Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Structural Control of the Sorik Marapi Geothermal Field – Surface and Subsurface Evidences

Maria Jhonnie Z. Villareal, Armando C. Licup, Xyza L. Omac-Canarias, Zosimo F. Sarmiento

Blk 82 Lot 21, 25th Street, Villamor Airbase, Pasay City 1309, Philippines

E-mail address, mjzvillareal@gmail.com

Keywords: Sorik Marapi, Sumatran Fault Zone, structural geology, subsurface geology, drilling, well permeability, LiDAR,

ABSTRACT

Geothermal sites in Sumatra are typically associated with the Sumatran Fault System (SFS) and young volcanic centers of the Barisan Mountain range – a volcanic arc related to the Sunda trench. The SFS is a highly segmented, 1,900 km long, right lateral strike-slip fault which traverses the entire length of Sumatra. The Barisan Mountain is comprised of at least 35 volcanoes, one of which is the active strato-volcano – Sorik Marapi (2,145m). A complex fault system exists within the Sorik Marapi geothermal field. The main structural feature is the 35km wide Panyabungan pull-apart basin which extends in the NNW–SSE direction along the prominent strikeline of the SFS. The fault trace of SFS in Sorik Marapi is delineated as a highly segmented fracture network with conjugate sets of strike-slip faults (synthetic and antithetic fault sets) which developed oblique to the main SFS. The fracture network is characterized by parallel right-stepping strike-slip faults, oblique normal faults, and anastomosing secondary faults.

Prior to the aggressive drilling campaign in Sorik Marapi geothermal field between 2016 to 2018, structural mapping was undertaken in order to identify fault permeability targets. The use of Lidar images coupled with ground-truthing proved to be an indispensable method in identifying structural targets for the drilling campaign. To date, a total of eighteen (18) deep wells have been drilled in five (5) pads across the field which confirms the existence of a commercial, high-temperature resource. These wells have provided an important insight of the subsurface geology, hydrothermal alteration at depth, and permeability potential of the SFS in Sorik Marapi geothermal field.

1 INTRODUCTION

The characterization of geo-structural controls during development of a geothermal field is an indispensable step in geothermal exploration to complement future drilling strategies. The information which can be gathered from structural mapping provides the foundation for identifying drilling site locations and permeability targets. Proper siting of geothermal wells during development of a geothermal field rely on careful selection of fault targets.

The Sorik Marapi Geothermal field has undergone an aggressive and accelerated campaign to develop an estimated power potential of more than 240MW. Drilling commenced in 2016, and since then, eighteen (18) deep wells have been successfully drilled and completed in the field which confirm the existence of a commercial, high temperature resource. Prior to this success, an extensive study of the surface was undertaken in Sorik Marapi which includes geo-structural mapping using LiDAR and groundtruthing in the field. Findings from this study was supplemental to the drilling campaign to aid in tapping permeable fracture network at depth. The occurrence and behavior of the Sumatran Fault System (SFS) in Sorik Marapi geothermal field, as observed at the surface and encountered in wells are narrated in this paper.

2 STRUCTURAL FRAMEWORK

2.1 Regional tectonic setting

The SFS is a 1,900 km long right-lateral strike-slip fault which traverses the entire length of the Sumatra Island. This zone of active deformation is attributed to the subduction of the northeast moving Indo-Australian plate beneath the Eurasian plate. This results in oblique convergence at the plate boundary known as the Sunda Trench. The SFS accommodates a significant amount of the trench-parallel shear component of the oblique motion.

The SFS is a highly segmented geomorphological feature, consisting of second order geometrical irregularities which splits the fault extent to at least nineteen (19) segments (Sieh and Natawidjaja, 2000). An important feature of the SFS is an irregularity called "equatorial bifurcation", where the fault splays to two sub-parallel structures – Angkola and Baruman segments, with a widest separation of 35km. This separation is known as the Panyabungan pull-apart basin, one of the thirteen (13) pull-apart basins mapped along the the extent of the SFS (Muroaka et al., 2010). At this segment the fault is relatively complex, exhibiting a geometry typical of a strike-slip duplex characterized by steep imbricate faults, dextral faulting across step-overs, pressure ridges along contractional left steps and sag ponds/basins at dilational jogs. The SFS runs the length of the Barisan Mountains in Sumatra, the volcanic arc related to the Sunda trench. The Barisan Mountain is comprised of at least thirty-five (35) volcanoes, one of which is the active strato-volcano – Sorik Marapi (2,145m).

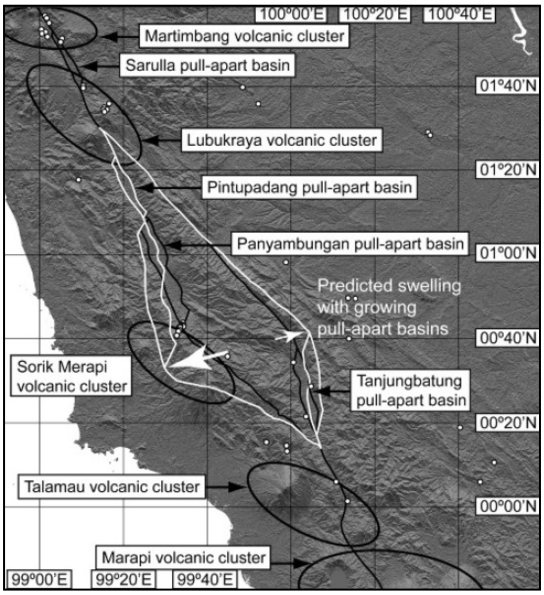

Figure 1: Volcano tectonic setting of Sorik Marapi showing pull-apart basins along the SFS. Muraoka et al., (2010).

2.2 Local geologic setting

The local geology of the study area is characterized by two main units of thick deposits of volcanics and associated volcaniclastics from two main volcanic sources. The predominantly andesitic with minor basaltic lava units and associated pyroclastic flow deposits, common in the southern half of the study area, is attributed to the Sorik Marapi volcano. Meanwhile, the older dacitic volcanic unit which exhibits significant degree of weathering and alteration, occupies the northern half of the study area and is attributed to an unidentified older volcanic center.

2.2.1 <u>Stratigraphic overview</u>

The stratigraphic units in the study may be summarized into four (4) formations, from oldest to youngest are: (1) Basement, (2) Roburan Dacite, (3) Sorik Marapi Volcanics and (4) Quaternary Alluvium.

The Basement consists of Mesozoic to Paleozoic metasediments (including shale and limestone), which are possibly intruded by plutonic rocks (including granodiorite and quartz diorite) (SKM, 2011). An exposure adjacent to the Sampuraga thermal area was previously identified as belonging to the basement formation (SKM, 2011). However, no outcrop of the supposed basement formation was encountered during the detailed structural mapping as well as during drilling of wells.

Overlying the metamorphic basement is the Roburan Dacite. The rock assemblage is predominantly dacitic to rhyolitic exhibiting pumiceous and porous texture. A dacite exposure was noted at a landslide area near Dolok Palayanan. The exposure at this location is overlain by a thick deposit of weakly altered, friable tuff and reddish clayey soil cover. In Purba Baru, outcrop of same dacite unit was exposed by ground construction works, overlain by the reddish clayey soil cover but lacking the tuff unit. The volcanic center from which this dacitic formation could have been erupted has not been identified. This unit is overlain by the Sorik Marapi Volcanics at the southwest portion of the geothermal field.

The Sorik Marapi Volcanics is predominantly andesitic in composition with minor occurrence of basaltic rocks. The young lava flows and pyroclastic/volcaniclastic deposits radiate outwards from the active Sorik Marapi volcano. The lava front of the volcano is terminated along the NW-SE trending Marapi Fault and the pyroclastic/volcaniclastics deposits persist and gradually thins out east of this structure. Figure 8 shows the outcrop belonging to the Sorik Marapi Volcanics.

The youngest formation are the Quaternary Alluvium which includes alluvial and slope wash deposits infilling valleys, grabens and low-lying areas composed of loose and fragmented sediments derived from older rock units.

2.2.2 <u>Surface Lithology Distribution</u>

Consistent to the stratigraphy, the surface lithology in the study area is comprised of predominantly andesitic to dacitic lava flows and associated pyroclastics and lahar deposits (Figure 2). Andesites and occasional basaltic rocks were noted along the flanks of Sorik Marapi volcano. Meanwhile, the more extensive dacitic rock units are distributed east of Sorik Marapi and towards Sirambas and Sampuraga areas. There are very limited outcrops in the field as thick soil generally blankets all other lithological units.

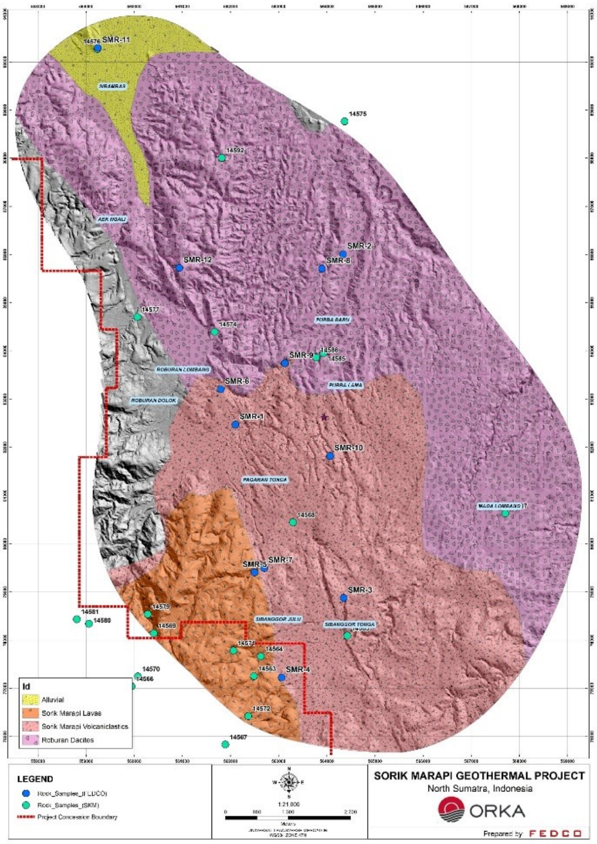

Figure 2. Distribution of lithological units showing rock sample locations (Modified from SKM, 2011)

3 SUMATRAN FAULT SYSTEM AT SURFACE

The study of LiDAR followed by ground-truthing of the identified features from the digital elevation model was the initial step in this undertaking. The use of LiDAR proved to be an effective tool in searching for points of interest that can be further investigated on foot. The fault trace of the SFS in Sorik Marapi is delineated as a highly segmented fracture network with conjugate sets of strike slip faults (synthetic and antithetic fault sets) which developed oblique to the main SFS. The fracture network is characterized by parallel right-stepping strikeslip faults, oblique normal faults and anastomosing secondary faults that sometimes are even more evident on LiDAR than in the field where thick soil cover and vegetation obscure these features.

3.1 Sumatran fault system in Sorik Marapi geothermal field

A complex fault system exists within the Sorik Marapi geothermal field. The main structural feature is the 35 km wide Panyabungan pull-apart basin which extends in the NNW–SSE direction along the prominent strikeline of the SFS. A systematic fault nomenclature was devised for the Sumatran fault system in Sorik Marapi (for simplification), mainly based on general location with reference to important features such as river, peaks and thermal areas. It also reflects the segmentation of the fault along stepovers, and thus warrant a unique name for each fault segment. Hence, the main segments of the Sumatran fault in Sorik Marapi are (1) North Sumatran Marapi Fault (NSMF), (2) Central Sumatran Marapi Fault (CSMF) and (3) South Sumatran Marapi Fault (SSMF).

The southern segment – SSMF, extends from Purba Julu to northeast of Huta Baringin Jae. It is comprised of three related fault strands – South Sumatran Marapi West (SSMW), South Sumatran Marapi Central (SSMC) and South Sumatran Marapi East (SSME). These three forms a positive flower-like structure budding from the intersection of the SSMC fault strand with E-W Maga fault. At this intersection, the SSME fault arcuate to more than 1960m strike length. Meanwhile, the 1138m long SSMW fault, splays at least 1000m offset from said intersection, measured along the strikeline of SSMC.

SSMC measures approximately 3853m steeply dipping to the SW. At depth, SSMC and SSME possibly converges to SSMW, considered the main stem of the flower structure, to form a single subvertical fault. Towards the SE fault trace of SSMC, the dip of the fault flips to an apparent NE dip indicating rotational movement along its strike. An EW trending fault cut across SSMC to terminate its fault trace where a sag pond also exist. SSMC appears to be a right overstep of the SFS segment which continue further south.

The middle segment - CSMF, measures approximately 3960m extending from Purba Julu to Roburan Lombang. Central Sumatran Marapi West (CSMW) parallels CSMF, enclosing toward-dipping NW-SE trending short faults, possibly a contractional bend feature. Anastomosing fault trends converge towards the Purba Julu thermal area which appears as another overstep of the SSMW to the CSMF. The fault trace of CSMW become less obvious towards Singolot River. Meanwhile, CSMF trace remain prominent towards Roburan Lombang. The right lateral movement of CSMF is evident on the morphological offset and sharp bend of Singolot River.

The northern segment – NSMF, measures approximately 4871m which extends from Aek Godang to Danau Marambe. Several faults branch from NSMF, North Sumatran Marapi East (NSME) and North Sumatran Marapi West (NSMW). The fault trace of NSME (3881m) trends NNE-SSW dipping SW and crosscut by several minor faults. NSMW stems from NSMF in Dolok area, trending NNW-SSE and its 1682m fault trace appears to have a reversed NE dip. More subparallel faults trending NNW-SSE to NW-SE persist west of NSMF.

The surface fault delineation of Sumatran Fault is obscure after Danau Marambe and reappears at Sampuraga thermal area. A fault breccia outcrop coincident to weak gas fissures was noted at this location. Thermal pools in Sampuraga rimmed with travertine deposits have a ph of 7 and temperature reaching more than 90°C. This structure was named the Sumatran Sampuraga Fault.

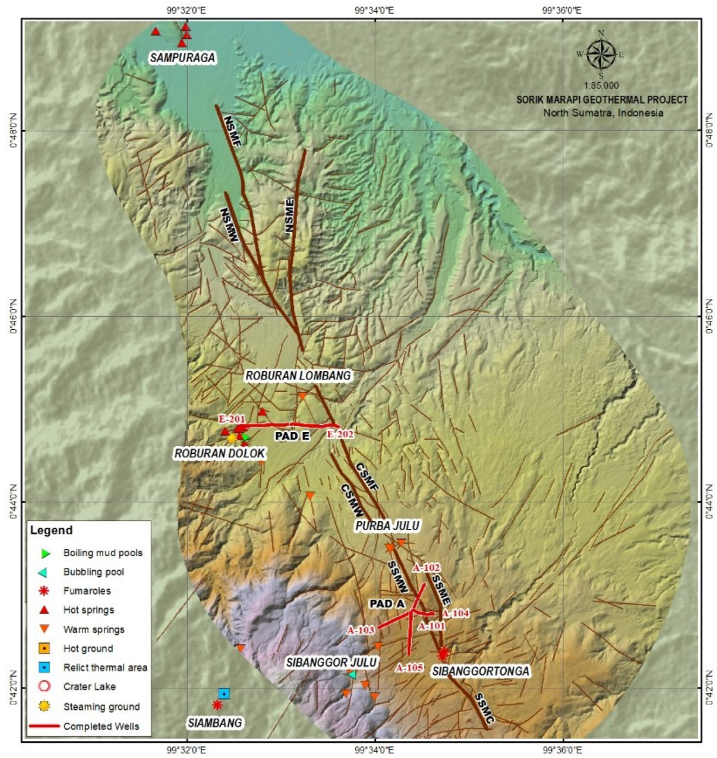

Figure 3: Structural geology map of the Sorik Marapi geothermal field showing Pads A and E (FEDCO, 2016b)

3.2 Thermal areas

3.2.1 Roburan Lombang

Two (2) springs located at an elevation of 506masl, comprise the thermal area of Roburan Lombang. Concealed beneath andesite boulders, the spring discharge neutral fluids with temperature of 48°C. The thermal area lies at the confluence a NE-SW and NNW-SSE trending major faults which are regarded as the main structural control this thermal area.

3.2.2 Roburan Dolok

Thermal features in Roburan Dolok includes steaming grounds, small pits with boiling water, mudpools, fumaroles and bleached white altered grounds. The thermal features in Aek Milas Balera, Aek Milas Sabatambal, Ayum Perak, Ongganan, Gajubak and Aek Sepurik are tightly spaced, located within a small area approximately 60m^2. Water temperature readings range from 78°C to 92°C but pH is consistent at 2. Mineral precipitates are also abundant particularly crystalline sulfur precipitates rimming fumaroles and vents, small mounds of amorphous silica and white sulfates that blanket the ground. The dominant rock type in this area are also andesite boulders that are generally bleached and, in some places, silicified. A NW-SE minor fault cuts across the section adjacent the soft ground. Fumaroles and more hot springs emerge along the point of intersection with a longer NE-SW fault that possibly connects Ayum Perak and Ongganan. Shearing on nearby andesite rock boulders trend N28°E.

3.2.3 Purba Julu

In Purba Julu, rivers – Aek Milas Bawo, Aek Urbaton, Danao Situwak and a bluish pool of water are the main thermal features. Aek Milas Bawo is the headwaters of the thermal springs, feeding small pools – Danao Situwak and a bluish pool, and towards Aek Urbaton where other spring sources possibly converge. At the headwaters of Aek Bawo, large volume of water flows out from the foot slope of a cliff made up of moderately to highly weathered tuffaceous volcanics. Abundant yellowish to white sulfates are accumulated along the river channel. Meanwhile, Aek Urbaton exhibit extensive, hard buff to rusty orange thermal spring deposits covered with green algae. Aek Bawo has a pH of 2.5 to 3 with slightly elevated temperature measured at 47°C, compared to Aek Urbaton's temperature of 44.6°C. The small thermal pools which can only be observed from a distance for safety reasons, have bluish acid-like water and a pungent sulfuric smell. The two blue lakes are associated with minor NE trending extensional faults located adjacent the South Sumatran Marapi-West Fault. These lakes are presumably smaller pull-apart basins resulting from the strike-slip motion along the SF.

3.2.4 Sibanggor Tonga

In Sibanggor Tonga, hot springs and fumaroles occur adjacent to the main road and is correlated to the conjunction of E-W and NE-SW trending minor faults with the South Sumatran Marapi-Central Fault. Warm pools were developed by the local community for bathing and cooking, in particular a "fumarole house" which exhibits hot springs, several gas vents and fumaroles with temperature reaching up to 97°C. Altered grounds are traced from the fumarole house to the other side of the road, down to the Maga river tributary where larger and more intense thermal activity exist. Boiling pools of liquid, fumaroles, mud pools and extensive altered rocks characterized both banks of this section of the Maga river tributary, bounded by an E-W wall of argillized volcanic breccia and pyroclastics.

3.2.5 Sibanggor Julu

This thermal area is located along the stream valley of Aek Sibanggor which trends WSW-ENE located on the NW flanks of Mt Sorik draining towards the town of Sibanggor Julu. It follows the strikeline of a fault delineated on Lidar and regarded as the main controlling structure of Sibanggor Julu thermal area. Sibanggor Julu thermal area is comprised of altered grounds and clusters of springs that drains towards the main river – Aek Sibanggor. Along the stream channel, the thermal activity noticeably increases towards the headwaters. Most springs deposit fine yellowish sulfur precipitates flowing from the riverbanks into the river with distinct bluish water. The maximum temperature measured in this area is 39°C while water pH is 2-3.

3.2.6 Bulutolang

Bulutolang is located on the eastern flank of Mt Sorik where thermal activities are just 20m apart. Both have small tributaries of several warm springs with temperature ranging 39-41°C and pH of 4. Thick deposits of white to yellowish sulfates are also persistent in both. Porphyritic andesite boulders are common in the vicinity, and most volcanic bombs exhibit bread-crust texture. A fault breccia outcrop with a NE-SW surface orientation was noted in Bulutolang.

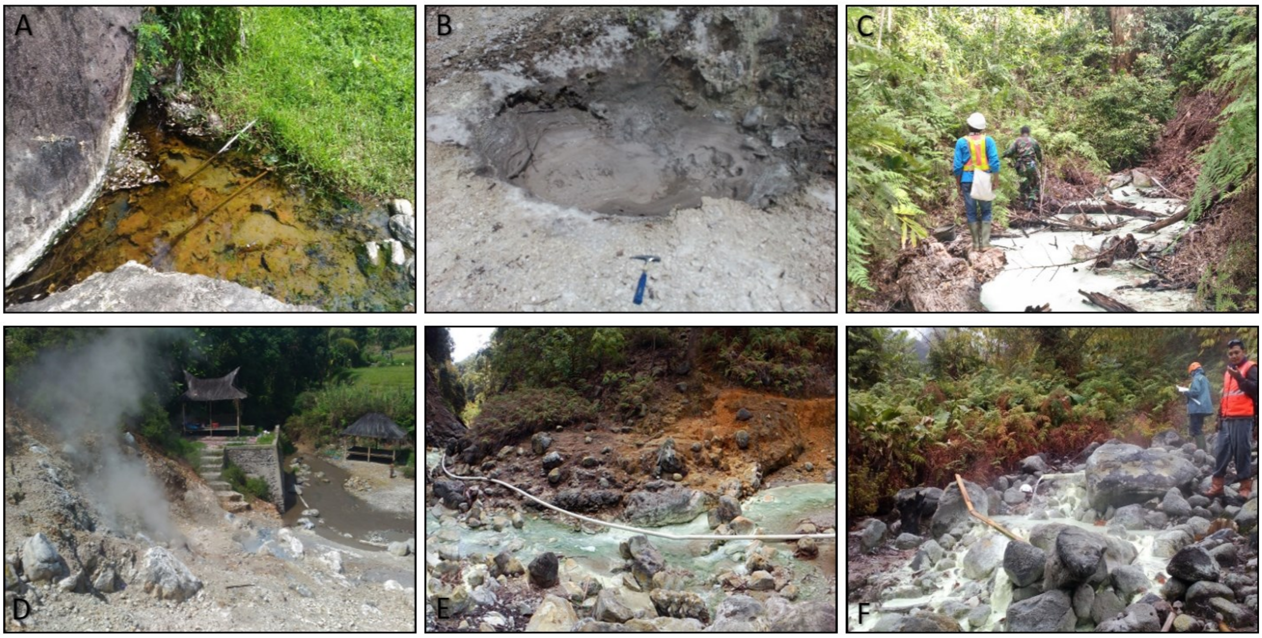

Figure 4: Surface thermal features in Sorik Marapi geothermal field: A. Warm, neutral springs in Roburan Lombang; B. Mudpool – Ayum Perak in Roburan Dolok; C. Thermal river -Aek Bawo in Purba Julu; D. Fumarole house in Sibanggor Tonga, E. Thermal river – Aek Sibanggor in Sibanggor Julu; F. Abundant sulfate deposit in Bulutolang

4 SUMATRAN FAULT SYSTEM AT THE SUBSURFACE

4.1 Pad A wells

The SFS segments in this area forms a positive flower-structure which stems from its intersection with EW-Maga fault. The thermal activity in this area is vigorous, particularly along Aek Maga and a tributary where the Fumarole house landmark is located. After the intersection, the morphology of SFS indicate a contractional bend along with coeval minor oblique thrust faults and related shears. In contrast, north of Pad A, the SFS slightly curves to an anastomosing fault network towards the Purbu Julu thermal area. This area is the NNE-SSW to NE-SW extensional section where SSFC right steps to the CSMF. This extensional bend is characterized by clusters of low ph, high flowrate - thermal rivers and ponds.

Exploratory wells – A102 and A104 were drilled to target the southern segment of the SFS in Sorik Marapi as well as associated minor faults.

4.1.1 Well SM-A102

Well A102 which has a throw azimuth of 24.65° was directed to intersect South Sumatran Marapi West and South Sumatran Central Fault. The onset of the west and central segment of the South Sumatran Marapi Fault as encountered in this well was averaged at

1100mMD/1069mVD. Persistent PLC's and short-lived TLC at 1100mMD where encountered. The presence of mylonites, weak shearing and veining were observed in the cuttings with the noted presence of quartz, calcite and pyrite veins. Shearing is most pronounced between 1285 to 1288mMD and cuttings remained sheared till 1711mMD. Injectivity tests indicates a minor permeable zone between 1245-1340mMD which places the true dip of SSMW and SSMC to be between 88° to 89°.

4.1.2 Well SM-A104

Meanwhile, Well A104 directed towards 119° azimuth was designed to intersect four structures, two of which are the main strands of the southern segment of SFS (South Sumatran Marapi Central and South Sumatran Marapi Splay), and two other secondary faults – Milas and Bondar Godang Fault. It would turn out that the intersection with the main fault strands of the SFS (1260-1500mMD) would occur as TLCs at depth, where high torque and fast ROP was experienced. These zones were also identified as a minor permeable zone during completion test. More interesting though, is the intersection of Milas Fault at shallower depth (955-1260mMD), which was later recognized the major permeable zone. During intersection of the secondary fault, PLC to TLCs were encountered as well as tight spots with erratic torque. Bladed calcite and drussy quartz were notably common at this fault intersection interval.

4.2 Pad E Wells

Well Pad E is located NW of Singolot River in Tanobatolamo. It lies to the west of the CSMF segment of the SFS where its fault trace is terminated by a NNE-SSW trending normal fault. Like Pad A, it is located within a narrow graben structure between the SFS and the Sorik Marapi volcanic range. The systematic near E-W structures are evident near the pad, which represents the minor antithetic fault groups in the field. Major faults extend from the volcanic slope in the west to the SFS segment in the east. Others occur in steps and or terminated by NNE-SSW and NNW-SSE structures. The segmented antithetic faults such as the structure coincident to the Singolot River were also found consistent in this area. The structural control of thermal areas in Roburan Dolok were found to be the short segments of NE-SW which can be traced at the toe of the volcanic range in the east. Wells drilled in pad E were targeted to explore the attendant permeabilities of these inferred structures.

4.2.1 Well SM-E201

This well was drilled to an azimuth of 268° to veer away from the main SFS fault and explore the attendant permeabilities that control Roburan Dolok thermal areas. A brecciated zone was encountered early in the well, intersected from 330-459mMD without loss of circulation. Mylonites and an increased amount of smectite clays and veins of pyrite filling in fractures was observed between 345-369mMD. "A buried fault" was regarded to have been intersected at this depth.

Well SM-201 intersected another target - Milas Dalan fault from 1188-1489mMD without loss of circulation. This is evidenced by the presence of gouge materials, increased alteration intensity, increased vein materials indicative of fracture zone and also experienced high torque associated with drilling breaks at 1489mMD. Permeability of the well could either be related to the intercept of Gajubak North Fault and Balera Fault or the intrusion of basalt dike at 1869-1929mMD or most likely combination of both.

4.2.2 Well SM-E202

SM-E202 was coursed to an azimuth of 95° to intersect and prove permeability associated with the northwest-southeast and northeast-southwest trending faults - Roburan Cross 1 fault, Roburan Cross 2 fault, Roburan Lombang fault, Lombang fault, Singolot West fault, Central Sumatran Marapi fault and Tanobato fault. All fault targets were intersected with indications showing Fast ROP with light WOB, drilling breaks, and in places swinging of the wells possibly structurally controlled, but disappointingly, no circulation losses. Alteration mineralogy from cuttings generally indicate calcite veins and microfractures filled in with abundant quartz. Fracture network associated to these faults appears to have been closely sealed by secondary minerals thus low permeability is to be expected.

5 CONCLUSION

Thermal areas are surface manifestations of permeability often associated with geologic structures. In the Sorik Marapi geothermal field, a consistent structural control has been observed for all thermal areas. General occurrence of thermal manifestations is observed along extensional faults antithetic to the main traces of the SFS. The major river systems within the geothermal field are generally coincident to NE-SW to ENE-WSW trending structures. Among the structures verified in the field, perhaps these set of structures are the most significant to the surface thermal manifestations. The locations of thermal areas exist along major NE-SW or along minor NE-SW faults transecting the main Sumatran Fault. The Sibanggor River for example, is controlled by the ENE-WSW oriented Sibanggor Besar fault. Thermal springs and altered grounds spread along the river's extent. Further North lies the Roburan Dolok thermal area where a set of NE-SW sub-parallel and cross cutting minor faults serve as conduits for the occurrence of thermal manifestations.

The extent of the SFS is of complex tectonic setting thus it is imperative to understand the regional setting but more importantly the local fault system. The proximity of the Sorik Marapi to the Panyabungan pull-apart basin may be an inference of the inherent dominance of extensional fault sets in the area. The main SFS remain to be the most obvious structural target in the area, however, the major synthetic shears are preferable over the minor synthetic shears, aside from the fault trace itself. Meanwhile, the dilative NNE-SSW to NE-SW antithetic features which are proven permeable structures on ground may be targeted at its intersection with the SFS and other faults sets.

The results of drilling in Sorik Marapi has confirmed the existence of a commercial, high-pressure geothermal reservoir in Resource Area 1. Drilling confirmed the subsurface permeability associated with ENE-WSW to E-W striking faults. This is contrary to other geothermal projects in Sumatra like Sarulla, where the SFS is the main source of permeability. In Sorik Marapi geothermal field, the second order ENE oriented antithetic faults serve as the main conduit of geothermal fluid flow.

6 ACKNOWLEDGMENT

The authors are grateful to KS Orka and PT SMGP for allowing us to present and publish this paper.

7 REFERENCES

Blanco, D.F., Philippon, M., and Hagke, C.V.: Structure and Kinematics of the Sumatran Fault System in North Sumatra (Indonesia). Tectonophysics (2015), pp 1-12.

FEDCO (2016a). Due Diligence Study Report on Sorik Marapi Geothermal Field. Report Prepared for KS Orka Renewables PT. Ltd. March 2016.

FEDCO (2016b). Structural Geological Study of Sorik Marapi Geothermal Field. Report Prepared for KS Orka Renewable PT. Ltd. Manila, Philippines. November 2016.

FEDCO (2017). Sorik Marapi Geothermal Power Plant ("PLTP Sorik Marapi") 240 MW, Notice of Resources Confirmation, Unpublished Technical Report.

Hochstein, M.P., and Sudarman, S.: Geothermal resources of Sumatra. Geothermics (1993), Vol. 22, pp 181–200.

Licup, A.C., Baltasar, A.S.J., Juandi, D., Maneja, F.C., Jhonny, Esberto, M.B., Villareal, M.J.Z., Sari, P.P., Musa, R., Mulyani, S., Chandra, V.R., Omac, X.L. and Sarmiento, Z.F. (2017). Geothermal 3D Subsurface Modeling – A Case Study from Sorik Marapi Field, Indonesia. Proceedings: The 5th Indonesian International Geothermal Convention and Exhibition (IIGCE) 2017.

Muraoka, H., Takashi, M., Sundhoro, H., Dwipa, S., Soeda, Y., Momita, M., and Shimada, K.: Geothermal systems constrained by the Sumatra Fault and its pull-apart basins in Sumatra, Western Indonesia. In: Proceedings World Geothermal Congress – Bali, Indonesia, (2010), pp. 1–9.

Sieh, K., and Natawidjaja D.: Neotectonics of Sumatra fault, Indonesia. Journal of Geophysical Research (2000), Vol. 105, pp. 1-30.

SKM, 2011. Preliminary Resource Assessment Report. Sorik Marapi Geothermal Project, Indonesia. Prepared for OTP Geothermal. Final Rev.1. 15 November 2011

Weller, O., Lange D., Tilmann F., Natawidjaja D., Rietbrock A., Collings R., and Gregory L.: The Structure of the Sumatran Fault revealed by local seismicity. Geophysical Research Letters (2011), Vol. 39., pp. 1-7