Geology Assessment of Permeability Distribution in Silangkitang Geothermal Field, North Sumatra, Indonesia

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Abstract. The Silangkitang (SIL) geothermal system is a fault-controlled and liquid-dominated reservoir associated to a deep heat source. Geology data from recent development drilling and reservoir monitoring demonstrated that the high permeability is concentrated within zone between two strands of Great Sumatra Fault (GSF). These faults are major dextral strike slip system that cross the entire length of Sumatra Island. The fault distribution has been defined by integration and interpretation of tectonic geomorphology, surface geology, and well geology. The highest permeability is controlled by faults and fractures associated with localized releasing steps within west of main Tor Sibohi Fault (TSF). This paper outlines the indication of high permeability zone based on recent geology evaluation outcome.

1. Introduction

The Silangkitang (SIL) geothermal field is located in the Tapanuli Utara District, North Sumatra Province, Indonesia. The field is located approximately 35 kilometers southeast of the town of Tarutung. Silangkitang and is one of several prospects in the Sarulla contract area (Figure 1). Sarulla Operation Limited (SOL), a consortium of Medco Energi Internasional Tbk., Itochu Corporation, Kyushu Electric Power Co. Inc., Ormat Technologies, Inc., and INPEX Corporation, has been granted the rights to utilize the Sarulla geothermal resource for power generation under the framework of a Joint Operating Contract (JOC) with Pertamina. SIL started commercial generation of 110 MW on Mar 18, 2017. Currently SOL has 3 units commercially running at Namora-I-Langit (220 MW) and Silangkitang (110 MW) under a single contract. Currently at SIL there are 4 production wells and 9 injection wells to support full power generation.

The SIL field is situated within the Barisan Mountains, which are both structurally uplifted and covered by young volcanic rocks. There are eleven active volcanoes along the mountain chain, but none of those is positioned in the Sarulla vicinity. However, there are abundant volcanic eruptive centers within and adjacent to the contract area that are less than 1 million years old.
The main surface expression of the SIL hydrothermal system is comprised of a series of boiling springs and fumaroles concentrated along a 2.5-km length of the eastern floor and foothills of the valley (Figures 1 and 2). The springs are located further out in the valley whereas the fumaroles are mostly found along the main Great Sumatra Fault Zone (GSFZ) trace in the foothills. The chemistry of the springs and fumaroles is strongly indicative of a high temperature neutral chloride geothermal system. Geophysical surveys executed in the prospect show an area of low resistivity related with the clustered thermal manifestations. This local conductive layer coincides with the shallow clay-rich alteration and elevated temperature of a geothermal system. The reservoir boundary shown in Figure 2 is delineated from the distribution of the shallow conductive layer.
2. Geology Framework

The geology in the Sarulla region of North Sumatra is dominated by two major superimposed tectonic features, a dextral strike-slip fault and an active volcanic arc (Figure 3). The regional basement in the Sarulla district is Paleozoic Meta-sediments which were initially part of Sundaland and have been accreted to the Eurasian boundary during the Triassic [1]. Mesozoic granitic rock intruded older facies including Jurassic and Cretaceous sediments, meta-sediments and mafic volcanic that covered Paleozoic basement.

A chain of thermal manifestations including fumaroles and hot springs is situated along the edge of the Sarulla graben, adjacent the district of Silangkitang. The thermal features are concentrated in a 1 x 2.5 km² band west of the Tor Sibohi fault and about 1 km north of a rhyolite dome with a K-Ar age of 0.12 ± 0.08 Ma [2]. It seems the Tor Sibohi fault is in critically stressed condition thus the fault zone has enhanced permeability [3]. The exploration, production, and re-injection wells drilled at SIL, encountered a geothermal system whose permeability is strongly controlled by the Great Sumatra Fault.

The Great Sumatra Fault (GSF) is likely to have been active as a right-lateral strike-slip fault when seafloor spreading started in the Andaman sea during the Mid-Miocene [1]. Pre-Volcanic sediments were deposited in the sea during Mid-Miocene to Pliocene. The Sarulla graben seems to have been constructed by extension nearly perpendicular to northwest GSF through Plio-Pleistocene [1]. The basin generally has an asymmetric graben to half-graben profile which is indicated by gravity models across...
the extent of basin in SIL (Figure 3). SIL lies above a local sub-graben formed between the Tor Sibohi fault and the intersecting Hutajulu fault. Neogene and Quaternary volcanic and volcanoclastic rocks cap Tertiary sediments.

Figure 3. General tectonic setting map of Sumatra. Red square denotes Sarulla location (top left). Regional tectonic map showing Sarulla graben. Red line denotes gravity model section line (right). Gravity model cross sections (bottom left) [1].

Faults which have an important role in the subsurface were defined by influencing flow, distribution of permeable entries, offsets in lithologies and other reservoir characteristics (e.g. tracer flow pathways, alignment of geophysical anomaly, pressure or temperature differences in the reservoir, subsurface fluid chemistry, etc.). The SIL structural map was mainly developed from lineament interpretation by different individuals from both aerial photos and satellite imageries and augmented with surface field mapping (Figure 4). With the new LiDAR data acquired in 2015, the surface structures were refined by
topographic interpretation based upon the tectonic geomorphology using stereoscopic images prepared from LiDAR DTM and later confirmed by field checking.

Figure 4. Surface geologic map of the Silangkitang area with major rock types and prominent faults. The low resistivity boundary (defined from MT surveys), well locations, and thermal manifestations are also indicated. Stratigraphy of SIL is described in right column.

The graben extends in a NW-SE direction, parallel to the GSF. The Paleozoic Meta-sediments are exposed at the surface east of the GSF in the SIL area [4]. Those rocks are mainly meta-argillites with minor composition of quartzites, marls, and marbles. The Paleozoic interval in one well is massive and rigid and comprises generally open fractures that are filled by secondary minerals based on observation from the recovered conventional core. The top of basement is deep within the graben and is overlain by mainly thick young volcanic rocks (Figure 4).

Tertiary sediments were encountered by two wells west of the GSFZ. These facies, which is a sequence of fine to coarse-grained sedimentary rocks, is interpreted extending east from the GSFZ as a thin layer underlying the thick ash flow tuff unit. These rocks ranging from shale to conglomerate are described as valley-filling river deposits preceding most of the volcanic activity in the area [4]. Overlying the Tertiary Sediments is a thick accumulation of Rhyolite ash flow tuff, namely Sarulla Graben Tuff formation. This formation which consists of primarily rhyolitic tuff and dacitic tuff with thin mudstone interbeds. Most production and re-injection wells found permeable zones in this formation.

In general, the hydrothermal alteration minerals are consistent with current thermal conditions [4]. Moving deeper into the reservoir, the clays grade from pure smectite near the surface, through mixed-layer illite-smectite, to pure illite. Epidote and chloride which are ferromagnesium minerals are less abundant than in a typical andesite-hosted system while illite mineral which represents the silicic
character is more common. In the deep section, SIL wells encountered high temperature minerals which consist of quartz, calcite, illite, chlorite, pyrite, hematite, magnetite, anhydrite, leucoxene, and epidote.

Younger facies atop the tuff, include a thick sequence of fine-grained rocks interpreted as lake deposits. The variation in lithology in this formation is thought to represent different source rocks for sediments laid down in the same depositional environment [4]. The uppermost part is a recent alluvium layer consisting of pebble conglomerate and poorly consolidated sandstone.

3. Permeability Assessment
Some NW-SE trending scarps crossing the entire SIL area could easily be identified as conspicuous features in LiDAR. In SIL, the Sarulla Graben was bounded by two main strands of GSF which are interpreted as right-lateral strike slip. The east boundary was indicated by the Tor Sibohi Fault (TSF) that is easily identified as a NW-trending break in slope with dextral offsets in rivers [1]. Two wells including a newly drilled well intersected basement subsequently penetrating this main fault at depth confirming substantial vertical offset of basement rock across the structure. This fault, as suggested by stream offsets, topography, the nature of fault development, designates a subtle releasing bend as shown in (Figure 5). The pattern of this fault was observed and could be divided into three segments. North of SIL2 the fault strikes between N20°W and N32°W (blue); for a distance of about 7.25 km along the fault north-northwest of SIL2 to SIL3 the fault strikes between N37°W and N45°W (green); south of this point the strike of the fault is between N30°W and N40°W (red).

![Figure 5](image-url)

(a) Satellite imagery with prominent geology structures and two NE-SW geology cross sections. Four main structures striking NW-SE are the TSF, ETSF, WTSF, and Hutajulu Fault. Three minor structures linked to main structure are located west of WTSF. Low resistivity boundary, well locations, and thermal manifestation. (b) Two NE-SW vertical sections crossing SIL2 and SIL3 show lithostratigraphy and low resistivity contours (small is below 2 Ω·m while big is below 5 Ω·m).

The GSF strand which parallel to TSF main fault bounded the Sarulla graben with Palaeozoic meta-sediment basement at eastern portion. This fault is referred to as the East Tor Sibohi fault (ETSF).
Uplifting along Barisan Mountain resulted the basement that was encountered at shallow depth. Since limited accommodation space within block between main TSF and ETSF strand, graben filled deposits such as Quaternary volcanic rocks, lake sediments, and alluvium were interpreted as thin layer.

The Hutajulu fault was indicated by less obvious western strand located 4-6 km southwest of the eastern fault trace and interpreted as western boundary of Sarulla graben in SIL [5]. This strand could be observed on LiDAR according to different surface texture and colour although not as clearly defined. It seems the western part of the fault has a smoother texture and darker colour. The Bouguer gravity anomaly also corresponds with NW-SE lineaments that coincided with these two fault strands in GSF. The gravity survey sharply defines the contact between graben-filled deposit and basement and indicated that the TSF is steeply dipping to the west or vertical. The occurrence of numerous steeply dipping faults with sub-horizontal slickensides recognized in the vertically drilled exploration wells core holes [6].

The West Tor Sibohi Fault (WTSF), another main lineament, was interpreted to the west of the main TSF which has variety of fault orientation ranging from N5ºW to N45ºW. The fault appears to be separated from major strain at north area where there was N-S narrow valley and it merged again 3 km southeast from southwestmost bicarbonate springs. The geomorphologic feature of this fault was less evident near SIL2 and SIL3 pad area. Nonetheless, based on drilling results at SIL3 well, dacite tuff within Sarulla Graben Tuff formation may prove offset because of West TSF movement. This WTSF and main TSF create an elongated zone with width ranging from 500m to 2 km where fumaroles nearby SIL1 pad were manifested. On map view, it can be clearly seen that this particular zone becoming narrow at south area of SIL. All production wells and most of injection well that drilled within this area encountered good to extremely good permeability.

![Figure 6](image_url)

**Figure 6.** The acoustic image log from a SIL1 pad well drilled to the west of WTSF, tabulation of interpreted open fractures, and lower hemisphere-stereonet showing interpreted open fractures in this well.
Two N-S lineaments in area of SIL3 pad were interpreted as conduit for hot geothermal fluid to reach surface. One lineament extended N-S from WTSF along two separated hills and minor NW structure may allow hot fluid to manifest as NW-oriented bicarbonate. Two well were drilled to hit this specific structure to gain injection capacity with low pressure interference to main production wells. Drilling result showing this fault caused depth offset in dacite tuff. Other N-S fault showing horse tail pattern which may contribute to the occurrence of bicarbonate spring in the valley. Other minor faults striking EW and NE in north were interpreted as pathway for geothermal fluid flowing to west from the system.

A 152.4 m interval of sonic image data was acquired from well drilled at SIL1 pad to west direction. In general, the sonic image showed massive tuff texture which is probably part of Sarulla graben tuff formation. Fractures were only observed in thin interval from 1,021 m to 1,030 m and these may correspond to less significant total lost circulation at 1,024 m (Figure 6). About six open fractures were identified with strike ranging from N140°E to N160°E and dipping range of 72° - 76°. These fractures may correlate with subsurface parallel subsidiary strands of main TSF fault that was not identified from surface expression. One of fracture with relatively bigger aperture which is about 1 m was identified at depth of 1,024 m. However, the well drilled in this portion showed permeability in below average indicating that although some open fractures were identified there was possibility that these voids were filled partially by conductive minerals or the fractures were not well connected to other fractures.

Figure 7 Sample depth of 400 m – rock cuttings consist of: (1) porphyritic andesitic lava with plagioclase as phenocrysts, volcanic glass as groundmass, argillic alteration with low to medium intensity. Hydrothermal clays replace plagioclase. One plagioclase is sheared and filled with hydrothermal clay and other is strongly altered by hydrothermal clay. (2) quartz chips might be from vein.

Microscopic analysis showed intermediate to silicic volcanic rock which may correlate with graben filled deposits. Assessment on some shallow thin sections from SIL1 well that drilled to west outflow direction indicated that the rock has low to medium intensity of hydrothermal alteration (Figure 7 and 8). The low to medium altered andesitic lava with plagioclase was recognized at 400 m. Small amount of hydrothermal clay replaced plagioclase phenocryst in andesitic lava. Sedimentary rock with abundant quartz was identified together with dacite lava contains plagioclase and quartz at 527 m. At this depth, the sample may correlate with low resistivity value layer that covered graben filled deposited. All samples show the chips are in low to medium degree of hydrothermal alteration.
Figure 8: Sample depth 527 m – rock chips consist of: (1) Porphyritic dacitic tuff with plagioclase, quartz, minor biotite and lithic fragment set in volcanic glass matrix. Argillic alteration of low to medium intensity with hydrothermal clay replacing matrix. (2) Altered tuff with secondary quartz replacing original rock matrix, the rock is strongly altered.

Vein mineral fluid inclusion data from three newly drilled wells were obtained and suggested that the measured temperature in the area between the TSF and WTSF is the same or higher than when the vein minerals formed (Figure 9). Higher measured temperature than fluid inclusion temperature was observed in three fluid inclusion samples from one well drilled at SIL1 pad where the upflow of SIL geothermal system was interpreted. Each well drilled at SIL2 and SIL3 which penetrated the area between WTSF and TSF indicated measured temperature closely matches with temperatures when the minerals were formed. In the same wells but at shallower depth, fluid inclusions yielded higher temperatures than measured, signifying that cooling occurred after the vein minerals were deposited.

Figure 9. Measured temperature profiles and temperatures based on fluid inclusion analysis on rock cuttings from newly drilled wells at SIL1, SIL2, and SIL3 pads.

At SIL2 there is an indication that the samples located at or near argillic clay-rich layer and between the TSF and WTSF which may be exposed to surface groundwater. The interesting fact that, the samples
at SIL3 located outside the band and below the top of reservoir showed evidence of cooling mineral deposition. At SIL, downhole temperatures are the highest along TSF, specifically near SIL1 location. The high temperatures were interpreted to propagate within vicinity between main TSF and WTSF area rather than to outside of this band where several wells showed limited permeability. Temperature also decreases as fluid outflows laterally away from main TSF. Within the band, temperature decreases to the southeast (SIL3) and northwest (SIL2) from SIL1. In the current 3D reservoir static model, to better represent the conceptual understanding about SIL temperature, especially in the vicinity where there is no well data, an interpolant was applied in the model using the trend of the TSF strike direction [7].

Figure 10. Graphic demonstrates whole-rock oxygen isotopes of cuttings and core samples from Silangkitang wells (Unocal North Sumatra Geothermal, Ltd., 1996). Oxygen isotope composition with depth from SIL1 (black), SIL2 (dark grey), and SIL3 (grey) wells.

Oxygen isotope compositions of whole rock samples can be used to evaluate the extent and nature of interaction between rocks and hydrothermal fluids. Chemical reaction between hot fluids and the minerals that comprise rocks cause the rocks to undergo alteration and experience temperature-dependent shifts in their oxygen isotope compositions. In most geothermal systems, high temperature (>150°C) water-rock exchange will result in a decrease in the δ18O values of the rocks. Increasing temperatures and water-rock ratios will magnify the extent of the 18O depletion in the host rock. The impact to geothermal fluid due to the water rock interaction will be the other way around. No additional data of rock oxygen isotope from newly drilled well however some fluids from newly drilled well were sampled and examined in term of oxygen isotope.

The oxygen isotope compositions in rock decrease with depth to minimum value ranging from 0.7 to 4.4‰ in four wells between WTSF and TSF (Figure 10). The presence of relatively lighter δ18O in fluid samples from newly well drilled within the band suggested although the exchange of δ18O with the rock was intense, there was mixing with other fluid contains low δ18O that contributed to reduce the oxygen isotope in the fluid.
4. Conclusion
The main strands of GSF play important role to define good permeability at SIL. The productivity test results from newly drilled wells, in concert with known geology, geochemistry, geophysics, suggest that areal extent of potentially good permeability zone of the Silangkitang geothermal system is restricted to area marked by fumaroles between TSF and WTSF. High temperature thermal features of the SIL area are concentrated in the area of releasing step in Sumatra fault system along the western portion of the TSF. As result of a strike slip fault becomes oblique to regional slip vector, local extension zone was formed between two segments of strike slip fault overlap. Strike-slip faults and any connected normal faults build a link zones of fractured reservoir. These reservoirs are possible to be strongly anisotropic with major fluid flow occurring along faults and linked fractures (Hickman et al., 1996). Individual faults of this system area acting as the main vertical conduits for the fluids.

The association with the fault suggests heat source in this prospect is the fault array allows deep circulation and heating of waters in a region with an abnormally high geothermal gradient and pressure. Series of structures defined fault zone in at least 500 m to 1.5 km wide in this area indicating that some slip may be transferred from main TSF to subsidiary faults. The possibility of good permeability reservoir to east of TSF or in between TSF and ETSF is low since the less fractured basement was encountered at shallow depth and volcanic rock may be deposited at shallow level where the clay cap was formed. Furthermore, thermal features were hardly found in this block. Three newly drilled wells from SIL1 and SIL3 pad which penetrated to west of WTSF obtained sub-commercial permeability showed by limited injection capacity.

SIL is located within Sarulla graben area where the fine-grained sediment fine was deposited at shallow level and was interpreted as lake sediment. Newly drilled wells identified that low resistivity layer at west area of WTSF corresponds with this lake sediment deposition. Rock cutting samples from these wells were analysed under polarization microscope showing low to medium alteration intensity of quartz-rich sedimentary rock coincides with depth of this conductance layer below 5 Ω⋅m. In addition to this observation, since reservoir extent is controlled by the intensity of fracturing, a symmetrical halo of argillic alteration common in many geothermal systems may not be present. Interpretation on borehole image from one well at outside the band showed open fractures were only identified within 6% of 500’ interval which correlates with less significant permeability. Moreover, there was no prominent structure that can be identified from satellite imagery in west area of WTSF suggesting that fractures corresponding to good permeability were not developed in this area. The wells drilled between WTSF and TSF showing agreement between measured temperature and temperature from fluid inclusion analysis. Although only samples from one well drilled to west of WTSF showing cooling process this observation indicating less intense shallow low permeability layer, clay cap, that sealing the geothermal system from surrounding meteoric water influx.

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