Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Permeability Control on Tompaso Geothermal Field and Its Relationship to Regional Tectonic Setting

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Keywords: structure, permeability, Tompaso

ABSTRACT

Tompaso geothermal field is located in the northern arm of Sulawesi Island, Indonesia. This field can be separated as a different geothermal system from Lahendong field that successfully developed by Pertamina. The hot fluid upflow at Tompaso postulate to be located in Riendengan – Sempu volcanic complex and it is moving to NE controlled by ENE-WSW trending fault indicated by manifestation appearances lineament.

Comprehensive structural geology analysis was conducted using satellite images, digital terrain model (DTM), and supported by two borehole fractures imaging log. Fault at the surface identified have trending NE-SW Tompaso Fault. The major fault identified ENE-WSW sinistral strike-slip Soputan Fault, which control manifestation distribution in Riendengan – Sempu and Tempang - Toraget. The other fault have trending NW-SE Sonder Fault. The open fractures from borehole imaging log trending dominant NE-SW, and sealed or close fractures are mainly trending NW-SE. The local maximum horizontal stress (Sh_{max}) trending NE-SW identified from drilling induced tensile fractures and borehole breakouts orientation. It is agreed with the trend of open fracture patterns.

There is a contradictive stress orientation between Sh_{max} (NE-SW) and the direction of regional stress derived from Molluca Sea collision zone that trends North West. Both those two stress vectors are almost perpendicular. The resultant stress from the north and the south part of Minahasa due to their difference of plate movement vectors are suspected as the primary cause of the local stress regime. It is also resulting a parallel couple strikes slip faults in North and South of Minahasa (Manado-Kema Fault and Amurang-Malompar Fault) that have opposite slip movement. This local stress regime controls the Soputan Fault that provides the permeability for geothermal fluids in the Tompaso geothermal system.

1. INTRODUCTION

1.1 Background

Permeability is one of the most important parameters in geothermal systems. It provides paths that allow fluid (steam or liquid) to flow into the surface. Open fractures are a very common type of permeability in geothermal systems, and most of the steam entries or feed zones are always associated with these fractures. This paper describes the structural geology model of Tompaso geothermal systems that control the orientation of open fractures and its relationship to the regional tectonic setting of North Arm of Sulawesi.

1.2 Location

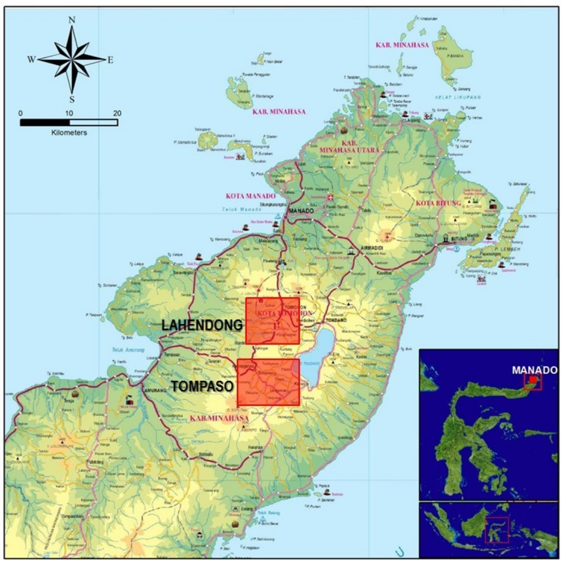

Figure 1. Map location of Tompaso geothermal field.

The Tompaso geothermal field is located about 40 km south of Manado City, the capital of North Sulawesi Province (Figure 1). The elevation of the field is ranges from 600 to 900 meters above the sea level. Physiographically, Tompaso field lies within the 30 km diameter Tondano volcanic depression, consisting of Tertiary and Quarternary volcanic rocks. This depression also contains Lahendong geothermal field that has been generating 80 MW electricity.

2. GELOGIC SETTING

2.1 Tectonic Setting

Sulawesi Island is located at the southeastern end of the Eurasian continental plate. It has a complex geological structure because it is the situated at the convergence of three tectonic plates, the Eurasian continental plate, the Pacific oceanic plate and the Australian continental plate. The Eurasian continental plate moves relatively toward the south-southeast, the Pacific oceanic plate moves relatively towards the west, and the Australian continental plates move relatively towards the north (Hamilton, 1979; Hall & Wilson, 2000).

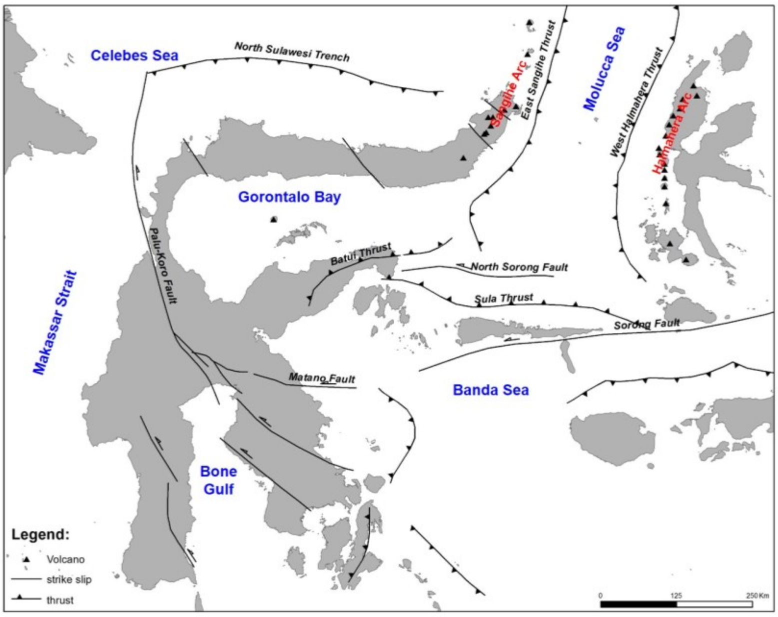

Figure 2. Tectonic elements of Sulawesi and Maluku (re-drawn from Hall & Wilson, 2000). Volcano database from Global Volcanism Program (last update May 2014)

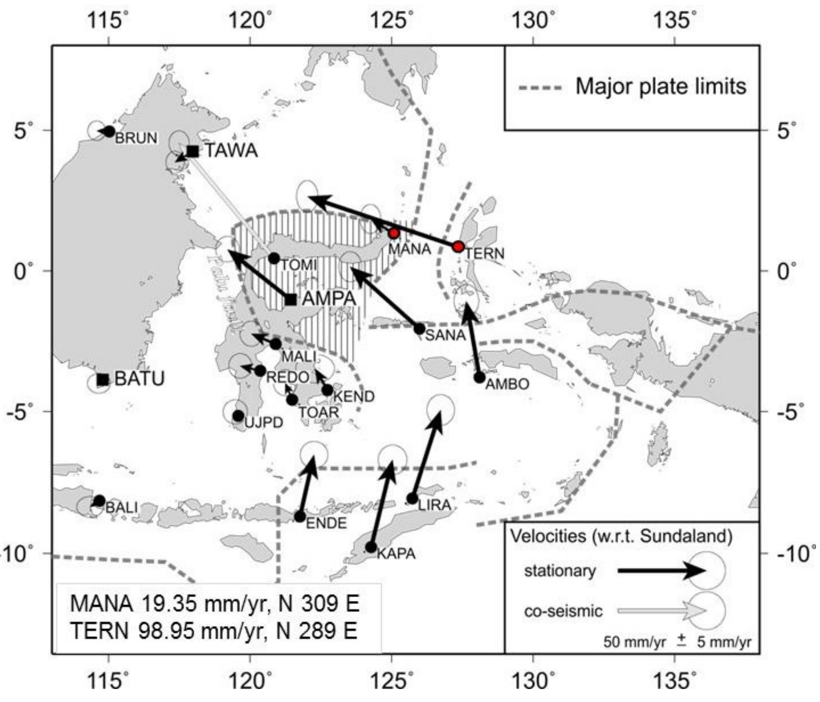

Figure 3. Direction and speed of plate movement velocities in Eastern Indonesia (Walpersdorf, et al., 1998).

Double subduction of the Molluca sea plate to the west and east results in the formation of Minahasa – Sangihe and Halmahera volcanic arc (Figure 2). Those two volcanic arcs are Quartenary in age with some of the volcanoes still active. Both volcanic arcs host active geothermal potential in the North Sulawesi and Maluku province.

Direction and speed of plate movement in Eastern Indonesia have been investigated by Walpersdorf et al. (1998) based on GPS measurements by GEODYSEA project in 1994 to 1996. They observed that both Minahasa – Sangihe and Halmahera arc moves relatively northwest with the azimuth N 289 ° E - N 309 ° E at different speed rates based on data in Manado (MANA) and Ternate (TERN) (figure 3). Minahasa – Sangihe arc moves 19.35 mm/year (N 309° E) and Halmahera arc 98.95 mm/year (N 289° E).

2.2 Regional Geology of Minahasa

The Minahasa area consist of Tertiary volcanic rocks overlay by Quarternary and Recent volcanic rocks (Effendi and Bawono, 1997). The Tertiary volcanic rocks are composed of andesitic to basaltic breccia, lava and tuff from Old Tondano Volcano. The major eruption of Old Tondano Volcano occurred during Plio-Pleistocene resulting 30 km diameter caldera and spread wide massive pyroclastic deposit (Verbeek, 1908; 1925; *vide* Ganda and Sunaryo, 1982). The wall of Tondano Caldera was exposed on the east side of Tondano Lake. The Quarternary volcanic activity occurred at the Lahendong complex on the central, Sempu-Soputan complex on the south and Lokon-Empung complex on the north Tondano Caldera. Mt. Soputan, Mt. Lokon-Empung, Mt. Mahawu, Mt. Klabat and Mt. Dua Saudara are still active. The NE trending Minahasa – Sangihe volcanic arc extends to Sangihe islands and South Philippine.

Geologic structures in the Minahasa area are mainly controlled by two major strike-slip fault that cut the North Arm of Sulawesi in two places, between Amurang - Malompar in the south and Manado - Kema in the north (Figure 4). Based on the shape of the western coastline of Minahasa, it can be interpreted that the faults moved laterally in opposite directions, The Manado - Kema Fault as sinistral strike-slip fault and The Amurang - Malompar Fault as dextral strike-slip fault.

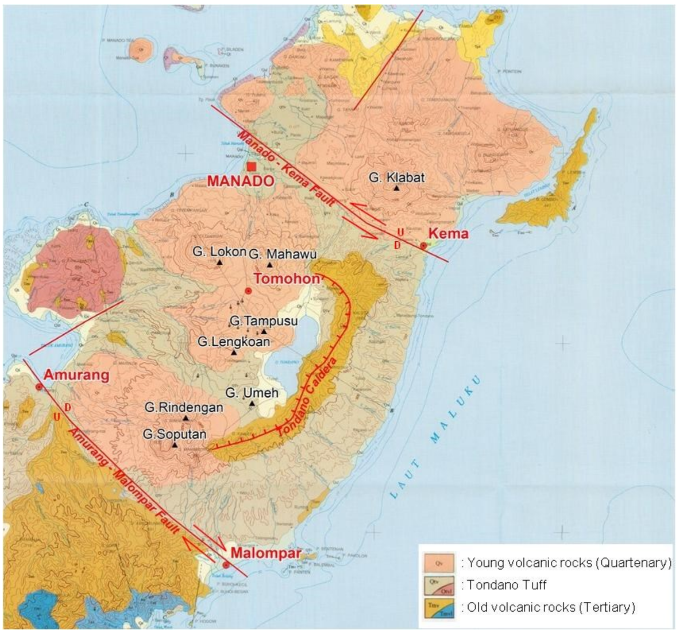

Figure 4. Regional geological map of Minahasa (Effendi and Bawono, 1997).

3. STRUCTURAL GEOLOGY ANALYSIS

The early geologic mapping of Tompaso geothermal field has been done by Bachri (1977), Ganda and Sunaryo (1982). The Landsat and aerial photo interpretation has been done by Siahaan (2000). More recent geological structure studies by Sardiyanto and Nurseto (2013) updated the structural map of the area. It has a clearer picture of the relationship between fault and spatial distribution of surface manifestations. It is also confirmed the result of drilling and subsurface fractures from borehole image logs.

3.1 Satellite Image Interpretation

Figure 5 shows the structural map of the Tompaso geothermal field with topography background. The ENE-SWS trending Soputan Fault is a major strike-slip fault in this area. Its fault scarp can be observed at the west slopes of Mt. Riendengan, on the north side of Riendengan caldera. Its northeast extension is arranged by the alignment of hills in the Tempang-Toraget thermal area. The fault controls the preferential geothermal fluid movement from the upflow zone in Riendengan-Sempu area to Tempang-Toraget area. At the center of the field, Tompaso Fault and other minor faults are relatively dominant fault orientation. It is appear that this fault provide permeability to geothermal reservoir. Another NW-SE trending Sonder Fault in the east side of the field relatively minor trend.

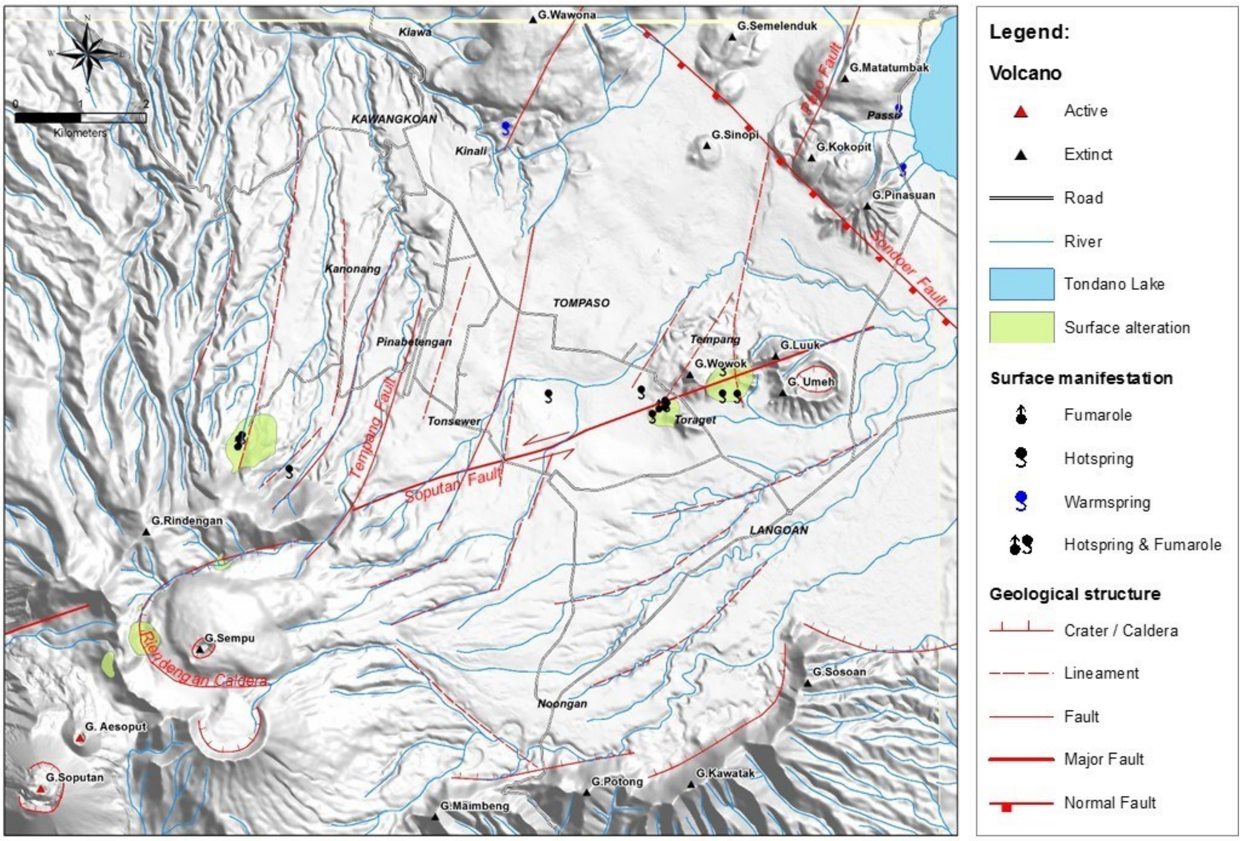

Figure 5. Geologic structure map of Tompaso geothermal field (Sardiyanto & Nurseto, 2013).

The wall of Tondano caldera is well-preserved in the south part of the field. It forms a mountainous range that extend to the east side of Tondano Lake. The west caldera wall is buried under Quartenary and Recent volcanic products from Riendengan-Sempu-Soputan volcanic complex.

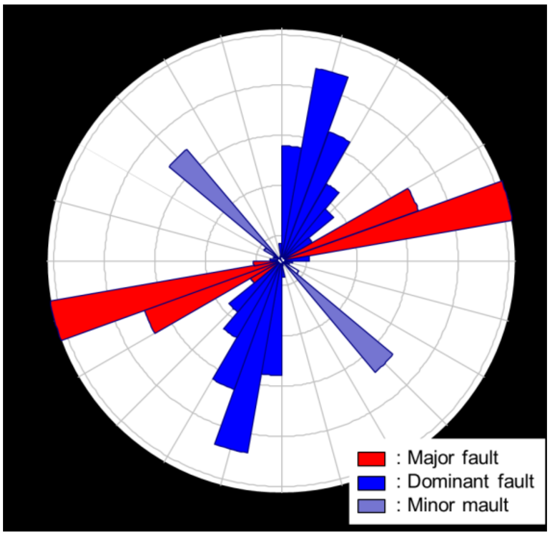

Figure 6. Rossete diagram of fault strike relative to fault length (Sardiyanto, 2013).

The statistical fault orientation is summarized in Figure 6. Faults striking NE-SW (N 0-45° E) comprise the dominant trend. The ENE-WSW (N 60-75° E) striking fault are the largest fault in this field. The length of this fault is more than 17 km. The NW-SE (N 135° E) striking fault are minor. It might be the older faults that covered by younger volcanic product.

3.2 Wellbore Fracture Image Log

Subsurface fractures were identified using borehole image logs from wells LHD-26 and LHD-27. Natural fractures that identified in logs were classified as continuous conductive (CCF), non-continuous conductive (nCCF) and resistive fractures (RF) based on whether the sinusoid features was visible on all pads and resistivity signature. CCF is low resistivity sinusoid features and clearly visible in all pads. CCF is interpreted either as open fractures or sealed fractures by conductive minerals. The nCCF is low resistivity sinusoid features and not visible in all pads. RF are high resistivity sinusoid features. RF could be interpreted either as tight fractures or sealed fractures by resistive minerals. Fractures with evidence of offsets were interpreted as faults.

Borehole image logs well LHD-26 for the depth interval 900–2,300 meter measured depth (MD) (1,400 meter) were analyzed. Figure 7 shows stereonet and rossete diagrams of fracture orientation for all observed natural fractures. The CCF has dominant NW-SE and E-W trend. The orientation of nCCF slightly N-S and NW-SE. RF has random fracture strikes. For LHD-27, the depth interval 900-1,700 meter MD (800 meter) were analyzed. Figure 8 show example fracture logs and stereonet and rossete diagrams of fracture orientation for all observed natural fractures. Both CCF and nCCF have dominant NE-SW trend. RF have random strikes.

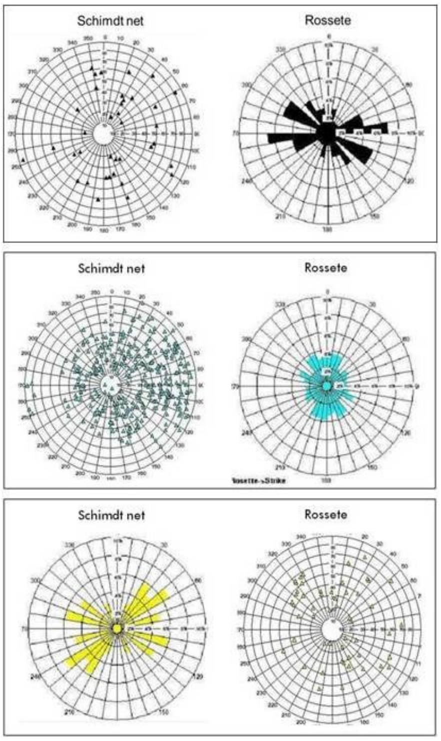

Figure 7. LHD-26 fracture orientation (CCF: black; nCCF: light blue; RF: yellow).

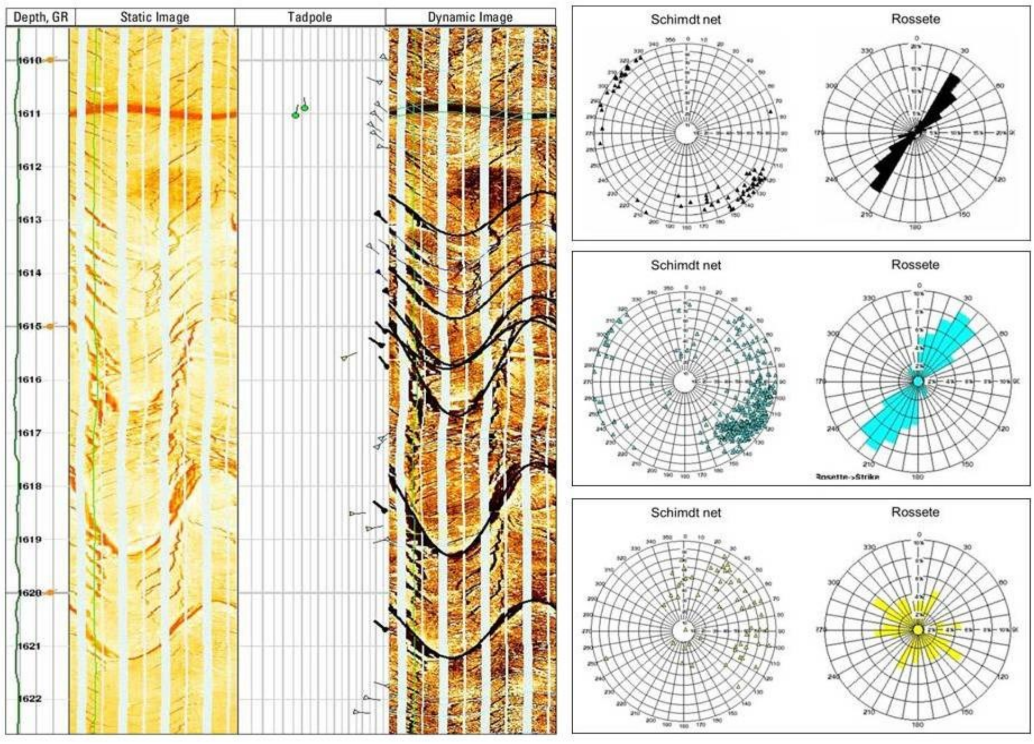

Figure 8. LHD-27 fracture image logs and orientation (CCF: black; nCCF: light blue; RF: yellow).

Fractures formed during the drilling process were classified as drilling-induced (tensile) fractures (DIFs) and borehole breakouts. DIFs are created when the stresses concentrated around a borehole exceed tensile strength of the rocks (Aadnoy, 1990). Stress-induced wellbore breakouts occur when the compressive stress concentration around the borehole wall exceeds the rock strength (Zoback, 1985). Illustration of DIFs and borehole breakouts orientation are explained in Figure 9. DIFs and borehole breakouts are present in pair 180° apart and 90° each other. In vertical well, the orientation of DIFs will be parallel to maximum horizontal stress (Sh_{max}) and borehole breakouts well be parallel to minimum horizontal stress (Sh_{min}).

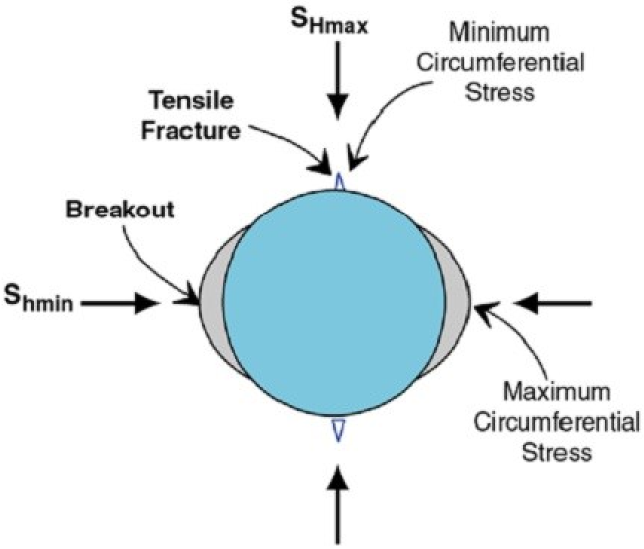

Figure 9. Illustration of DIFs and borehole breakouts toward Sh_{max} and Sh_{min} direction.

No borehole breakouts were observed in the image logs from LHD-26 and few in LHD-27. Whereas DIFs are common in both wells. In well LHD-26, DIFs were observed with orientation NE-SW (Figure 10). The DIFs in LHD-27 are also NE-SW (Figure 11) and borehole breakouts NW-SE. DIFs data from both wells confirmed that relative Sh_{max} orientation is NE-SW, approximately N 45° E to N 50° E. Whereas, the relative Sh_{min} orientation is NW-SE, approximately N 140° E. It is confirmed with the orientation of open fractures trend in LHD-27. The orientation of open fractures should be parallel with Sh_{max} and perpendicular to Sh_{min}.

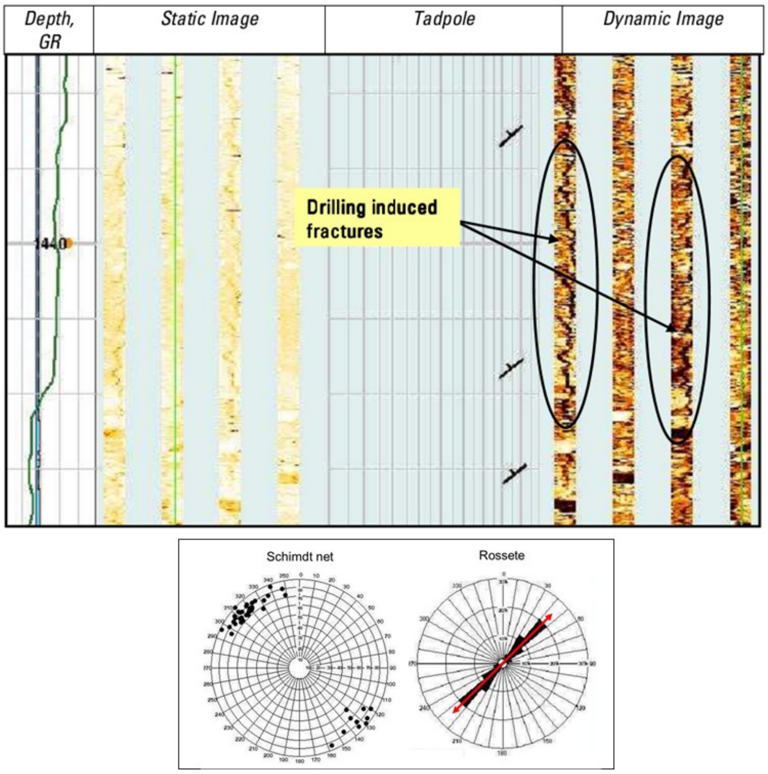

Figure 10. Drilling induced tensile fractures LHD-26.

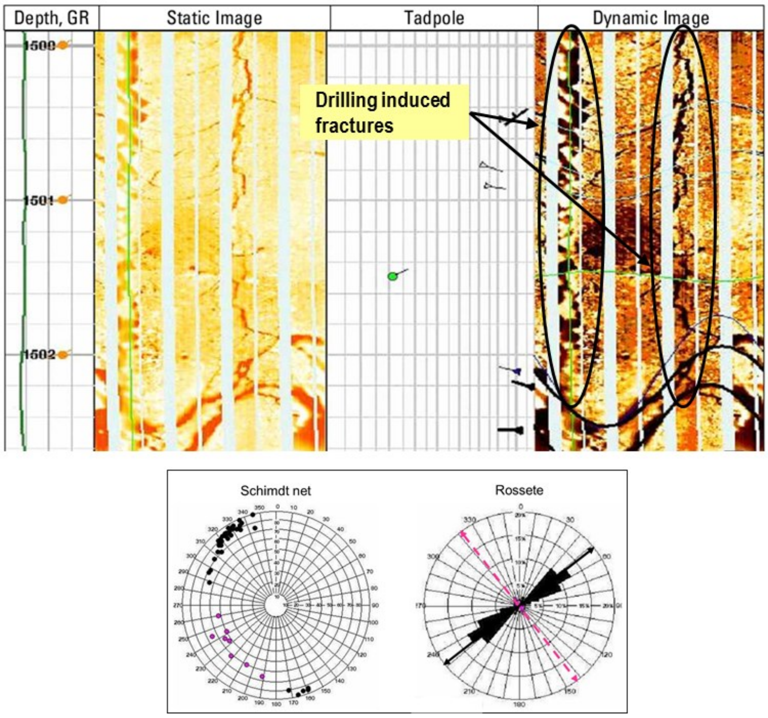

Figure 11. Drilling induced tensile fractures and borehole breakouts LHD-27.

3.3 Structural Geology Model

The geological structure model based on geologic mapping, satellite images interpretation and borehole images data from Tompaso field are correlated with the regional geological conditions in North Sulawesi, especially with the Minahasa-Sangihe Arc. The direction of local horizontal stress (Sh_{max}) in Tompaso field is trending NE-SW, while the direction of convergences in Molluca Sea is NW-SE. Both of Sh_{max} and regional stress are almost perpendicular (Figure 12). Sh_{max}, usually, parallels with the direction of convergences. Thus, there must be a process that causes this difference. Before discussing the possible factors that cause the changes in the direction of Sh_{max}, first we will discuss the differences of two major strike-slip faults movement in Minahasa, the Manado - Kema and the Amurang - Malompar Fault.

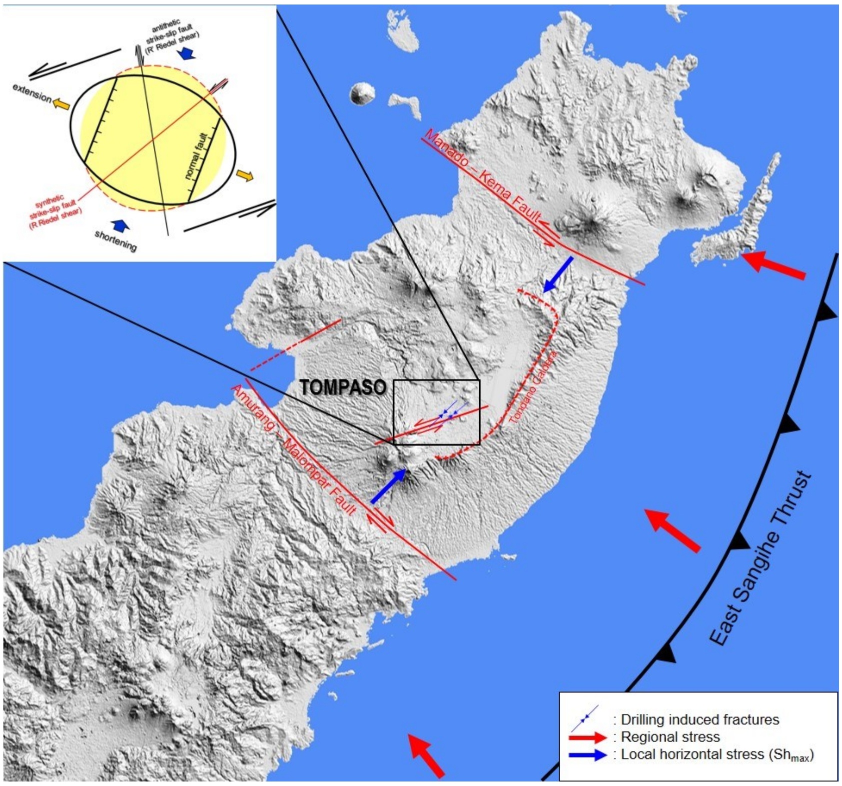

Figure 12. Geological structure model of Tompaso geothermal field.

Theoretically, one stress direction should only produce one type of parallel shear fault i.e. sinistral or dextral. However, in Minahasa, we have a couple of parallel shear faults with opposite movement (sinistral and dextral). This probably due to the difference in the stress direction that affects each of the faults. Research data from Walpersdorf et al. (1998), shows little difference in the stress direction between southern and northern Minahasa (Figure 12). The stress direction along Minahasa-Sangihe arc is following the shape of East Sangihe Thrust (Figure 2). It is slightly rotated clockwise to the south of Minahasa. Not only the stress direction differences, but also clockwise rotation experienced by the northern arm of Sulawesi and Palu - Koro fault affect the kinematics of fault in Minahasa (Walpersdorf et al., 1998).

Back to the difference between regional and local stress direction in Tompaso field. The two major strike slip faults that bound the Minahasa region are most likely causes the different direction of the local stress in Tompaso geothermal field with respect to the regional stress. Those fault planes produce tangential stress in response to the regional stress with direction perpendicular to the fault plane. This happens because between fault planes and regional stress vector form an acute angle.

When the horizontal local stress is NE-SW, the permeable structure is expected to be trending NE-SW. Soputan fault that is a major sinistral strike slip fault as mentioned above would be generated open fracture sets with NE-SW orientation (figure 12).

4. CONCLUSION

Fracture patterns determined from satellite image interpretation, geologic mapping, and borehole image logs indicate that the dominant permeable fractures trend NE-SW. These permeable fractures are associated with the Soputan Fault. The maximum local horizontal stress (Sh_{max}) in Tompaso geothermal field is different with the regional stress direction because of the vector stress difference in the north and south of Minahasa.

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