volcanoclastic materials. A low-lying tuff-ring, named Maruadua crater is very prominent volcanic feature on the southern end of the main production borefield. Just south of this crater is an inferred circular feature, the Karangrejo crater. These volcanic rocks were cut predominantly by NW-SE striking faults. These set of faults and fracture zones are the geothermally-significant structures as they provided the plumbing system for thermal fluid flow and circulation in the geothermal system.

The surface thermal manifestations emerged both inside and outside the depression at elevations ranging from 140 to 900 m asl. Just like in many producing geothermal systems associated with andesite stratovolcanoes, the Pagaralam and Maruadua fumaroles and acid-SO4 features are perched at higher elevations, 700-900 m asl, near the southern edge of the production sector. Conversely, the warm to boiling neutral pH high-chloride springs of Way Panas and Way Ngarip emerge at lower elevations, 140-200 m asl, and about 14 km to the south-southeast.

4. STRUCTURES IN THE ULUBELU GEOTHERMAL FIELD AND ITS VICINITY

The results of our structural studies are presented in the structural map of UGF shown in Figure 2. We recognized three sets of faults: the NW-SE striking Pagaralam and Talangmarsum gravity faults, the almost E-W to ENE-WSW striking Sula and Gunung Tiga faults, and the NW-SE striking Karangrejo. We also recognized three Rindingan 1-3 faults inside the depression. As mentioned earlier, these set of parallel faults are geothermally-significant as they provided the fracture-permeability in the UGS' upflow region. A NW-SE trending subsurface or buried structure was also inferred based on drilling, subsurface geology, and reservoir engineering data.

The Muaruadua-Datarajan and Talangmarsum faults act as the west- and east-bounding structures of the Ulubelu depression, respectively. Both faults also define the western and eastern boundaries of the geothermal resource. For example, most wells whose trajectories went beyond the Maruadua fault encountered decreasing temperatures with distance from the center of the field. These wells also exhibit distinct temperature reversals implying field boundary conditions. Wells drilled from reinjection clusters A and R1 that intersected the Maruadua and Datarajan faults show that both faults are highly permeable.

Stress ellipsoid analysis such as shown in Figure 4 reveals that these faults are synthetic faults formed as a result of the right-lateral strike-slip movement of the Semangko master fault acting as a couple and the greatest principal stress. This will be further discussed in the succeeding section.

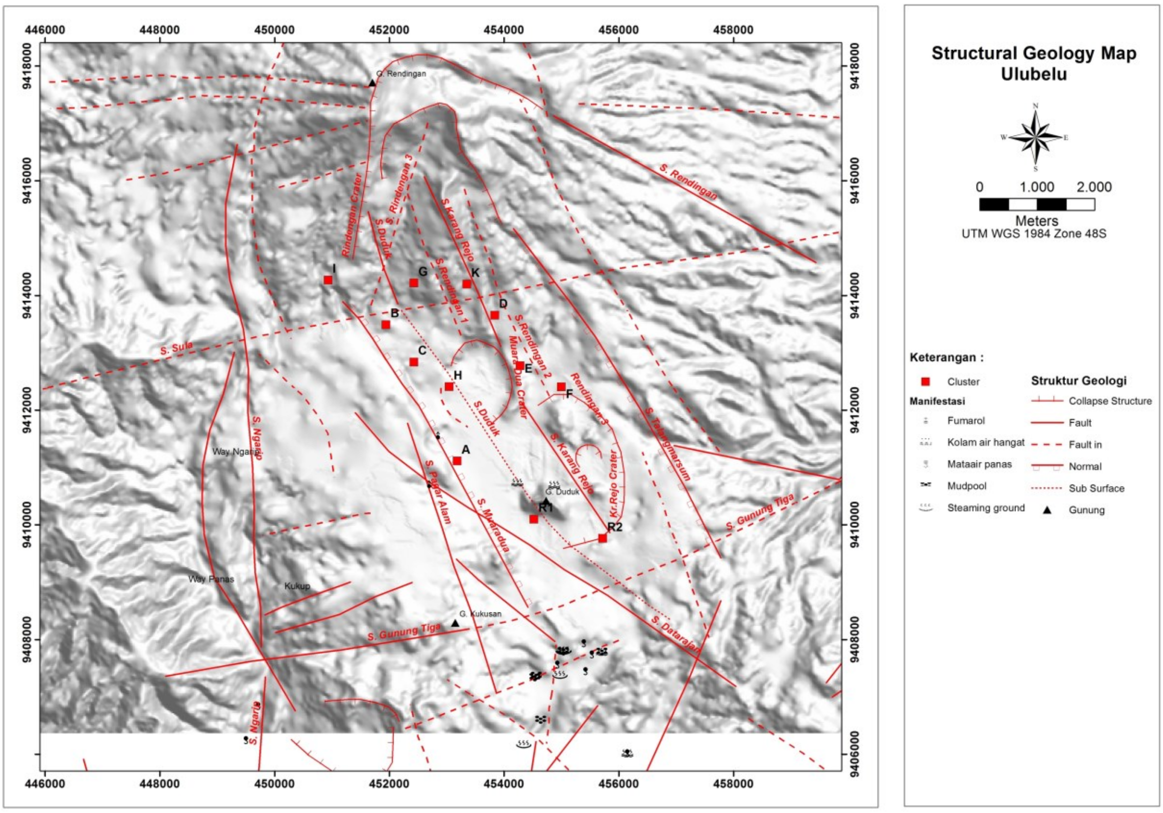

Figure 2: Structural map of the Ulubelu geothermal field. The production and reinjection well pads or clusters are shown in red squares.

The other set of major structures are the almost E-W to ENE-WSW striking Sula and Gunung Tiga faults. These faults traversed the northern and southern ends of the Ulubelu depression. Drilling and reservoir engineering data show that Tiga fault roughly represents the southern boundary of the geothermal resource area. In contrast, Sula fault has no control on the lateral extent of the geothermal field to the north. Recently drilled production wells from clusters G and I, located north of the fault, are still good producers. These wells encountered high-temperature, > 280ºC, two-phase geothermal fluids. Similar stress modeling finds Sula and Gunung Tiga faults as antithetic faults. As antithetic faults, their relative displacements are likely to have both horizontal (sinistral) and vertical (normal) components.

Inside the Ulubelu depression, the volcanic deposits are cut by at least three normal faults striking NNW-SSE: the Karangrejo and Rindingan 1-3 faults. These SW-dipping high-angle faults are found to be productive structures in UGF. Most of the wells, particularly those drilled from clusters B, D, G, and I that intersected these faults and their fracture zones are good producers. A buried fault also contributed to the bulk permeability of many wells. These faults are thought to control the geothermal fluid flow coming from the upflow zone located at the mid-upper slopes of G. Rindingan towards the south-southeast and lower elevations. These faults, together with other subordinate NNW-SSE striking normal tension structures, are good targets for the additional production and make-up wells. These productive structures were confirmed by the image logs.

Two formation micro image (FMI) logs, from UBL-3 (B2) and UBL-26 (H2), were analyzed. These wells, drilled from cluster B and H, respectively, are good producers with steam flows equivalent to ~ 11 and 19 MWe, respectively. The logs (Fig.3A-C) show that the continuous conductive (CCF) and the discontinuous conductive (DCF) fractures in both wells are oriented to the NW-SE. The faults are likewise striking NW-SE (azimuths 120-160º) and dipping 60-75º to the SW with few dipping NE. These fractures zones correspond to the PLCs and TLCs encountered while drilling and feed zones identified from temperature profiles taken during water-loss and heat-up PT surveys. The trajectories of recently-drilled wells were designed principally to intersect at higher angles these permeable faults and fracture to insure higher probability of success.

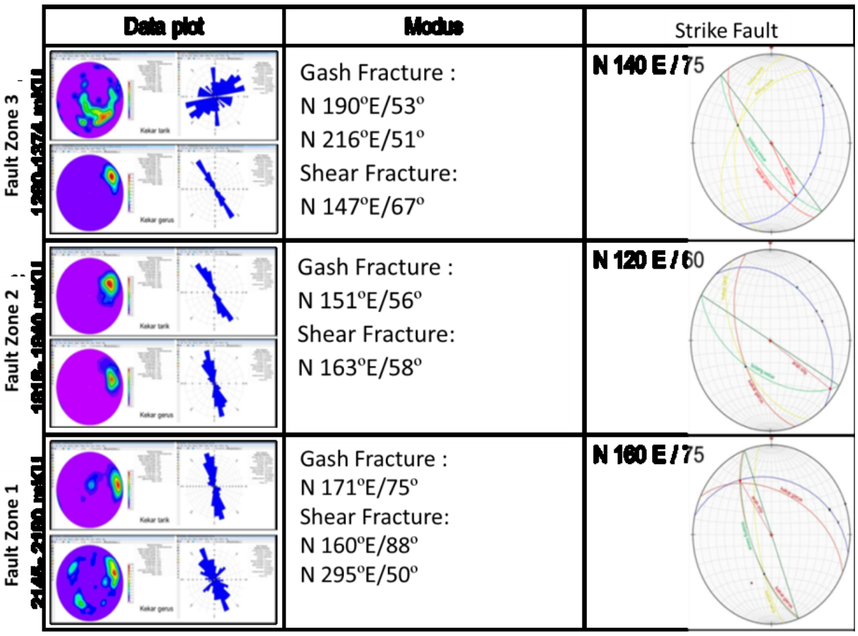

Figure 3A: Strikes and dips of fractures and faults identified from formation micro image log of UBL-3. The log covers the depths between 1280 m and 2180 m below CHF. The faults' azimuths range from 120 to 160° and dipping from 60 to 75 °.

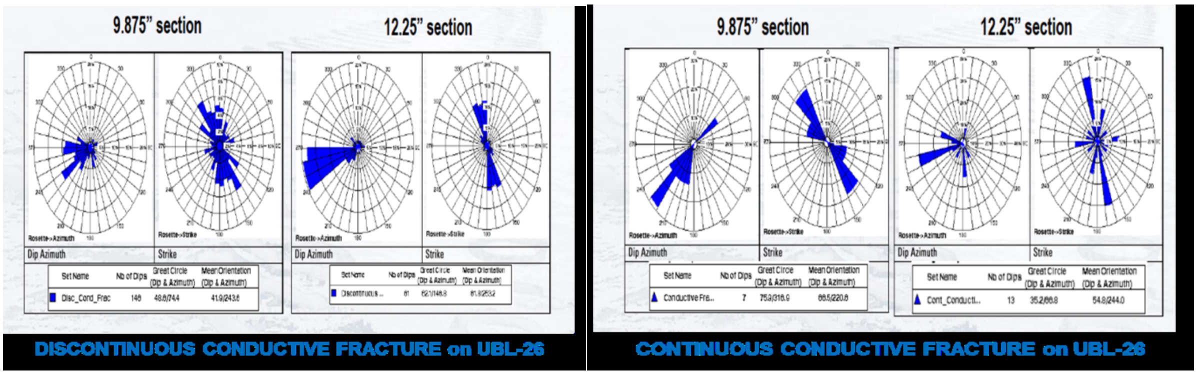

Figure 3B: Rose diagrams of continuous and discontinuous conductive fractures in UBL-26. The dominant trend is NW-SE

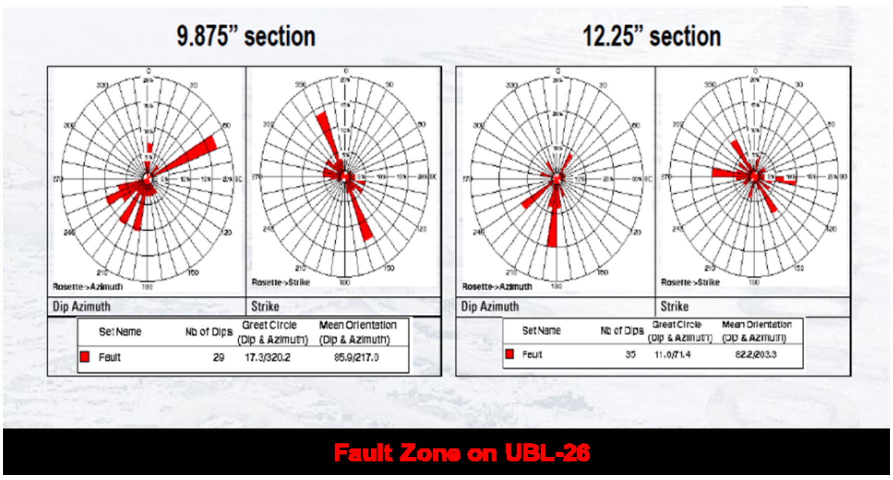

Figure 3C: Strike and dip of faults interpreted from image logs of UBL-26.

5. DISCUSSIONS AND CONCLUSIONS

We carried out stress analysis using stress ellipsoids (Fig.4) to determine the types of fractures, whether tension or shear, that will develop in the UGF and its vicinity considering the dextral movement of the Semangko fault acting as a couple and at the same time the greatest principal stress (Riedel, 1929 and Harding, et al. 1973).

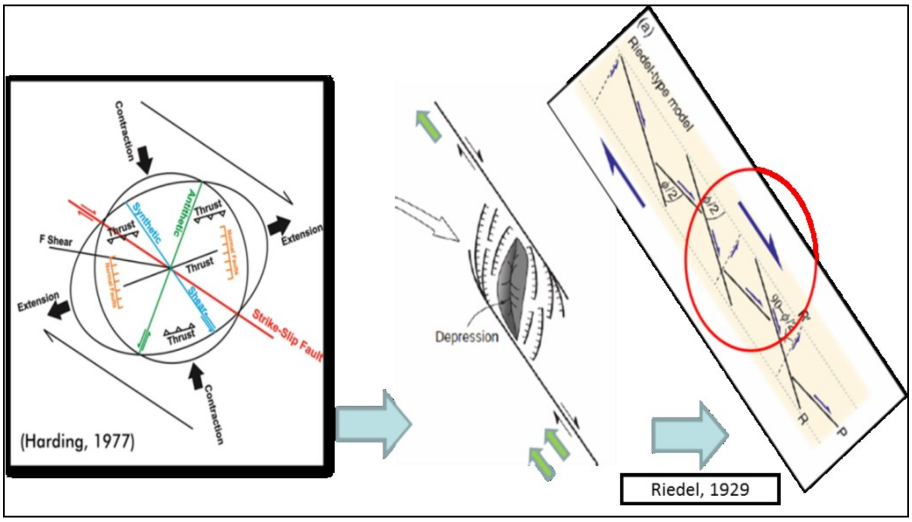

Figure 4: Stress ellipsoids of Harding, et al. (1977) and Riedel (1929).

Based on this stress-strain model and validated by field observations, both the maximum local and regional horizontal stress directions is NNW-SSE. The Maruadua, Datarajan, and Talangmarsum faults, the west- and east-bounding faults of the Ulubelu depression, respectively, are synthetic faults of the Semangko segment (Fig.5). As such they are also extensional in nature and exemplified in UGF by the Karangrejo and the three Rindingan 1-3 faults. These NW-SE striking faults are permeable faults as confirmed by the FMI logs of the prolific wells UBL-26 and UBL-3. These faults are also the P-shears in the Riedel shear model.

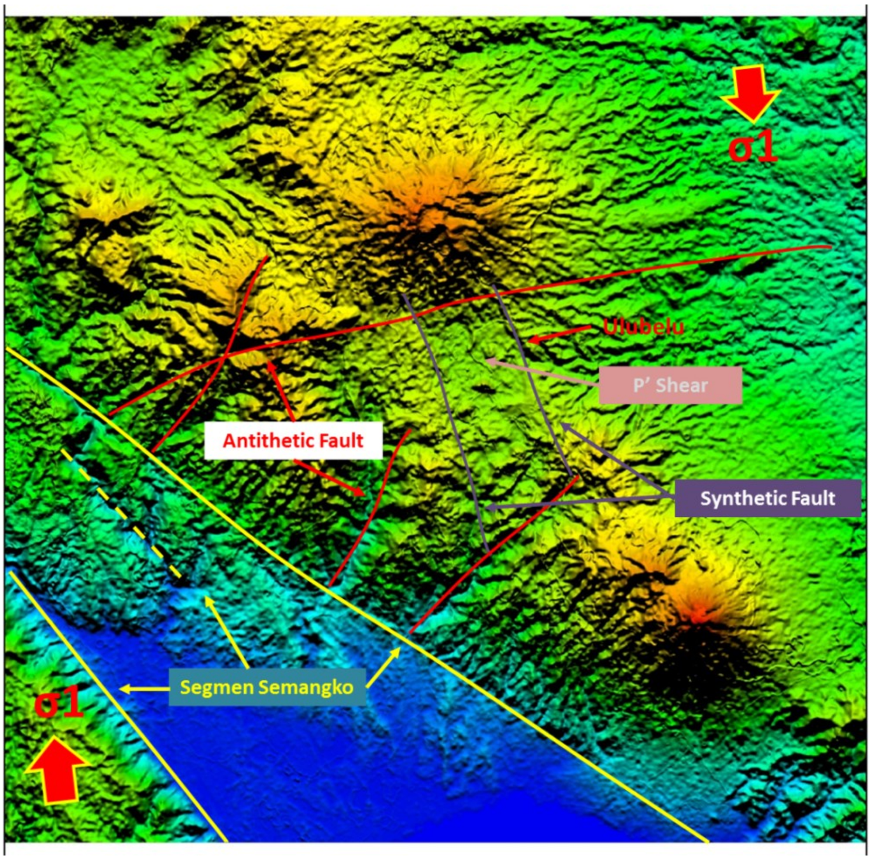

Figure 5: The fault system in the UGF and its vicinity resulting from the dextral movement of the Semangko segment acting as the greatest principal stress and couple.

In contrast, the Sula, Gunung Tiga and possibly Wayans faults are antithetic faults of the Semangko segment. These faults are expected to be closed and relatively impermeable. The Gunung Tiga fault lies on the southern edge of the geothermal resource area. It also serves as barrier that diverted the lateral fluid flow to the southwest towards the Way Panas area.

In conclusion, it has been shown by stress modeling and using results of drilling both production and reinjection wells in UGF, that the permeable structures are those striking NW-SE inside the depression. These faults and fracture zones are excellent targets for drilling make-up, production and reinjection wells.

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