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Geothermal Resource Exploration along Great Sumatera Fault Segments in Muara Laboh: Perspectives from Geology and Structural Play

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ABSTRACT

We review the key geologic elements of stratigraphy, structure, and hydrothermal alteration to better understand their roles in controlling the Muara Laboh geothermal system. The oldest rocks in the Muara Laboh region are the metamorphic Paleozoic Barisan Formation. Late Oligocene to Middle Miocene volcanism is represented by the Painan Formation, consisting of mixed volcanic and sedimentary rocks of andesitic to dacitic composition. In the Middle Miocene, granitic and granodioritic rocks intruded the Barisan and Painan Formations. Undifferentiated Silicic Volcanic and volcaniclastic rocks consisting dominantly of dacitic to rhyolitic tuff and sediments, are widely distributed northwest, west and southwest of Muara Laboh. Evidence from exploration wells indicates that this rock sequence is present mostly in the western Muara Laboh basin. In the eastern Muara Laboh Basin Andesitic Volcanics were erupted to the SE of Muara Laboh at about the same time. These sequences are overlain by Quaternary andesitic volcanics over almost the entire Muara Laboh area. These products come from several eruption centers respectively from the NW to SE including Mt. Patah Sembilan and Mt. Anak Patah Sembilan. Flow patterns are generally from the eruption centers along the Siulak fault in the south towards the north. Field geologic mapping indicates that all of these volcanoes are composed dominantly of andesitic rocks and consist mainly of lava, tuff, breccia, lahar, and debris flow deposits. The more distal deposits consist dominantly of volcaniclastic equivalents of the eruptive products. The most recent volcanic deposits at Muara Laboh consist of andesitic to dacitic tuffs and debris flows. Carbon in the tuffs yielded ages of ~34 to 41 ka. Debris flows underlying the tuffs may be related to sector collapse and debris avalanches from Patah Sembilan crater, providing a likely minimum age of this event.

The Muara Laboh geothermal system is situated within a pull apart basin along the NW-SE Great Sumatera Fault (GSF). About 8 km north of the prospect, the Suliti Fault segment juxtaposes uplifted metamorphic basement with young basin fill deposits. South of Muara Laboh, the Siulak Fault segment has accommodated the magmatic intrusion that provides geothermal heat sources. Cross sections constrained by mapping, gravity, and well data indicate two main grabens in Muara Laboh i.e. West Muara Laboh Basin and East Muara Laboh Basin. The proposed model is for an asymmetric basin system with a narrower and deeper western basin along the Siulak master fault, and a shallower but wider eastern basin within the main step over fault structure.

Analysis of structures at surface and in borehole image logs show dominant trends of open fractures are N-S, NW-SE, and NE-SW. The NW-SE fracture trend is associated with the GSF and based on image logs is important in the deeper section of exploration wells (H pad well), while surface mapping found this orientation in areas near the main GSF (Suliti and Siulak Fault segments). The N-S structural trend is considered to be the step over fault trend, and associated with the pull apart basin structures generating a horst and graben system. This N-S set corresponds with extensional fractures that are interpreted as the most important in controlling permeability, fluid flow, and thermal discharges in Muara Laboh geothermal system. The NE-SW fault trend is interpreted to be antithetic to the GSF and is considered to be the youngest structure based on the field mapping data. The image log data also support this interpretation because NE-SW fractures are more abundant at shallower depth.

An extensive clay cap overlies the Muara Laboh geothermal system and its outflow area, but thick clay on the eastern flank of the system is in part related to basin fill deposits. The commercial reservoir top conforms to the base of the conductor best near Idung Mancung fumarole, where it hosts a 240°C steam cap. This zone appears to have recently been heated and host quartz, wairakite and prehnite veins open space texture. Some of the edges of the MT conductor have also been shown to approximately parallel the traces of inferred faults. The top of the propylitic alteration zone does not typically conform to the base of the conductor because a zone of transitional alteration defined by mixed-layer clay and chlorite underlies the smectite cap that corresponds with resistivity of ≤ 7 ohm-m. The highest deep permeability in the area is associated with epidote-adularia veins with open space textures that produce fluid at ≥ 270°C, but permeability is locally reduced by late-stage infilling by calcite, quartz, and prehnite.

1. INTRODUCTION

The Muara Laboh Geothermal Field is located in Sumatera, the largest island in the western part of Indonesia, about 135 km SE the capital city of Padang, West Sumatera Province (**Figure 1**). Muraoka et al. (2010) suggested that there are two types of geothermal systems in Sumatera, with the first situated on the slopes of volcanic edifices, and the second associated with pull apart basins along the Great Sumateran Fault. The Great Sumatera Fault system is a complex of NW-SE dextral strike-slip faults running the length of the island (~1,900 km) through the center of the Barisan Mountains from Banda Aceh in the NW to Bandar Lampung in the SE. The fault system is highly segmented with zones of compression and extension. Compression results in areas of uplift whereas extension results in pull apart basins that form graben and horst blocks. Extension also accommodates volcanism along the line of the fault system (Bellier and Sebrier, 1994; McCarthy and Elders, 1997; Sieh and Natawidjaja, 2000; Barber et al., 2005). Movement of this transcurrent fault system is attributed to the oblique subduction of the Indo-Australian Plate beneath Sumatera. The Muara Laboh geothermal field is situated in pull apart basin at a right step over between two segments of the GSF (**Figure 1**), and is also associated with the Quaternary to Recent active volcanic arc of Barisan Mountains Range.

The geothermal resource in Muara Laboh is indicated by the presence of thermal manifestations consisting of fumaroles, hot springs, mud pools, and steaming grounds which discharge along structures associated with the Great Sumatera Fault near young volcanic centers such as Patah Sembilan (**Figure 1**). In this paper we examine a combination of information from surface geology, geophysics, and exploration wells drilled in 2012-2013. This information is used to better constrained the geological setting and structural evolution relevant to the geothermal system. This geologic framework includes the distribution of intrusion and related volcanism, as well as sedimentation within a broad strike-slip environment, and integration of the stratigraphic and structural analysis into conceptual models for the Muara Laboh geothermal system.

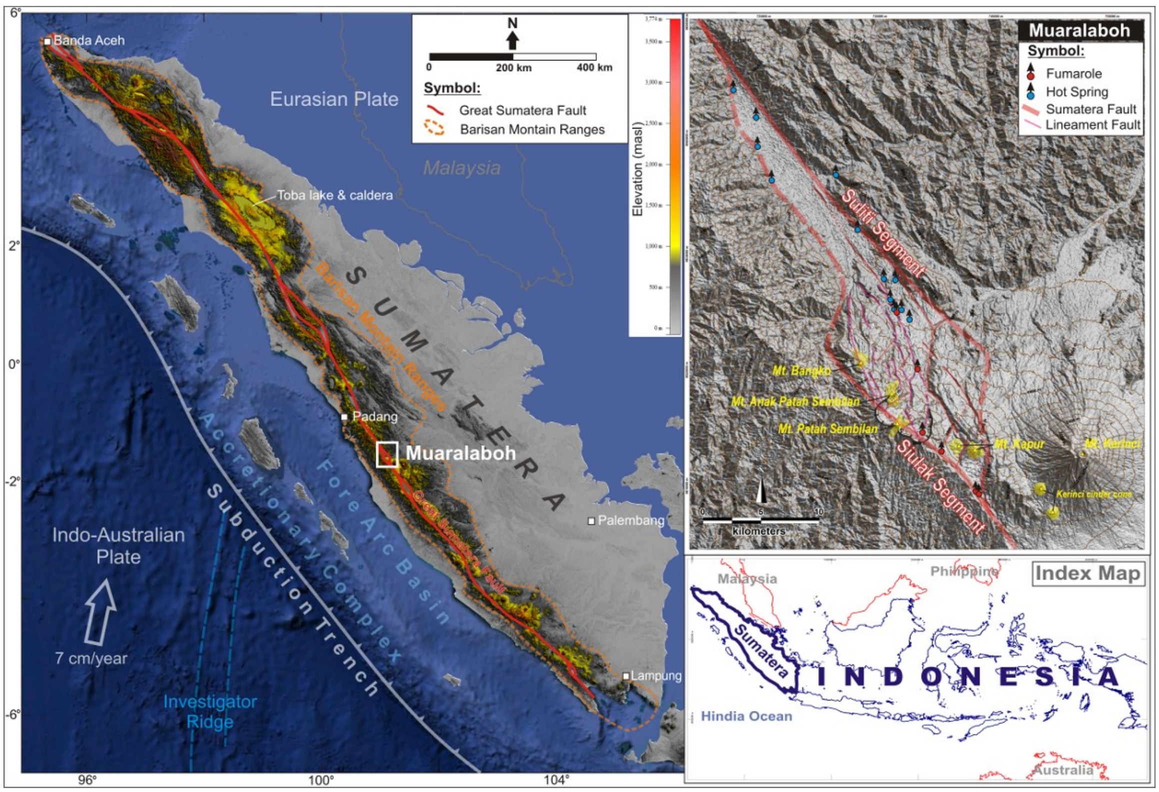

Figure 1. Left: Sumatera Island, Barisan Mountain Ranges, and Great Sumatera Fault crossing the western part of the island. Tectonic setting of Sumatera is attributed to oblique subduction of the Indo-Australian Plate beneath Eurasian Plate resulting in the transcurrent Great Sumatera Fault (GSF), volcanic arc and associated geothermal systems. Right: The segmentation of GSF system resulted in the pull-apart basin and volcanism at Muara Laboh field. Thermal manifestations in Muara Laboh discharge along the main GSF and near Patah Sembilan Crater.

2. GEOLOGY SETTING

2.1 Stratigraphy

The stratigraphy of Muara Laboh can be simplified into a pre-Tertiary basement overlain by a sequence of Tertiary to Mesozoic age volcanics, intrusions and sediments. To date, the reservoir has only been found within the latter (**Figures 2 & 3**). The oldest rocks in the Muara Laboh area comprise the Paleozoic Barisan Formation (Pb) consisting of slate, phyllite, hornfels, meta-greywacke and limestone recrystallized to marble (Pbl). In some areas the Barisan Formation overlies the Siguntur Formation (Ps) consisting of quartzite and intruded by Cretaceous Granite (Kgr). These rocks are uplifted, folded, faulted and locally metamorphosed, typical of the Pre-Tertiary basement. This basement sequence outcrops 8-10 km north and east of the Muara Laboh field.

The Painan Formation (Tomp), consisting of mixed volcanic and sedimentary rocks, unconformably overlies the Pre-Tertiary basement. The volcanic sequence consists mainly of andesitic to dacitic lava, breccia, crystal tuff, ignimbrite, and lithic tuff. Crystal tuff contains abundant feldspar and quartz with groundmass of sericite, clay mineral, and glass. Sedimentary rocks included arkose, bituminous shale, shaley coal, and tuffaceous sandstone (Rosidi et al., 1996). The Painan Formation outcrops in the northwest, forming the western side of fault scarps bounding the Muara Laboh basin (**Figure 2**). $^{40}K/^{40}Ar$ dates on volcanic rocks yield ages ranging from 23 to 14 Ma (Late

Oligocene to Middle Miocene; **Table 1**). This age is also supported by *Dicotylendenblad* biomarker fossils (Rosidi et al., 1996). In the Middle Miocene, granitic (Tgr) and granodioritic (Tgdr) rocks intruded the Barisan and Painan Formations. These intrusive bodies outcrop to the west and south of Muara Laboh and extend to the south of Mt. Kerinci following the main structural trend of the GSF. Their exposure implies extensive uplift and erosion of these formations occurred during Middle Miocene to Early Quaternary.

Undifferentiated Silicic Volcanic rocks (Qou and Qol) are widely distributed in the mountainous terrain northwest, west and southwest of Muara Laboh field (**Figure 2**). These volcanic products consist of dacite, rhyodacite, and rhyolite lava and tuff, crystal tuff, vitric tuff, tuff-breccia, ignimbrite and obsidian. The crystal tuff is composed of quartz and feldspar with silica matrix, chlorite, hornblende, and calcite, and locally containing andesitic lithics fragments (Rosidi et al., 1996). A few banded rhyolite lava flows also occur. The eruption center(s) of this silicic volcanic sequence are unknown, however, multiple vents to the SW and W of Muara Laboh are likely. Evidence from exploration wells indicate that this rock sequence is up to 1000 m thick in the Muara Laboh basin, underlying more recent andesitic rocks. During approximately the same period, Andesitic Volcanics (Qyu) were erupted to the SE of Muara Laboh, filling the Muara Laboh basin with basaltic to andesitic lava, tuff, tuff breccia, volcanic breccia, lahars, volcanic sediment, fluvial and lacustrine sediment and detritus of marine sediment. These volcanic products and sediments are mixed and intercalated inside on Muara Laboh basin.

Young Quaternary volcanic products covered the earlier silicic and andesitic volcanic sequences over almost the entire Muara Laboh area. These products come from several eruption centers respectively from the NW to SE consist of Mt. Bangko, Mt. Patah Sembilan, Mt. Anak Patah Sembilan, Mt. Kapur, and Mt. Kerinci (**Figure 2**). Volcanic and sedimentary products generally flowed from the eruption centers along the Siulak fault in the south towards the north. Field geologic mapping results indicate all of these volcanoes are composed dominantly of andesitic rocks and consist mainly of lava, tuff, breccia, lahar, and debris flow deposits. The more distal deposits consist dominantly of volcaniclastic equivalents of the eruptive products. The most recent volcanic deposits at Muara Laboh consist of andesitic to dacitic tuffs and debris flows. Carbon in the tuffs yielded ages of ~34 to 41 ka (**Table 2**). Debris flows underlying the tuffs may be related to sector collapse and debris avalanches from Patah Sembilan crater, but further work is required to confirm this. This provides a likely minimum age of the sector collapse.

Table 1. Dating of the Painan Formation from Bellon et al. (2004) in Barber et al. (2005).

No	Sample	Dating Method	Ages (Ma)	Ranges of Geological Ages
1	Basalt flow, Painan Formation (PN 26)	^{40}K-^{40}Ar	23.7 ± 0.55	Late Oligocene to Early Miocene
2	Andesite dyke in Painan Formation (TP 34)	^{40}K-^{40}Ar	24.3 ± 0.60	Late Oligocene to Early Miocene
3	Dacite dyke in Painan Formation (TP 33)	^{40}K-^{40}Ar	25.5 ± 0.59	Late Oligocene to Early Miocene
4	Andesite flow in Painan Formation (PN 31)	^{40}K-^{40}Ar	19.2 ± 0.54	Late Early Miocene to Middle Miocene
5	Andesite flow in Painan Formation (PN 22)	^{40}K-^{40}Ar	19.1 ± 0.45	Late Early Miocene to Middle Miocene
6	Basalt flow in Painan Formation (PN 24)	^{40}K-^{40}Ar	19.0 ± 0.45	Late Early Miocene to Middle Miocene
7	Andesite flow in Painan Formation (TP 32)	^{40}K-^{40}Ar	14.3 ± 0.34	Late Early Miocene to Middle Miocene

Table 2. Dating of carbon from young tuff deposits at Muara Laboh.

No	Carbon Sample	Description of Unit Containing Carbon	C-14 Age (years BP)	Error (±) years
1	8-14-C1	White to gray dacite fallout tuff	>49,500	-
2	8-14-C2-1		33,490	520
3	8-14-C2-2		34,680	600
4	8-12-C1	Cream andesite ash-flow tuff	40,900	1300
5	8-12-C2		>48,800	-

Carbon-14 ages determined by Supreme Energy Muara Laboh at University of Arizona AMS Laboratory, 2017.

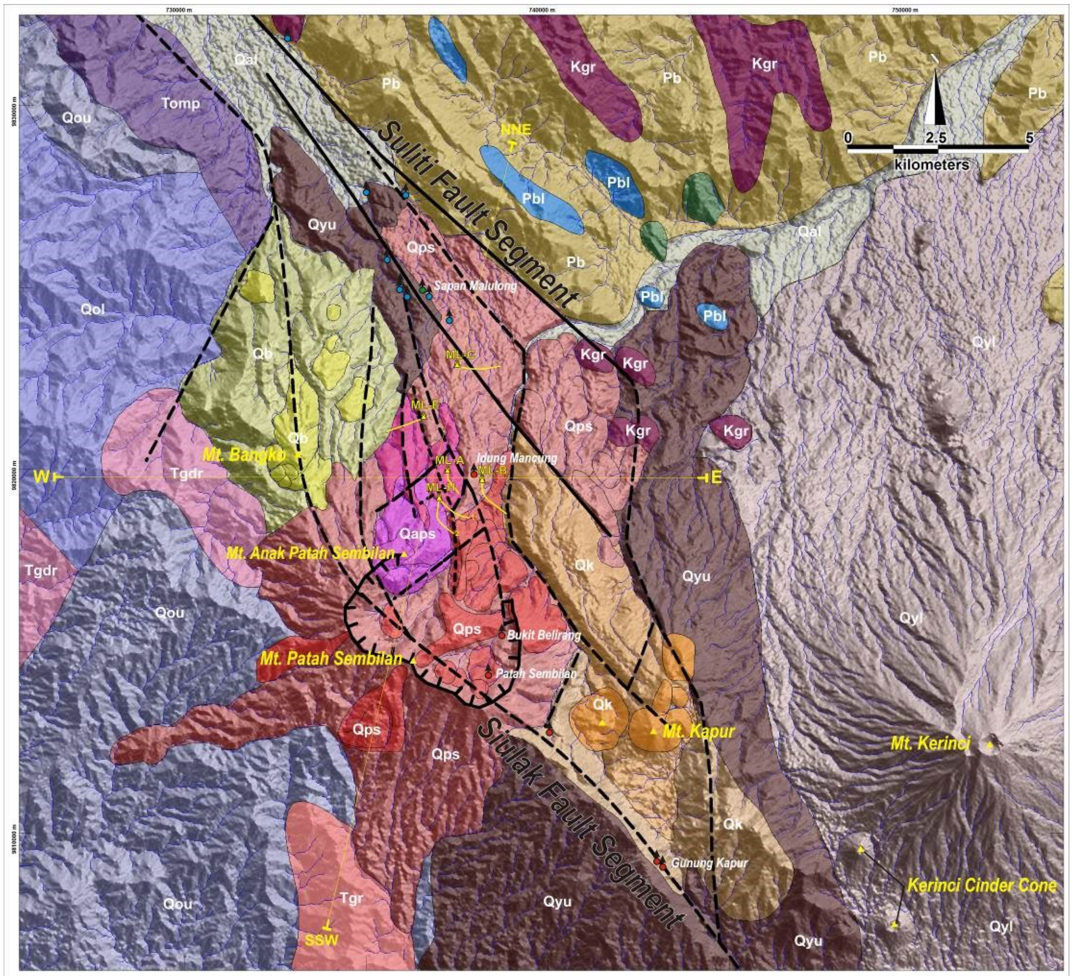

Figure 2. Geologic Map of Muara Laboh. See Figure 3 for map legend.

Reference Ages	Regional Tectonic Stratigraphic Stages	Volcanic & Sediment	Intrusive	Formation/ Volcanic Product & Lithology	Geohistorical Stratigraphy & Fault Structure	Stratigraphy & Geothermal System
Quaternary (*<1.8 Ma*)	ACTIVE VOLCANISM AND BASINAL IN-FILLING BY VOLCANIC PRODUCTS Reactivation-Continuity Active GSF	Qal Qyl Qaps Qps Qb Seds Qyu	Qk Qou/l	Aluvium Mt. Kerinci Mt. Kapur Mt. Anak Patah Sembilan Mt. Patah Sembilan Mt. Bangko Undifferentiated silicic volcanic rocks Andesite volcanic rocks and Intercalation andesite & silicic	Recent alluvium actively filling the valley and river plain. Mt. Patah Sembilan, Kapur & Kerinci volcanic complexes and with andesitic composition sequence of tuffs, breccia and lava. Silicic (dacite to rhyolitic) sequence (Qou/l) dominated by tuffs but including lava and volcaniclastic units. Andesitic volcanic sequence (Qyu). Products dominated by lava, pyroclastic, and associated volcanic sediment & sediment. Intercalated with silicic volcanic sequence. *Step-over initiates local depocentre formation (right lateral dextural strike slip).*	**Hosts Reservoir Clay Cap** **Shallow Reservoir** **Intermediate Zone**
Tertiary (Oligocene to Miocene *33-5.3 Ma*)	HORST AND GRABEN STAGE GSF start active faulting	Tomp	Tgdr Tgr	**Granite & Granodiorite** **Painan Formation:** Volcanic (andesitic to silicic) & Sedimentary (shale to sandstone)	**Unconformity** - uplift exposes granite & granodiorite to surface. Initiation of GSF in mid-Miocene (13 Ma) (Barber et al., 2005 and references therein). Magmatic arc granites & granodiorites (Tgr & Tgdr) intruded, within horse and graben structures. Tertiary lava, pyroclastic, volcaniclastic, and sedimentary deposits (Tomp) fill the horse and graben system. *Faulting of the Pre-Tertiary rocks creates horse and graben system (extension).*	**Deep Reservoir**
Mesozoic (Cretaceous *144 Ma*)	PRE-RIFT Final stage of stable craton	Ps	Kgr	**Granitic Rocks** **Siguntur Formation:** Quarzite	**Unconformity** - Pre-Tertiary rocks are uplifted, folded, and faulted, with local metasomatism (McCarthy & Elders, 2014.) Intra-continent sedimentation (Ps) while the granites (Kgr) intruded the Paleozoic rocks.	**Outside Reservoir**
Paleozoic (Permian *248 Ma*)		Pbl Pb		**Bukit Barisan Formation:** Phyllite, slate, limestone, metagreywacke	**Unconformity** - uplift and erosion. Offshore deposition, burial and metamorphism.	

Figure 3. Simplified stratigraphy of Muara Laboh.

2.2 Structure

The Muara Laboh geothermal field is situated within a step-over (pull apart basin) of two segments of the GSF, the Siulak and Suliti segments, respectively (**Figure 4**). Quaternary to Recent volcanism of the Barisan Mountains occurs mainly along Siulak segment indicating some extension along this structure has been taken up by intrusion. Wu et al. (2009) used sandbox modeling to understand the pull apart basin mechanism as shown in **Figure 5**. As the two strike slip fault segments propagate and interact, a depression with bounding extensional faults forms as shown in the block diagram. Pull apart basins typically form sigmoidal to rhombic deep grabens, the geometries of which are dependent upon the offset architecture of the underlying basement faults. The Muara Laboh basin appears to have reached an advanced stage in its development, with mature cross-basin faults.

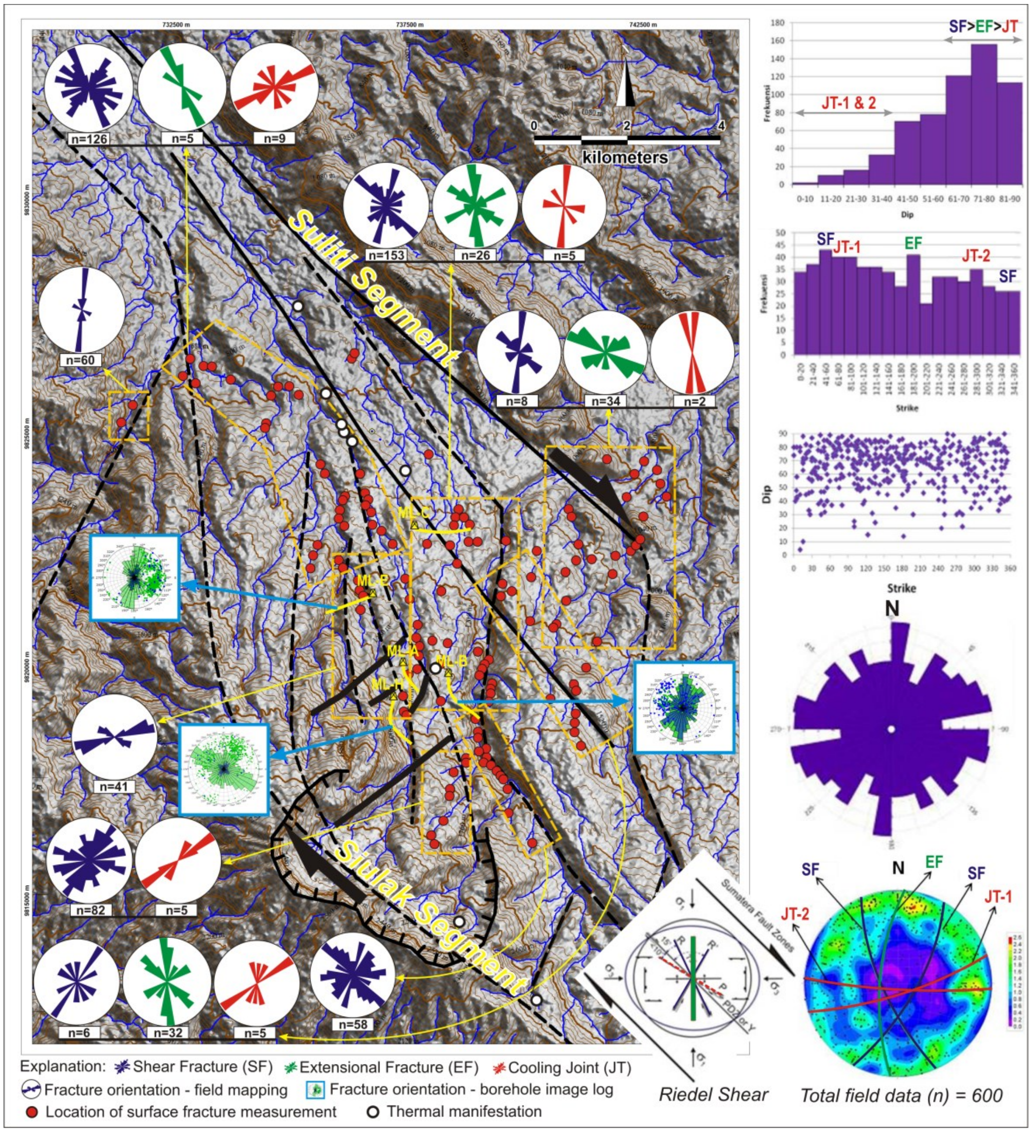

Figure 4. Left: Map of interpreted geologic structures with fracture data from field geology mapping, rosette diagrams of surface structures and open fracture trends from specific locations and borehole image logs. Right: Plots of surface structure strike and dip, rosette of all surface fractures, and lower hemisphere plot of all surface fractures.

Local faults identified in the Muara Laboh field were interpreted using a variety of data including surface lineaments, surface fracture measurements, fractures interpretation from borehole image logs, interpreted lithologic offset from exploration drilling, and gravity modeling. The integration of these data has allowed us to resolve the structural pattern from surface to depth. A total of 600 surface measurements of shear fractures (minor faults), extension fractures (including joints), fault and striations were collected during field mapping and combine with around 2000 fractures intepreted from image logs. These fractures are shown in stereonet using lower hemisphere equal area projection (**Figure 4**).

Structural data indicate three dominant orientations of fracturing at Muara Laboh (see **Figure 4**):

1) N-S (extension fracture/EF),
2) NW-SE (shear fracture/R) and lesser WNW-ESE (joints/JT1&2), and
3) NE-SW (shear fracture/R’).

Interpretation of open fractures from borehole image logs show the same dominant trends for open fractures, namely N-S, NW-SE, and NE-SW. The NW-SE fracture trend is interpreted to be associated with the GSF and based on image logs is important in the deeper section of exploration wells (H pad well), while surface mapping found this orientation in areas near the main GSF (Suliti and Siulak Fault segments). The N-S structural trend is considered to be the step over fault trend, and associated with the pull apart basin structures generating a horst and graben system. A Bouguer gravity interpretation also supports the existence of this horst and graben geometry (**Figure 6**). This N-S set corresponds with extensional fractures, found as the most important orientation controlling permeability and fluid flow in Muara Laboh geothermal system. Thermal manifestations are also localized along N-S fractures, supporting this interpretation (**Figure 4**). The NE-SW fault trend is interpreted to be antithetic to the GSF. The later orientation is considered to be the youngest structure based on the field mapping data, where NE-SW fault crosscut the older NW-SE and N-S. The image log data also support this interpretation because NE-SW fracture orientation is found at shallower depth. All of these fractures trends are consistent with the pull apart basin setting.

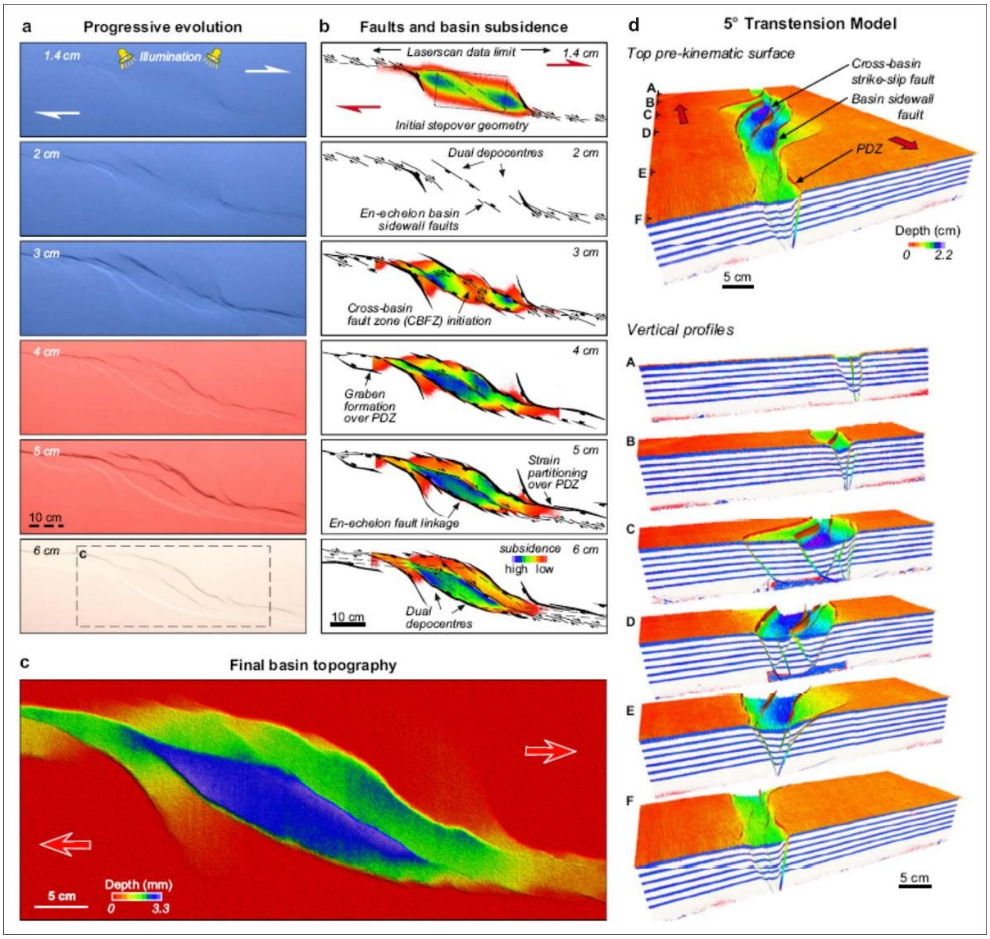

Figure 5. Plan view evolution of transtensional pull-apart basin model illustrated with: (a) time-lapse overhead photography; and (b) fault interpretation and incremental basin subsidence calculated from differential laser scans. Initial and final baseplate geometry shown with dashed lines; (c) basin topography at end of experiment, (d) 3D visualization of pull-apart basin model reconstructions transtensional model. Figure from Wu et al. (2009).

2.3 Muara Laboh Basin System

Santoso et al. (1995) produced a Bouguer gravity map using a density value of 2.4 gr/cc that showed a NW-SE low gravity anomaly trend and N-S moderate gravity trend. We have interpreted the N-S trend as the horst and graben system of the Muara Laboh basin (**Figure 6**). A prominent very high gravity anomaly in the northeastern part possibly correlates with uplifted basement rocks, while the existences of Mt. Bangko and Anak Patah Sembilan volcanoes show a coherency with high anomaly closure in the western portion of the field.

The interaction of fault segments of the GSF system has developed basin systems within the step-over faults. These act as local depocenters in releasing bends (horst and graben system) of the strike-slip fault system in Muara Laboh. The Bouguer gravity anomaly and geologic cross section interpretation show two main grabens in Muara Laboh referred to as the West Muara Laboh Basin and East Muara Laboh Basin (**Figures 6** & **7**). The proposed model is for an asymmetric basin system with a deeper fill of western basin near the Siulak master bounding fault, and shallower but wider eastern basin within the main stepover fault region and eastern bounding fault.

The Silicic Volcanic products (Qou & Qol) are mainly filling the West Basin, and based on well data reach ~1000 m in thickness. The East Muara Laboh Basin is mainly filled by Andesite Volcanic Products (Qyu). The volcanic sediment and sediment (Seds) are associated with andesitic and silicic volcanic products, based on well drilling data (ML-B and ML-A) this sediment mainly found in East Muara Laboh Basin as infilling sediments derived from older sedimentary rocks exposed in that eastern and northeastern parts of Muara Laboh, consist of limestone and tuffaceous sandstone. The thickness of each silicic and andesitic volcanic sequence is about ~1000 meter at the main depocenter of Muara Laboh Basin and thinner toward the eastern and west bounding faults (Suliti & Siulak Segment) as mentioned by Busby and Bassett (2007).

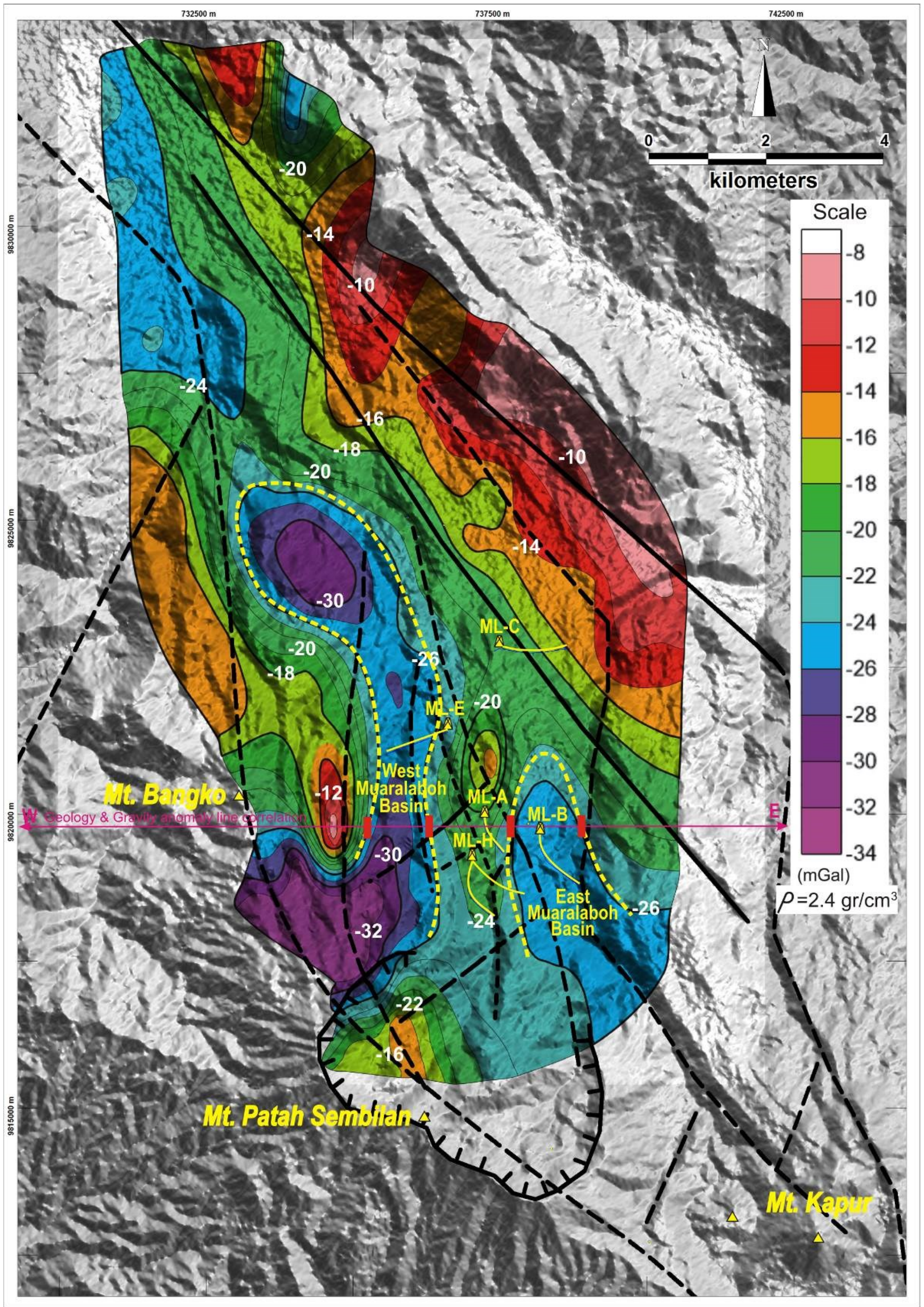

Figure 6. Bouguer gravity map with low gravity anomalies indicating a horst and graben system in Muara Laboh (modified from Santoso et al., 1995). W-E correlation line with geology shows respectively from the west high anomaly gravity may correlate with Mt. Bangko and Anak Patah Sembilan volcanoes, while low gravity anomaly corresponds with graben structure of West and East Muara Laboh Basin and horst structure in between. Very high gravity anomaly at eastern part corresponds with uplifted basement rocks while at eastern high terrain may correlate with granite-granodiorite intrusion (see Figure 2).

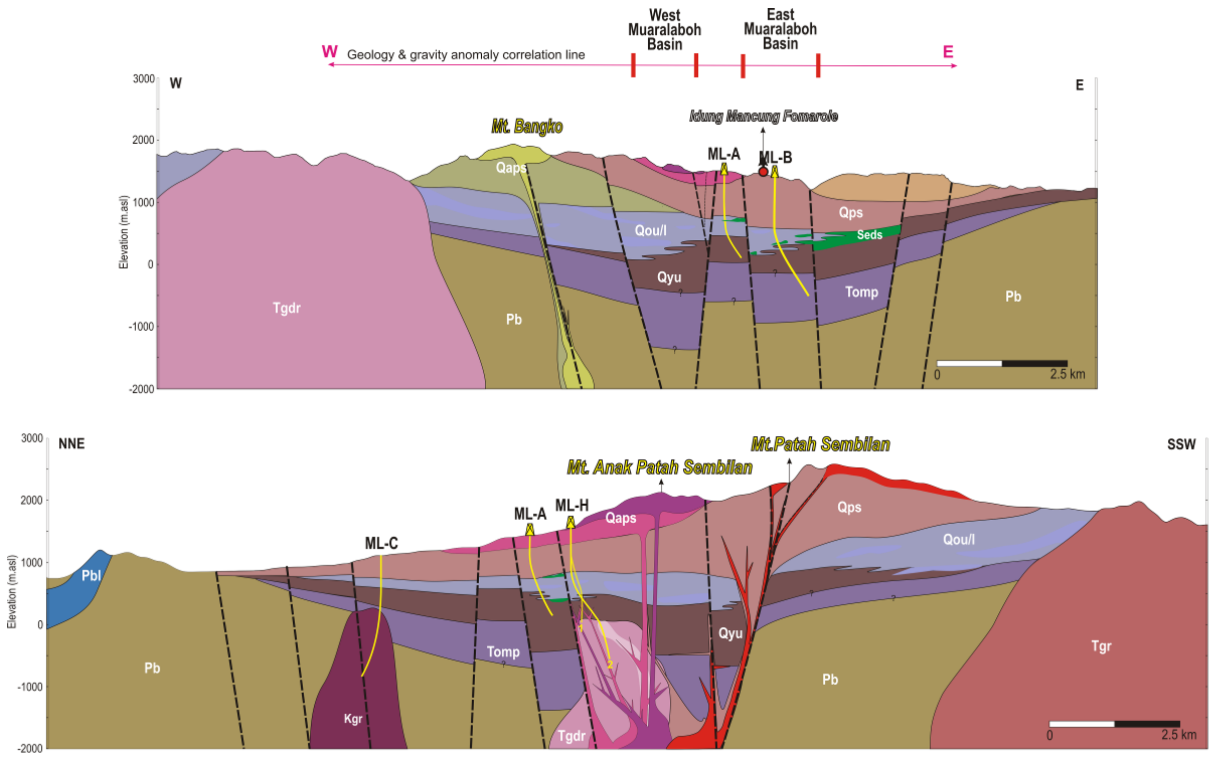

Figure 7. The geology cross sections. Top: E-W; Bottom NNE-SSW. Line is a correlation between Bouguer gravity anomaly (see Figure 6) and subsurface geology.

2.4 Volcanic Vents and Intrusions

Volcanism at Muara Laboh is linked to the structural evolution of the Great Sumatera Fault system. The young Quaternary volcanic centers are located along the Siulak Fault segment respectively from the NW to SE consisting of Mt. Bangko, Mt. Patah Sembilan, Mt. Anak Patah Sembilan, Mt. Kapur, and Mt. Kerinci (**Figure 2**). Superimposing topography and volcanic product distribution shows the magmatism and volcanic activities are migrating laterally from the NW to SE following the main structural trends. The main trends of young vents signals extension and infilling by magma at depths > 4 km with dikes, sills, and stocks extending to higher levels. This is consistent with well temperature trends showing the highest values at Pad H. The lateral extent of young vents along this NW trend leave open the possibility of multiple upflows along this trend related to distributed fracturing and volatile release from cooling magmatic intrusions, followed by deep circulation of meteoric water at brittle edge of intrusive complex. Drilling data has identified a dike complex at the deeper part of ML-H wells (**Figure 7**). These dikes are interpreted as overlapping hypabyssal intrusive complexes of Mt. Anak Patah Sembilan and Patah Sembilan itself.

3. GEOTHERMAL SYSTEM OF MUARA LABOH

The general configuration of the Muara Laboh geothermal reservoir is shown in cross section in **Figure 8**. The deep reservoir (H well) is dominated by a plutonic complex that represents multiple stages of intrusion including coarse grained dioritic to granodioritic rock, and later stage dikes of wide compositional range, but mostly microdiorite. Dikes interpreted from image logs have the same orientations as the main fracture trends (NW, NE, N-S) and are probably intruding faults and extensional fractures. Permeability in wells seems to be locally related to dike intrusion and stock margins. A superheated fumarole in the Patah Sembilan crater provides additional evidence for hydrothermal circulation along the trend of vents. The shallow reservoir (A well) is capped by the Patah Sembilan volcanic complex, with the highest reservoir permeability localized near its base and in the top of the underlying silicic volcanic rocks.

3.1 Resistivity, Alteration, and Vein Paragenesis Volcanic

An extensive capping of clay altered volcanic rocks overlies the Muara Laboh geothermal system and its outflow area (Dyaksa et al., 2016). The cap was original mapped by magnetotellurics (MT) surveys that were used to infer the depth to the reservoir top and the likely extent of hydrothermal circulation. After drilling it became clear that the thick clay on the eastern flank of the system is in part related to basin fill deposits, and that the commercial reservoir top does not always conform to the bottom of the conductor. However, it has been confirmed that a portion of the shallow cap near Idung Mancung fumarole hosts a 240°C steam zone that represents the shallowest part of the system (Situmorang et al., 2016). This zone appears to have recently been heated and host quartz, wairakite and prehnite veins open space texture (**Figure 9)**. Some of the edges of the total conductance map from surface to 1000 m depth have also been shown to approximately parallel the traces of inferred faults (**Figure 10**).

The top of the propylitic alteration zone, as defined by the presence of megascopic epidote, does not typically conform to the base of the conductor because a zone of transitional alteration defined by mixed-layer clay and chlorite underlies the smectite cap that corresponds with resistivity of ≤ 7 ohm-m (**Figure 8**). In addition, extensive relict propylitic alteration and local potassic alteration (not in equilibrium with measured temperature) are present in some edge wells drilled for injection. This indicates that multiple hydrothermal systems have existed in the area over time. The highest deep permeability in the area is associated with epidote-adularia veins with open space textures that produce fluid at ≥ 270°C, but permeability is locally reduced by late-stage infilling by calcite, quartz, and prehnite (**Figure 9**).

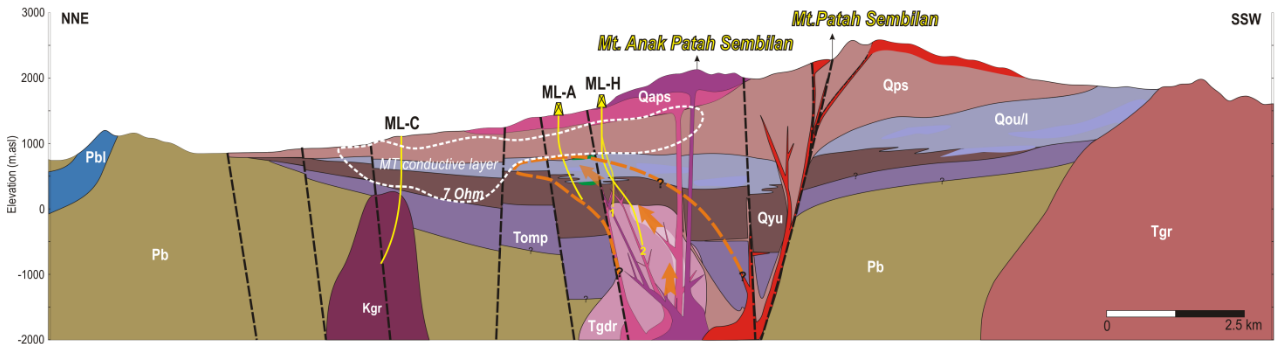

Figure 8. Cross section of the MT conductor (white dashed line) and geothermal system in the vicinity of the ML-A (shallow cap) and ML-H wells (deep reservoir) at Muara Laboh. Arrows indicate the general direction of upflow and outflow. The section is cut slightly oblique to the outflow to the northern springs so it represents the low permeability zone to the east of the outflow in the vicinity of ML-C rather than the full outflow extent.

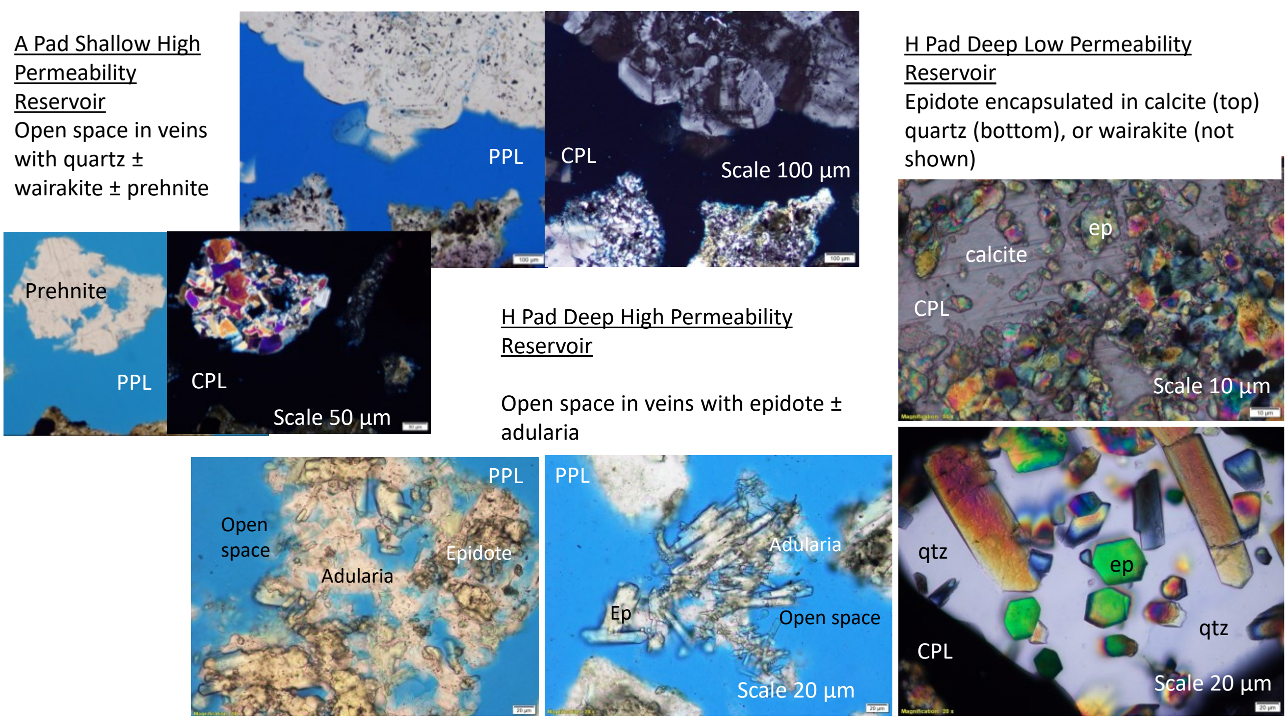

Figure 9. Summary of vein paragenesis in the Muara Laboh geothermal reservoir. The shallow A pad has high permeability associated with quartz ± wairakite ± prehnite veins with remaining open space (upper left). The high permeability deep H reservoir is associated with intrusion margins, dikes, and epidote ± adularia veins with remaining open space (lower middle). In the lower permeability intermediate-depth H reservoir, epidote veins are mostly sealed with later-stage calcite, quartz, and wairakite (right). PPL=plane polarized light; CPL=crossed polarized light. Euhedral crystal form and epoxy blue dye indicates open space.

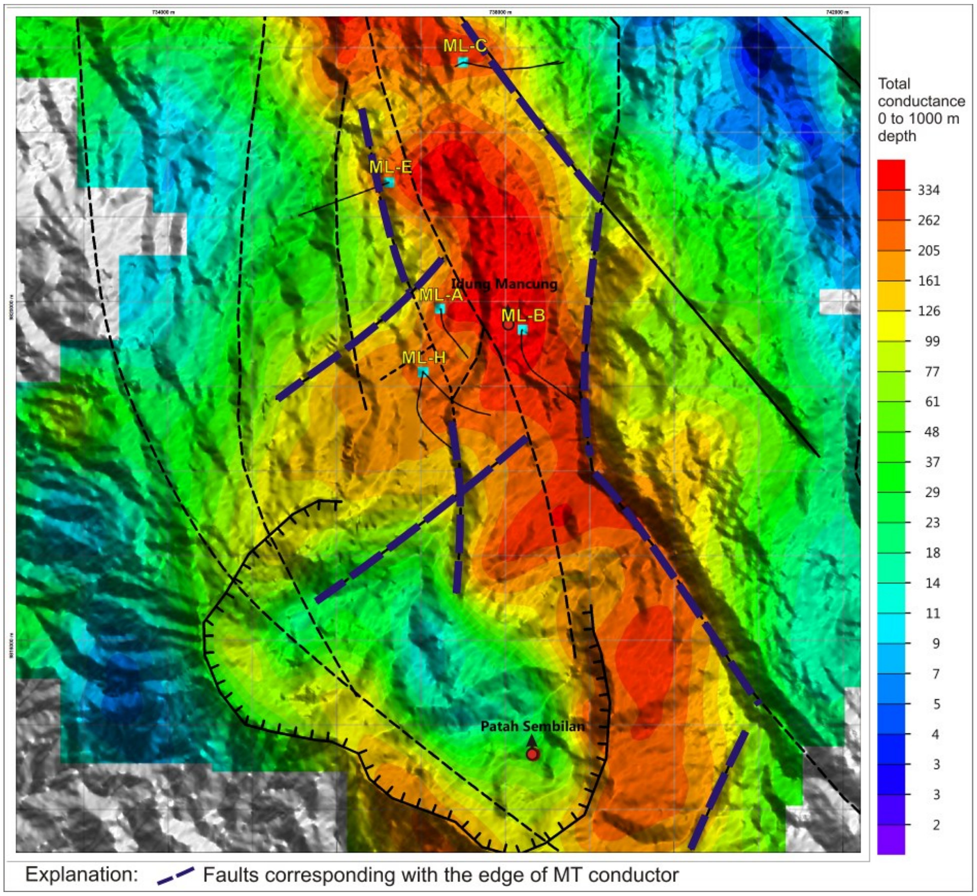

Figure 10. Total conductance map surface to 1000 m depth.

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