

TWO CONTRASTING GEOTHERMAL FIELDS IN SUMATRA, INDONESIA: MUARA LABOH AND RANTAU DEDAP

Ridwan Permana Sidik¹, Wildan Mussofan¹, Irene Wallis², Herwin Azis¹, Jim Stimac³, Novi Ganefianto¹

¹ PT Supreme Energy, Menara Sentraya, 23rd Floor. Jl. Iskandarsyah Raya No 1A, Jakarta 12160, Indonesia

² School of Environment, University of Auckland, 23 Symonds Street, Auckland Central, New Zealand

³ Stimac Geothermal Consulting, 4210 Chaparral RD, Santa Rosa, CA USA 95409

ridwan-sidik@supreme-energy.com

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ABSTRACT

Muara Laboh and Rantau Dedap share a tectonic setting but their different distances from the Intra-Arc Volcanic Barisan Mountains and Great Sumatra Fault (GSF) results in contrasting reservoir rocks, structure, and permeability. Muara Laboh is located in a pull-apart basin between two GSF segments and the reservoir is hosted dominantly in multiple granitic-dioritic intrusives, silicic volcanics, and intercalated andesitic-silicic volcanic rocks with minor sediments. Productive permeability is influenced both by NW-SE and NNE-SSW oriented faults and the geometry of intrusions, but overall the reservoir is oriented in the NW direction and parallel to the GSF. The reservoir top at Muara Laboh varies greatly in depth, and does not correlate well with the base of the conductor imaged by MT.

In contrast to Muara Laboh, Rantau Dedap is offset approximately 15 km east from the GSF and has a structure and stratigraphy that resembles the South Sumatra Back-Arc Basin. The reservoir in Rantau Dedap appears to be dominated by volcano-sedimentary rocks and includes a marine sequence that is absent at Muara Laboh. The reservoir permeability, in terms of the feedzone locations, appears highly influenced by the distribution of the brittle rhyolitic lavas that host intense fracturing. Reservoir rocks are faulted by NNW-SSE and NE-SW oriented structures that appear to be influenced by large basement faults. The reservoir is oriented in the NE direction, perpendicular to Muara Laboh and the GSF. In contrast with Muara Laboh, the reservoir top at Rantau Dedap is nearly flat. However, like Muara Laboh, reservoir top does not correlate well with the base of the conductor.

1. INTRODUCTION

Sumatra is an island in Indonesia whose modern structural setting is dominated by the NW-trending Great Sumatra Fault (GSF), a segmented, right-lateral strike-slip fault system that accommodates the oblique motion of subduction (Bellon, 2004; Figure 1). Active arc volcanoes of the Barisan Range have formed above the subducting slab and about half are within 10 km of the GSF (Acocella et al., 2018). Volcanic vents are commonly aligned parallel to and perpendicular to the GSF (where the latter is parallel to arc convergence), but the relationship between the fault system and the distribution of volcanism is the subject of debate (Bellier and Sébrier, 1994; Sieh and Natawidjaja, 2000; Acocella et al., 2018).

Around 30 high-temperature geothermal resources have been recognized in Sumatra (Hochstein and Sudarman,

1993; Muraoka, 2010) and this region is currently a focus for active geothermal exploration and development. Supreme Energy is developing two Sumatran resources (Rantau Dedap and Muara Laboh) whose geologic setting and reservoir character illustrate the diversity of this region. There are 18 wells in the Muara Laboh field and, at present, only 6 wells at Rantau Dedap. At Muara Laboh the development drilling campaign has just finished while at Rantau Dedap is has just begun.

Muara Laboh and Rantau Dedap are, respectively, located in West and South Sumatera province and are ~390 km apart (Figure 1). Both geothermal systems are thought to be associated with volcanism within the Barisan Mountain Ranges. Regional geologic maps show that the Quaternary-recent volcanic deposits are widespread in the Muara Laboh area, with Pre-Tertiary Basement just the north of field (Figure 1). Rantau Dedap is blanketed by Quaternary-recent volcanic deposits and outcropping nearby are Tertiary volcano-sedimentary formations interpreted as correlating with those found in the South Sumatera Basin provenance. One of the most significant differences between these resources is that Muara Laboh lies on the main grain of the GSF while Rantau Dedap slightly offset to the east.

Our paper summarizes the geological setting of the two resources and discusses these differences in terms of impact on permeability, the geometry of the convection cell, and the top of the reservoir. Recognition of the key differences between these resources enhances our ability to explore and develop geothermal resources within the diverse geologic settings that occur in western Indonesia's largest island.

2. TECTONIC SETTING

Muara Laboh and Rantau Dedap are situated in Sumatra where there is oblique subduction of the Indo-Australian beneath Eurasian plate. This results in partitioning of strain into a contracting fore-arc region, and transcurrent dextral offset in the main volcanic highland (the Barisan Mountains), and a series of back-arc basins (Figure 1). In contrast to the Alpine Fault in New Zealand or San Andreas Fault in California, the GSF is discontinuous, with 19 individual segments that have slip rates varying between 5 and 26 mm/yr (Sieh and Natawidjaja, 2000; Acocella et al., 2018). This segmentation creates a variety of regional to local structural settings related to segment tips and interactions, such as the pull-apart basin at Muara Laboh. Areas where segments overlap commonly show N to NE-directed extension basins. The subduction process has not only resulted the NW-SE dextral strike-slip GSF, but also accommodates the regional maximum horizontal stress and triggers reactivation of NE-SW pre-existing basement structures, which are thought to influence the structure of Rantau Dedap.

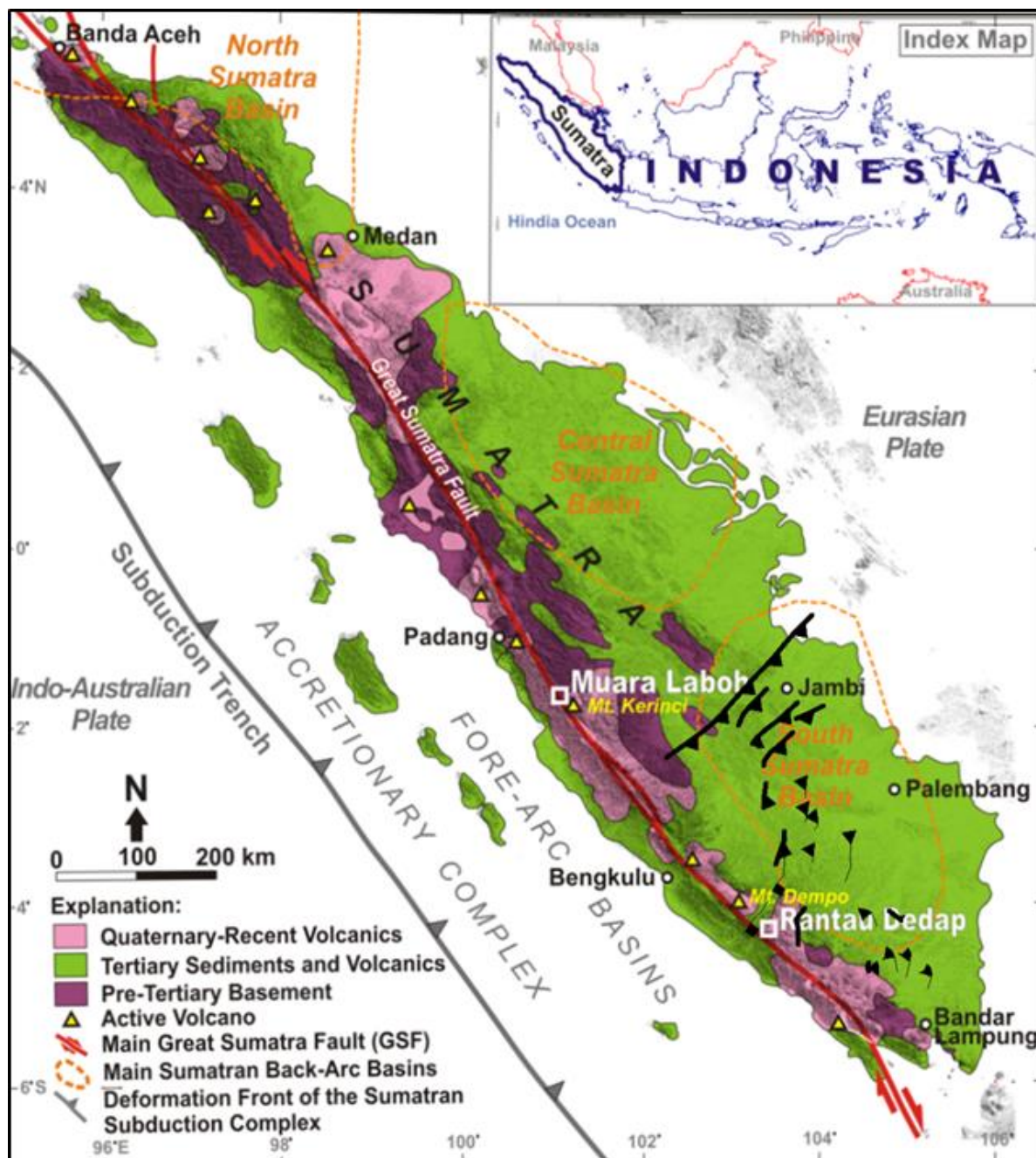


Figure 1. Regional tectonic and geology map of Sumatra (modified from Barber et al., 2005). Muara Laboh is located within the GSF zone, in a pull-apart basin, surrounded by wide-spread Quaternary-recent volcanic deposits (pink), and close to outcropping Pre-Tertiary Basement. Rantau Cedap is offset eastward from the GSF. It is located near the edge of the Quaternary-recent volcanic deposits and close to outcropping Tertiary Sediments and Volcanic deposits (green) that are part of South Sumatera Basin system. Black lines are basement structure (from Bishop, 2001; Barber et al., 2005) while the line that extends toward eastern Rantau Cedap field is referred to as the Kikim Fault.

3. STRUCTURAL SETTINGS

Muara Laboh is situated in a pull-apart basin along the NW-SE striking GSF formed within a 10 km wide step-over between the Suliti and Siulak fault segments (Mussofan et al., 2018; Figure 2). The Suliti master fault segment is obviously expressed by surface topography and it juxtaposes basement outcrops with Quaternary deposits on the northeast side of the field. The Siulak fault segment accommodates the extensional strain and appears to localize an alignment of volcanic vents in the southwest part of field. As the two dextral strike-slips fault segments propagate and interact, a depression with bounding extensional faults forms as shown

in Figure 2. Subsequent intra-basin extension forms structures oriented N-S and NNW and generated a horst and graben system (Mussofan et al., 2018). The NE-SW fault trend is interpreted to be antithetic to the GSF.

The pull-apart basin would have originally been initiated through the Tertiary-aged Painan formation (Figure 3). As the depression formed, it was infilled by a volcano-sedimentary sequence. Drilling induced tensile fractures in wellbore image logs indicate that NNE is the current maximum horizontal stress orientation (Baroek et al., 2018). Trends of open fractures interpreted from micro-resistivity image logs are mainly N-S to NE-SW within the pull-apart

basin and dominantly parallel to the GSF (NNW to NW-trending) near its margins. These local structural trends also appear to control the distribution of thermal manifestations and reservoir fluid flow direction.

The Permian-Cretaceous basement outcrops in the NE part of Muara Laboh influences the reservoir extent (Figure 2). A NE deviated exploratory well intersected this rock type at quite shallow depth (Mussofan et al., 2018) and, because this well was low permeability, it is likely that the basement defines the northeast boundary of the system.

Young volcanic vents at Muara Laboh are concentrated mainly along the SW margin of the pull-apart basin coincident with the Suliti fault segment. Based on deep wells drilled in the SW, we recognize that Tertiary and Quaternary intrusions are also present along this boundary. The highest temperature up-flowing fluid appears to be associated with young intrusions in the vicinity of the Anak Patah Sembilan volcanic center. A second, lower temperature upflow may also be occurring eastward of the first along major faults.

Rantau Dedap is 15 km east of the nearest GSF segment. Although there is a set of NW fracture orientations in wells and at surface, to date, no large NW oriented structural features have been recognized that would indicate a strong influence from the GSF. Subsequently, the relationship between the GSF and Rantau Dedap is less clear than at Muara Laboh. The main fault orientation at Rantau Dedap is ~NE, an orientation that reflects the regional basement structure which has been imaged by gravity in the South Sumatra Basin (Barber et al., 2005; Figure 1). Further work is required on the structure and kinematics of Rantau Dedap, particularly the relationship between reservoir- and regional-scale structure, and data acquired during development drilling will contribute significantly to this.

The arrangement of regional structure surrounding the Rantau Dedap resource is not yet fully resolved. Geomorphology indicates that there may be a splay of the GSF that extends east toward the edge of South Sumatra Basin (Figure 1), but the northwestward curvature of this feature is unusual given the kinematics of the GSF. There is an obvious NW-SE lineament observed in the NW sector of Rantau Dedap that extends from Mt. Dempo, and it may have some relationship to the GSF. The NE-orientated Kikim Fault, which is likely to be a reactivated basement structure, appears to emanate from the South Sumatra basin and pass just north of Rantau Dedap (Barber et al., 2005). It is possible that interaction with the Kikim Fault, or other buried NE-oriented basement structures, is responsible for the unusual orientation of the GSF splay. Further work resolving the regional structure, including the interaction between basement faults, reservoir-scale structures, and the GSF, may contribute to our understanding of what controls the localization of the Rantau Dedap reservoir.

Preliminary investigation of the natural fracture distribution in exploration wells at Rantau Dedap indicates dominant NE-SW and NW-SE fracture orientations that correspond with the fracture orientations mapped at surface. A Quaternary volcanic edifice, Bukit Besar, dominates the surface geomorphology. The field mapping on this edifice found fractures clustered in NE-SW and NNW-SSE orientations (Sidik et al., 2016). However, NE-SW

fractures/faults found at the surface may also indicate that old, basement structures have been reactivated upward through the recent volcanic deposits. Additional Quaternary-age volcanic centers extend from Bukit Besar to the ENE, including a large silicic dome and flow complex (Anak Gunung: see Figure 5&6).

3. STRATIGRAPHIC CONTEXT

3.1 Regional and Local Geology

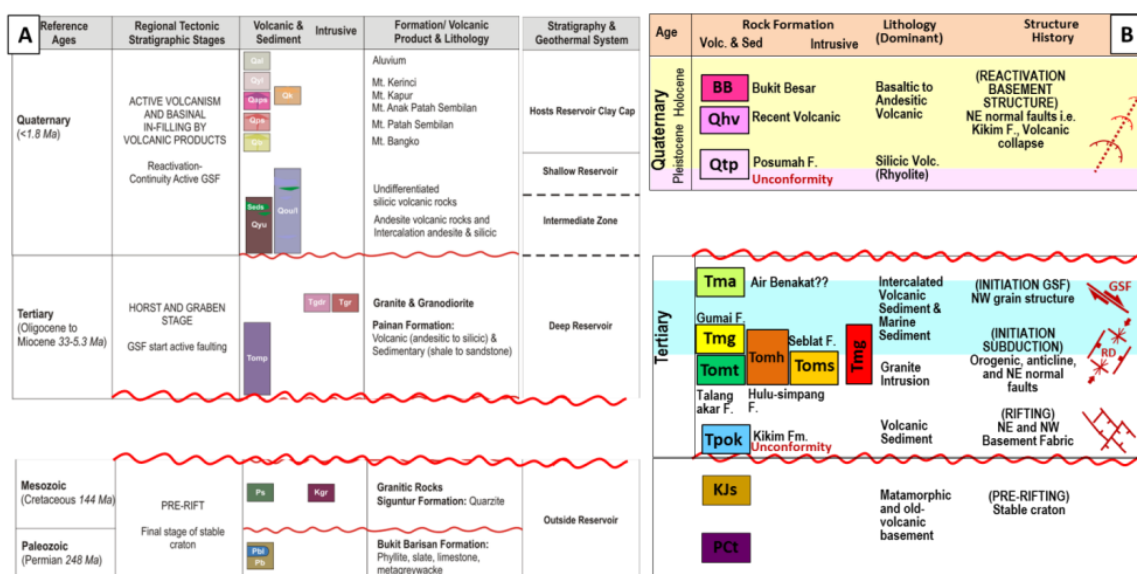
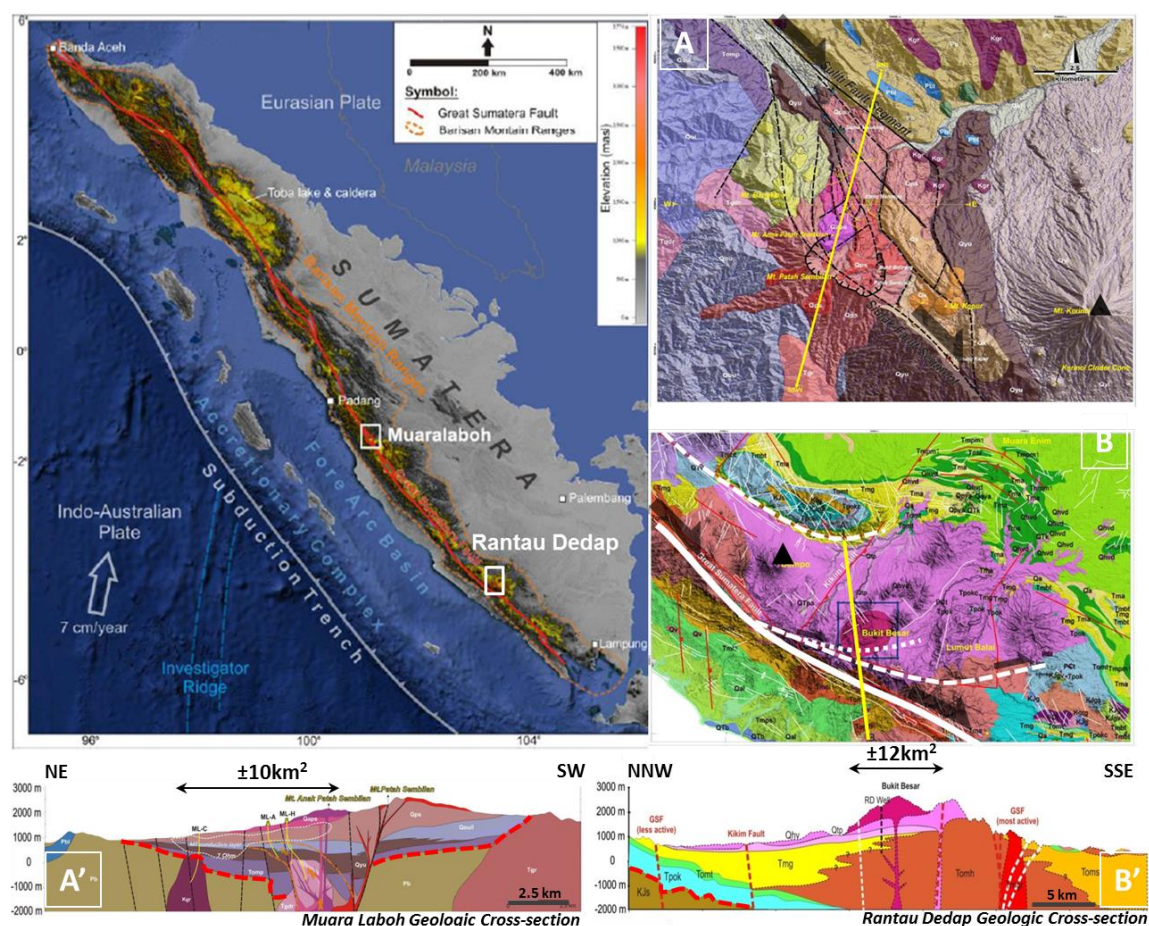
The regional stratigraphy of both reservoirs is summarized in Figure 3. In summary, the main stratigraphic difference between Rantau Dedap and Muara Laboh results from the latter being a progressively extending depocentre (i.e., the pull-apart basin), whereas the former is a relatively flat Tertiary terrain mantled by quaternary volcanics. Based on a number of prominent arcuate scarps at Rantau Dedap, these young deposits may also conceal older caldera collapse structures.

The stratigraphy of the Muara Laboh can be divided into a Permian to Cretaceous-age basement that is intersected by and overlain with a sequence of Tertiary intrusions, volcanics and sediments. Those units are covered by Quaternary andesitic to silicic rocks. As mentioned above, Cretaceous Granite was intersected by one of exploratory wells in the northern sector of the field at a quite shallow depth and the intersection is quite close to where Cretaceous Granite outcrops at the surface. The basement sequence (Paleozoic Barisan Formation; Pb/l), intruded by Cretaceous Granite; Kgr outcrops 8 to 10 km north and east of Muara Laboh (Figure 2).

Rantau Dedap regional geology consists of Tertiary aged andesitic volcanic rocks intercalated with sandstone referred as the Hulusimpang formation (Tomh) which is intruded by granitic rock (Tmgr). The granitic intrusions are distributed along the GSF. An interfingering relationship was likely to be forming while the Hulusimpang formation was deposited. Toward the north, this formation is mixed with the Gumai formation (Tmg) while in the south it is mixed with the Seblat formation (Toms). The Seblat formation consists of marine sediments and the Gumai formation (Tmg) consists of mixed marine sediments and volcanoclastic deposits (Gafoer et al., 1992: published Geological Map of Bengkulu sheet, Sumatra). These Tertiary rock units are covered by Quaternary andesitic-basaltic volcanic rocks from various sources. The active Mt. Dempo volcano may be one of the sources of this young volcanic deposit (Amin et al., 1993: published Geological Map of Manna and Enggano sheet, Sumatra).

There is an interpreted unconformity between the Quaternary andesitic-basaltic and Tertiary intercalated andesitic-sandstone that relates to a period of shortening and mountain building (Barisan Mountains) that occurred in response to the initiation of subduction. Although the unconformity is above the top of reservoir, it may be a useful stratigraphic marker and could operate as a weak zone of possible horizontal permeability.

Unlike Muara Laboh, no pre-Tertiary basement rocks have been intersected by drilling completed to date at Rantau Dedap. Outcropping basement has also not been located by surface geological surveys, though no radiometric ages have been determined for mapped units.



4. KEY RESERVOIR ELEMENTS

4.1 Reservoir-hosting Rock Types

Muara Laboh and Rantau Dedap have different reservoir host rocks. In Muara Laboh, there are two reservoir areas: one with dominantly structurally-influenced permeability (shallow NE) and the other associated with a series of intrusions (deep SW). The structurally-influenced reservoir area has permeability dominantly hosted in Quaternary undifferentiated silicic volcanic rocks and the intrusive-related area is a Mesozoic to Tertiary granodiorite to diorite intrusion complex, cut locally by younger dikes and surrounded by andesitic-composition volcanics (Figure 2; see the cross section).

Meanwhile, Rantau Dedap is hosted in Tertiary-aged mixed marine sediments with layers of silicic and andesitic volcanic rock. Because these rocks pre-date the initiation of subduction, they record a complex structural/tectonic history. Unfortunately, because total losses were experienced in all wells, the relationship between feed zones and this interfingering sequence of mixed marine sediments and volcanic deposits is uncertain. The clay cap is hosted within the Quaternary volcanic deposits.

4.2 Controls on Permeability

Muara Laboh has distinct shallow and deep reservoir sectors. The shallow NE reservoir is capped by the Patah Sembilan volcanic complex, with the highest reservoir permeability localized near the base of those deposits and in the top of the underlying silicic volcanic rocks. The deep SW reservoir is dominated by a plutonic complex that represents multiple stages of stock intrusion, and later-stage microdiorite dikes. 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 lends weight to our interpretation that hydrothermal circulation is occurring along the trend of vents (Mussofan et al., 2018).

Baroek et al. (2018) describe two preferred fracture orientations associated with the feedzones in the Muara Laboh reservoir. NE-SW and N-S fractures are commonly found in the shallow reservoir with minor NW-SE trends. Meanwhile, NW-SE fracture trends are dominant in the deep SW reservoir, which is interpreted to be influenced by the GSF. Deep feedzones have been identified either within intrusions or at or near intrusion contacts (Figure 4). N-S and NE-SW fracture trends identified in both the shallow and deep reservoirs are thought to be associated with step-over faults antithetic to the GSF. The occurrence of NE-SW striking fractures in both the deep and shallow reservoir suggests this trend is relatively young.

Development at Rantau Dedap is in an earlier stage than Muara Laboh, and so the controls on permeability are less well known. Furthermore, as mentioned above, understanding the relationship between geology and permeability is hampered by drilling losses that led to an absence of drill cuttings returns from the deepest parts of all wells drilled to date. Preliminary analysis of image logs acquired in the deep sections of four wells has, however, indicated that there is a strong lithologic control on the distribution of permeability. The fracture distributions at feedzones include NW, NNW to NS, and NE orientations (Figure 5). The feedzone distribution at Rantau Dedap varies in depth, but the shallowest zone in almost all wells is

around 1000 masl (Figure 6), consistent with the observations of lithologic control at depth.

4.3 Reservoir Geometry

The different degree of influence of the GSF in the two resources is most apparent in their overall geometry. The outflows of both reservoirs are oriented along the local structural trends. The Muara Laboh reservoir is oriented N to NNW, parallel with the GSF segments that bound the stepover which contains the reservoir. The long, narrow outflow at Muara Laboh appears to be strongly influenced by structure. In contrast, Rantau Dedap is oriented to the NE, parallel to a broadening in the volcanic arc. This orientation reflects both NE basement faults and the Kikim Fault (Figure 6).

4.3. Top of Reservoir

Muara Laboh has a shallow reservoir top (i.e., top of the convecting portion of the resource) on the NE side that plunges down to the SW. In contrast, Rantau Dedap has a flat reservoir top that has a slightly higher elevation to the S (toward the upflow). However, both reservoirs show a complex alteration history that has impacted the current depth to the top of the reservoir.

The top of reservoir is commonly controlled by the distribution of smectite alteration (Cumming, 2009). However, both Muara Laboh and Rantau Dedap show poor correlation between the reservoir top and the base of the smectite-altered zone (Dyaksa et al., 2016). Muara Laboh has a ~300 m discrepancy in the SW area between the reduction in smectite alteration and the top of the convecting reservoir. Analysis of alteration minerals indicate that the deepening of the reservoir top is likely to be due to plugging of permeability due to boiling and ingress of peripheral waters, perhaps caused by sector collapse of the adjacent Patah Sembilan volcano. Similar permeability reduction in response to boiling has been recognized at Karaha-Telaga Bodas and is also interpreted as the consequence of sector collapse (Moore et al., 2008).

Dyaksa et al. (2016) describes the Rantau Dedap 3D MT inversion and these data showed good correlation with the hydrothermal clay cap distribution and overall reservoir geometry. At Rantau Dedap, the base of smectite clay alteration (i.e., base of the clay cap or conductor) is as shallow as 100-400 masl whereas the top of the reservoir occurs at an elevation of about 1000 masl across the resource. The discrepancy is a thick transition alteration zone (interlayered clays) and this transition is consistent across the field. The reason why this thick zone of transition alteration exists is not yet clear. In addition, epidote, a mineral that is typically used as an indicator of the hot reservoir temperature, is not a reliable indicator in this case. Petrographic analysis confirmed that epidote is relict or has been partly replaced by chlorite (corroded/outlining epidote edge by chlorite; Dyaksa and White, 2015). Moreover, recent petrographic analysis suggests that the epidote is found in propylitically altered clasts that were deposited with the mixed marine sediment. The mechanism that controls the reservoir top and the distribution of hydrothermal alteration at Rantau Dedap is the subject of ongoing work.

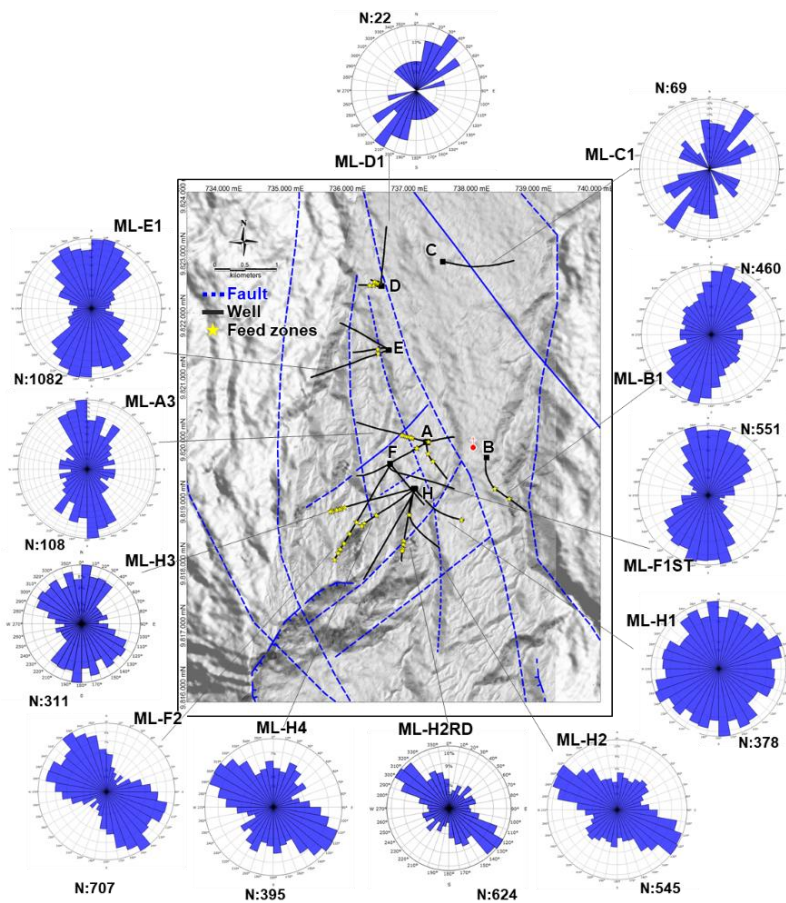


Figure 4. (left) Rose diagrams showing the strike orientations of both conductive and partially conductive fractures interpreted from image logs (i.e., fractures that are either open or filled with conductive minerals such as clay). The dominant trends in these data are NW-SE, N-S and NE-SW, and the orientations are similar faults that have been identified using offsets in well geology and surface mapping. Yellow stars on the welltracks highlight feedzone location (from Baroek et al., 2018).

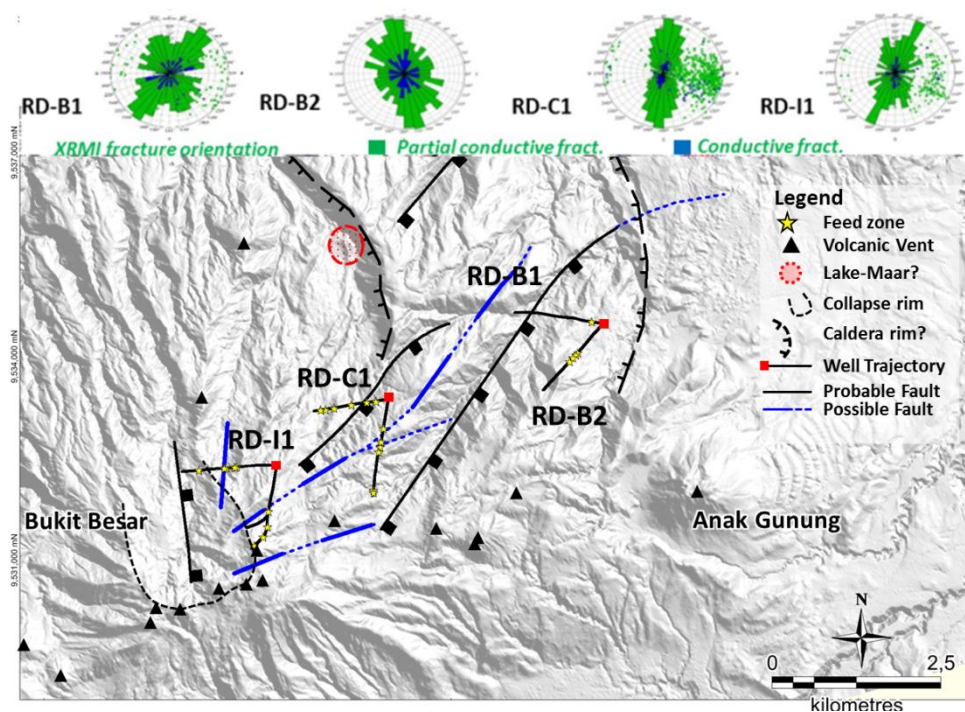


Figure 5. (left) Distribution of conductive and partially conductive fractures from Rantau Dedap wells. Data acquisition is mostly from near feedzones (yellow stars).

5. CONCLUSION

Analysis of surface and subsurface data at two Sumatran geothermal systems has shown them to have both similar and contrasting characteristics including:

1. The Great Sumatra Fault system appears to have a different degree of control in Muara Laboh and Rantau Dedap. Permeability in the Muara Laboh is generated within a step-over of the GSF system. In contrast, while Rantau Dedap may be influenced by the splay of the GSF, it appears to be more influenced by a reactivated NE-orientated basement structure and broadening of the volcanic arc.
2. Both reservoirs appear to have outflows that are strongly controlled by local structure, but at Muara Laboh the outflow is to the NW (reflecting the GSF) and at Rantau Dedap the outflow is NE (reflecting the regional basement fault trend and the Kikim Fault).

3. The top of a reservoir in Muara Laboh and Rantau Dedap both show poor correlation with the base of the smectite-altered zone, probably because of complex, overprinting alteration histories.

Development drilling at Muara Laboh concluded in June 2018 and the data acquired during this time revealed much about the resource. Development drilling at Rantau Dedap began in August 2018 and, no doubt, more will be learnt about this reservoir during this campaign.

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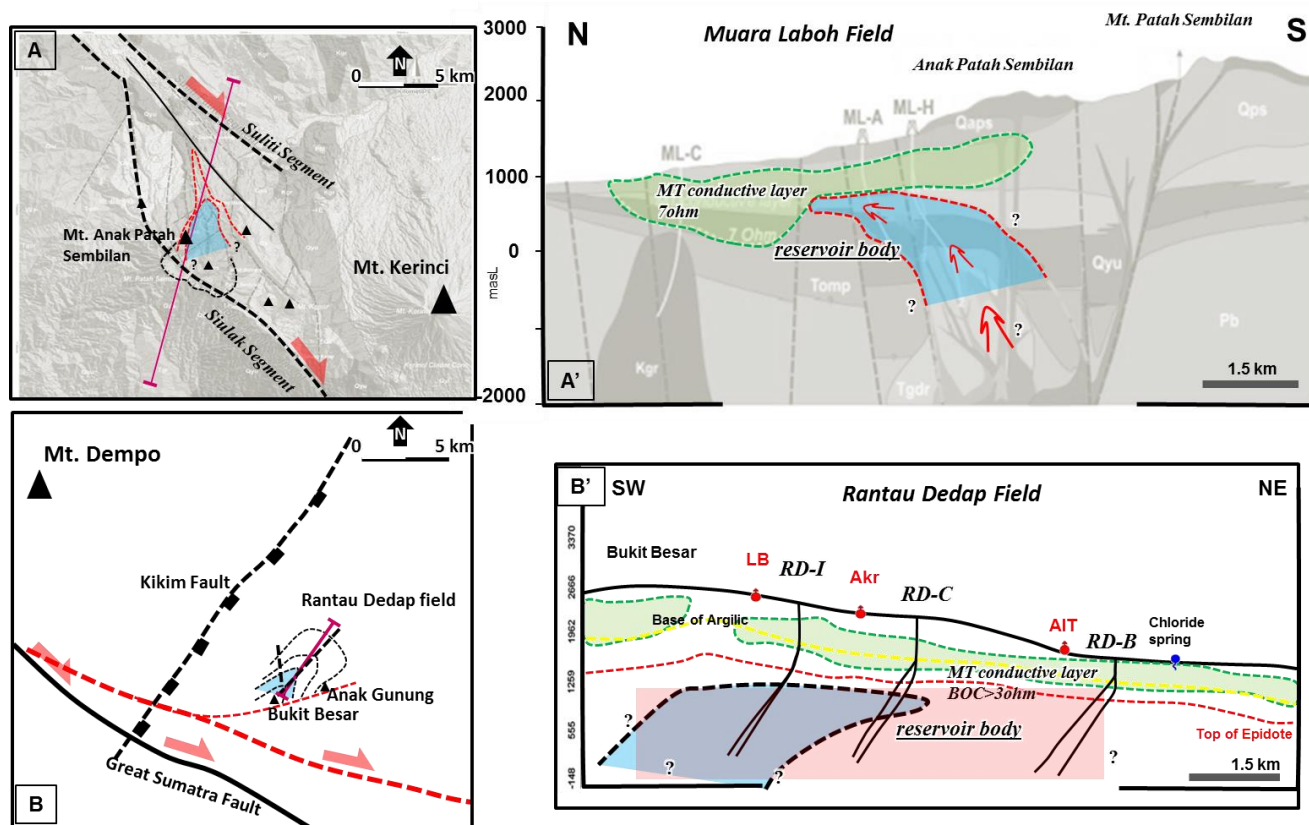


Figure 6. Reservoir geometries at Muara Laboh and Rantau Dedap fields reflect the different degree of influence from the GSF. Rantau Dedap cross section (panel B': NE-SW) was modified from Dyaksa et al. (2016), while the Muara Laboh cross section (panel A': N-S) was modified from Mussofan et al. (2018). Purple lines on the maps indicate the position of the cross section. The dashed red line in panel B is an interpreted fault that possibly associated with volcanic vent distribution.

REFERENCES

- Acocella, V., Bellier, O., Sandri, L., Sebrier, M., Pramumijoyo, S.: Weak Tectono-Magmatic Relationships along an Obliquely Convergent Plate Boundary: Sumatra, Indonesia. *Frontiers in Earth Science* 6:3, doi: 10.3389/feart.2018.00003. (2018).
- Amin, T.C., Kusnama., Rustandi, E., Gafoer, S.: *Geological Map of The Manna and Enggano Sheet, Sumatra. Scale 1:250,000.* Geological Research and Development Centre. (1993).
- Barber, A.J., and Crow, M.J.: Chapter 13: Structure and structural history. In: Barber, A.J., M.J. Crow, and J.S. Milsom (eds) *Sumatra: Geology, Resources and Tectonic Evolution.* Geological Society, London, Memoirs 31, p 229. (2005).
- Baroek, M., Stimac, J., Sihotang, A.M., Putra, A.P., Martikno, R.: Formation and Fracture Characterization of the Muara Laboh Geothermal System, Sumatera, Indonesia. *GRC Transactions*, Vol. 42. (2018).
- Bellier, O., Sébrier, M.: Relationship between tectonism and volcanism along the Great Sumatran fault zone deduced by SPOT image analyses: *Tectonophysics*, v. 233, no. 3, p. 215-231. (1994).
- Bellon, H., Maury, R.C., Sutanto., Soeria-Atmadja, R., Cotton, J., Polve, M.: 65 m.y.-long magmatic activity in Sumatra (Indonesia) from Palaeocene to Recent. *Bulletin de la Societd geologique de France*, 175, 61-72. (2004).
- Bishop, M.G.: South Sumatera Basin Province, Indonesia: The Lahat/Talang Akar-Cenoic Total Petroleum system. *United States Geological Survey Open-File Report 99-50-S.* (2001).
- Cumming, W.: Geothermal Resource Conceptual Models using Surface Exploration Data. *Proceedings, 34th Workshop on Geothermal Reservoir Engineering, SGP-TR-187.* (2009).
- Dyaksa, D.A., White, P.: Relict and Modern Epidote: Lessons from Rantau Dedap, Sumatera, *Proceedings 37th New Zealand Geothermal Workshop*, Taupo, New Zealand. (2015).
- Dyaksa, D.A., Ramadhan, I., Ganefianto N.: Magnetotelluric Reliability for Exploration Drilling Stage: Study Cases in Muara Laboh and Rantau Dedap Geothermal Project, Sumatera, Indonesia, *Proceedings, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-209. (2016)
- Gafoer, S., Amin, T.C., Pardede, R.: *Geological Map of the Bengkulu Quadrangle, Sumatra. Scale 1: 250.000.* Geological Research and Development Centre. (1992).
- Gafoer, S., Cobrie, T., Purnomo, J.: *Geological Map of The Lahat Quadrangle, Sumatra. Scale 1: 250.000.* Geological Reserch and Development Centre. (1986).
- Gafoer, S., Amin, T.C., Pardede, R.: *Geological Map of the Baturaja Quadrangle, Sumatra. Scale 1: 250.000.* Geological Research and Development Center. (1993).
- Hochstein, M., and Sudarman, S.: Geothermal resources of Sumatra: *Geothermics*, v. 22, no. 3, p. 181-200. (1993).
- Jones, C.G., and Moore, J.N.: Hydrothermal Alteration at the Rantau Dedap Geothermal System, South Sumatra, Indonesia. *Unpublish report to Supreme Energy.* (2017).
- Moore, J.N., Allis, R. G., Nemcok, M., Powell, T.S., Bruton, C.J., Wannamaker, P.E., Raharjo, I. B., Norman, D.I.: The Evolution of Volcano-Hosted Geothermal Systems based on Deep Wells from Karaha–Telaga Bodas, Indonesia: *American Journal of Science*, v. 308, p. 1-48. (2008)
- Mussofan, W., Baroek, M.C., Stimac, J., Sidik, R.P., Ramadhan, I., Santana, S.: Geothermal Resource Exploration along the Great Sumatera Fault Segment in Muara Laboh: Perspectives from Geology and Structural Play. *Proceedings, 43rd Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-213. (2018).
- Muraoka, H., Takahashi, M., Sundhoro, H., Dwipa, S., Soeda, Y., Momita, M., Shimida, K: Geothermal Systems Constrained by the Sumatran Fault and Its Pull-Apart Basins in Sumatra, Western Indonesia. *Proceedings World Geothermal Congress.* Bali, Indonesia. (2010).
- SERD,: Detail Surface Mapping and Structure Geology Evaluation Services of Rantau Dedap Geothermal Field. *Unpublished report.* (2016).
- Sidik, R.P., Mussofan, W., Santana, S., Azis, H.: Structure geology of southwestern sector Rantau Dedap Geothermal Field”. *Proceedings Annual 4th Indonesia International Geothermal Convention & Exhibition*, Jakarta. (2016).