# THICK SILICIC VOLCANIC SEQUENCES AT MUARA LABOH AND RANTAU DEDAP GEOTHERMAL FIELDS, SUMATRA, INDONESIA: IMPLICATIONS FOR RESERVOIR ARCHITECTURE AND PERMEABILITY

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## ABSTRACT

Thick silicic tuff sequences and silicic intrusives are found in deep wells drilled at the Muara Laboh and Rantau Dedap Geothermal Fields, Sumatra, Indonesia. Petrographic and petrophysical investigation of cuttings, core, gamma ray and image logs were used to understand the silicic stratigraphic controls on reservoir permeability. Regional geologic constraints and limited U-Pb zircon ages show that silicic explosive volcanism most likely occurred mainly during the Miocene to Plio-Pleistocene, and locally continuing into the Holocene. Wells in both fields show that silicic tuff sequences reach thicknesses of 500 to >1000 meters, and silicic intrusive complexes intrudes to reservoir depths. In Muara Laboh, thick silicic tuffs are found in a basin generated between major strike-slip fault segments. The dominant rock type is variably welded to non-welded silicic ash-flow tuff with a variety of devitrification textures. A long-lived sheared and altered granite-granodiorite-microdiorite intrusive complex representing multiple magmatic episodes (96 to 20 Ma) occurs in the SW sector of the field. In Rantau Dedap, similar silicic tuff sequences are found as caldera fill deposits overlain by debris flows. A weakly altered, poorly deformed granite to granodiorite intrusive complex occurs at depth. The silicic volcanics have high resistivity in image logs, fine fragmental textures (tuffs) to massive textures (intrusives), and high gamma ray counts (65 to 200 API) in both fields. Fracture intensity of the thick silicic tuff sequences increases with welding, primary devitrification, and possibly the thickness and cooling history of individual eruptive units. Major feed zones are associated with faulted lithological contacts and very limited at thick silicic tuffs in Muara Laboh. Fluid entries at Rantau Dedap are most abundant in the relatively thin Upper Rhyolite Tuff and underlying Dacite Tuff, and near the basal contact of the thick Lower Dacite Tuffs with intrusions. Permeable zones are encountered at the margin of the intrusive complexes in both fields.

## 1. INTRODUCTION

Silicic volcanism in Sumatra has occurred from the Paleozoic to Quaternary-Recent time. **Figure 1** shows the distribution of silicic volcanic deposits based on a regional compilation of Sumatra geology at 1:250,000 scale (maps published by the Geological Research and Development Center, Indonesia, between 1975 and 1996). Silicic volcanic formations are significant to geothermal development in Sumatra because they frequently form significant portions of reservoir host rocks in many fields, e.g. Muara Laboh, Rantau Dedap and Sarulla-Silangkitang (Gunderson et al., 2000, Mussofan et al., 2018, Baroek at al., 2018, Sidik et al., 2018, Stimac et al., 2019a and b) (**Figure 1**).

Sumatra and the adjacent Sunda Strait are well known as the site of large Quaternary silicic eruptions from calderas like Toba and Krakatau (Chesner, 2012; Mandeville et al., 1996). However, there are few detailed studies on the silicic volcanic formations and their relationship to geothermal reservoir permeability in Sumatra.

At the Silangkitang Geothermal Field, silicic volcanic rocks ranging in age from 0.1 to 1.8 Ma fill a graben along the GSF (Gunderson et al., 1995). Based on cross sections in Moore et al. (2001) and Drestanta et al. (2018), more than 1.5 km of dominantly silicic volcanics accumulated in this graben and serve as the main host rock for the geothermal system (Gunderson et al., 2000). Permeability in this sequence is largely restricted to the highly fractured zones near the main fault traces (Moore et al., 2001). At Danau Ranau, the silicic Ranau Tuff has been dated at 33,830–33,450 years BP using the $^{14}C$ method (Natawidjaja et al., 2017). Numerous other less well studied systems are likely to have silicic volcanic reservoir rocks. In some cases, they are known but not dated or studied in detail (e.g. Sibayak, Sorik Merapi, Lumut Balai, Ulubelu), and in others anticipated from surface exposures (e.g., Suoh-Sekincau, Rajabasa) (**Figure 1**).

The reservoir in Muara Laboh is hosted in a granite-granodiorite intrusive complex (96 to 20 Ma), and andesite volanics interlayered with thick silicic (dacite to rhyolite) tuff sequences dated at ~3 to 0.5 Ma (Stimac et al., 2019b). The reservoir in Rantau Dedap is hosted in Tertiary aged mixed marine sediments with thick layers of silicic and andesitic volcanic rocks (Sidik at al., 2018). In this paper we describe the geologic constraints including stratigraphy, structure and physical characteristics of the silicic tuff sequences and silicic intrusions at Muara Laboh and Rantau Dedap Geothermal Fields to better understanding their controls on geothermal reservoir permeability.

## 2. GEOLOGIC SETTING

Both Muara Laboh and Rantau Dedap Geothermal Fields are located in Sumatra, the largest island in western Indonesia. Muara Laboh is located about 135 km SE of the capital city of Padang, West Sumatra Province, and Rantau Dedap is located about 200 km SW of Palembang, the capital city of South Sumatra Province (**Figure 1**).

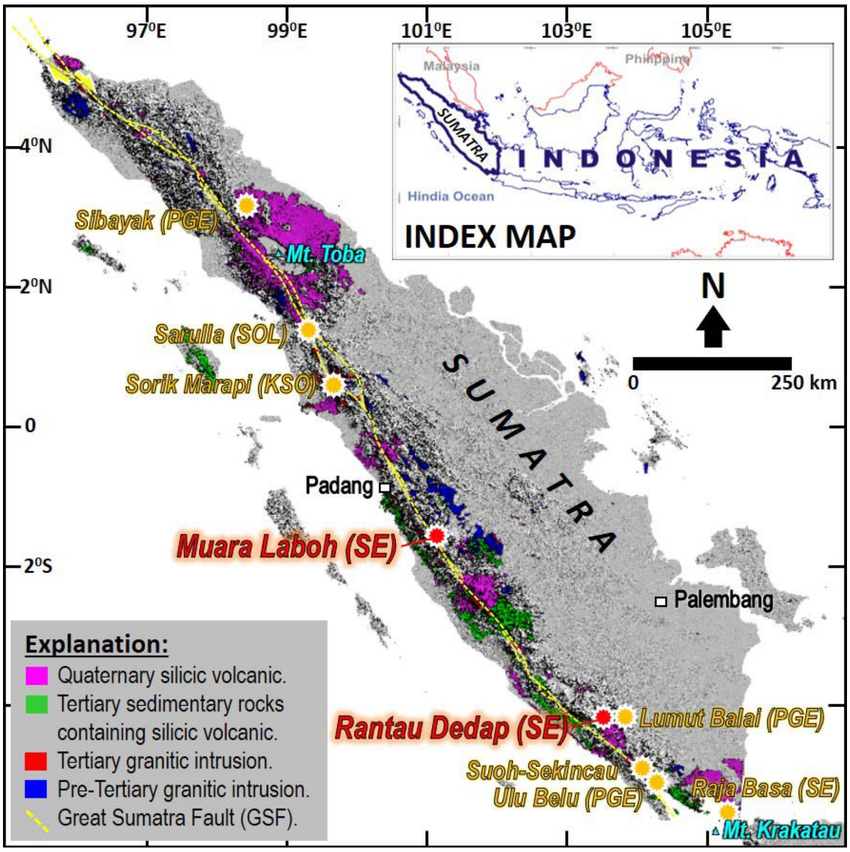


**Figure 1. The distribution of silicic volcanic rocks in Sumatra, Indonesia. Pre-Tertiary (Paleozoic-Mesozoic) granitic rocks are exposed on both sides of Great Sumatra Fault (GSF). Exposures of Tertiary volcano-sedimentary formations containing silicic volcanic tuffs and ignimbrites are obscured by younger overlying volcanic and volcaniclastic rocks of dominantly andesitic composition. Tertiary granites to granodiorites were emplaced along the main corridor of GSF and interpreted intruding the pre-existing Tertiary volcanic and sediments. Quaternary silicic products are found in broader areas, some associated with surrounding caldera eruptive centers including Krakatau (Mandeville, 1996) and Toba (Chesner, 2012). Geothermal systems mentioned in the text are shown along with abbreviation of the operators (SE, Supreme Energy; PGE, Pertamina Geothermal Energy; SOL, Sarulla Operation Limited; KSO, KS ORKA).**

The geologic settings of Muara Laboh and Rantau Dedap are strongly controlled by the movement of Great Sumatra Fault (GSF), as well as magmatism, volcanism, and sedimentation processes. Sieh and Natawidjaya (2000) and Muraoka et al. (2010) studied the topographic features of the trace of the GSF and concluded that it is highly segmented with pull-apart basins at segmented boundaries and near clustered volcanoes. Barber et al. (2005) and references therein estimated that the GSF became active during the Miocene. Sieh and Natawidjaya (2000) interpreted that the NW-SE strike-slip movement of GSF results in the maximum horizontal displacement of about ~20 km distance but varies in each location.

### 2.1 Muara Laboh Geology

The geology of Muara Laboh has been described in detail by Mussofan at al. (2018), Baroek et al. (2018), and Stimac et al. (2019a and b). Muara Laboh is located within a step-over of two GSF segments: Suliti fault segment in the north and Siulak fault segment in the south (**Figure 2**). This step-over generates a ~7 km wide extensional pull-apart basin, bounded by Pre-Tertiary basement (Mussofan et al., 2018). The basin is filled with the Painan Formation (Tomp), based on K-Ar ages of Miocene (23.7 to 14.3 Ma) (Bellon et al., 2004). Rosidi et al. (1996) described this formation as consisting of basaltic-andesitic lava, silicic dacitic-rhyolitic tuff, ignimbrites and sedimentary rocks. During the Plio-Pleistocene, younger undifferentiated silicic volcanic (Qou/l) sequences consisting of volcanic rhyolitic tuff and lava were deposited, infilling the western part of the Muara Laboh basin. Concurrently, andesitic products (Qyu) and sediments (Seds) filled the eastern part of the Muara Laboh basin (**Figure 6**). Quaternary andesitic products from several eruption centers along the southern Siulak fault segment erupted mainly lava flows to the north covering almost the entire Muara Laboh field.

The primary structural trends affecting the reservoir in Muara Laboh are NW-SE, N-S and NE-SW, interpreted to be associated with GSF (Baroek et al., 2018). The NW-SE trend is parallel to the GSF, whereas the N-S and NE-SW trends are thought to be younger and more developed mainly due to the stepover mechanism between the two GSF segments.

The Muara Laboh geothermal system has two main reservoir sectors – the NE and SW sectors – with a narrow outflow to the NE. Overall, the system interpreted to be a mix between intrusion-related and fault-controlled systems (Stimac et al., 2019), where the NE sector including the outflow has shallow permeability which is more fault- and fracture-controlled and the SW sector has deep permeability which is associated with intrusion margins. The Tertiary granitic-granodiorite intrusions (Tgr-Tgdr), the Oligocene to Miocene Painan Formation, the Plio-Pleistocene silicic and andesitic volcanic sequences are the main reservoir rocks and the Quaternary Patah Sembilan andesitic products mainly host the clay cap overlying the reservoir.

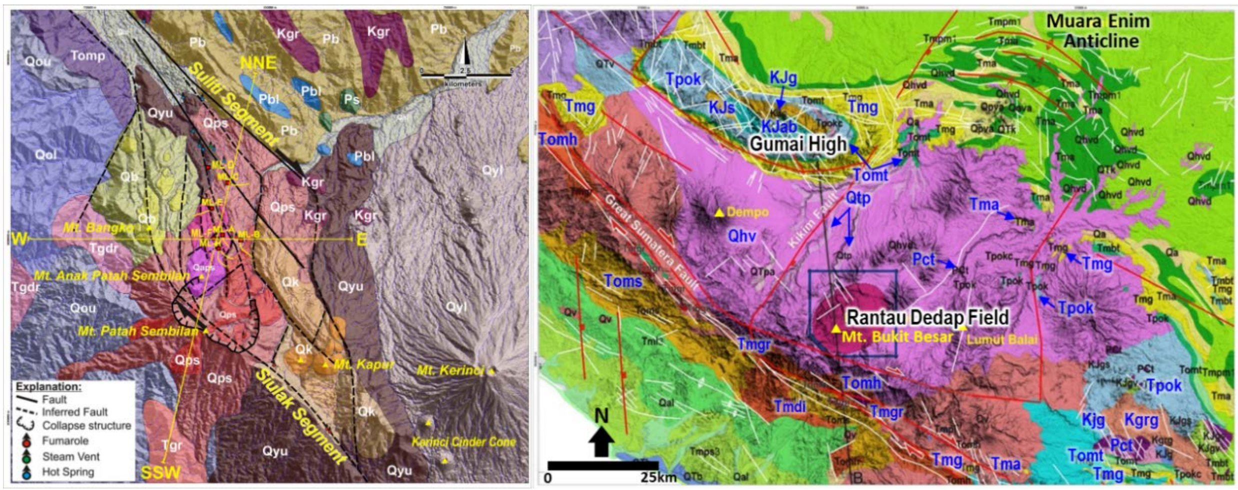


**Figure 2. Geologic maps of Muara Laboh (left) and Rantau Dedap (right). Lines section are shown for geologic cross sections presented in Figure 5.**

### 2.2 Rantau Dedap Geology

The Rantau Dedap Geothermal Field is located 15 km to the northeast of the main GSF corridor. The field is located within a volcanic complex which is characterized by a sedimentary basin to the north and high mountainous terrain to the south. Regional geology shows an anticline called the Gumai High ~35 km to the north composed of Mesozoic ultramafic rocks and Tertiary volcanio-sedimentary rocks including Kikim (Tpok) and Gumai Formations (Tmg) (**Figure 2**). On the southern margin of the field, the GSF bends slightly and truncates high mountainous terrain containing silicic volcanics of the Hulusimpang Formation (Tomh), based on K-Ar ages of Miocene (13.2 to 10.9 Ma) (Bellon et al., 2004).

The geology of Rantau Dedap consists of Tertiary aged andesitic to silicic volcanic rocks of the Hulusimpang Formation, intercalated with marine sediments of the Seblat Formation and the Gumai Formation consisting of mixed marine sediments and volcaniclastic deposits intruded by granitic rock (Tmgr) (Sidik et.al, 2018). These Tertiary units are covered by Quaternary andesitic-basaltic volcanic rocks from multiple vents (e.g. Bukit Besar, Anak Gunung and nearby active Mt. Dempo volcano).

The structural setting is associated with NE-SW, NW-SE and N-S fault trends, and circular features. These structures control the locations of all surface manifestations suggesting these structures might control reservoir permeability as well (Santana et al., 2013). Geothermal heat sources in Rantau Dedap are predicted to be related to intrusives beneath the satellite vents. Geothermal fluids ascend vertically via permeable pathways that were created by a combination of caldera rims and younger cross-cutting fault structures, whereas lateral outflow paths at the top of the reservoir are stratigraphically-controlled by welded silicic tuffs overlain by less permeable debris flows. As in Muara Laboh, the clay cap is hosted within the younger Bukit Besar Andesite at Rantau Dedep, and a thick transition alteration zone also occurs within andesitic to dacitic tuff sequence and the underlying debris flow (Dyaksa et al., 2013).

## 3. WELL STRATIGRAPHY

Individual well stratigraphy in Muara Laboh and Rantau Dedap is defined based on a combination of well geology and drilling data including cuttings and core descriptions in the wellsite, lithology and alteration mineralogy from petrographic analysis, XRMI image log (resistivity rock textures and fracture picking), gamma ray log, alteration mineralogy by x-ray diffraction (XRD), mechanical specific energy (MSE), drilling losses and feed zone locations (see Stimac et al., 2019b, Figure 5). The stratigraphic logs from individual wells were correlated across the field to better understand the distribution of the silicic volcanic sequence in the reservoir (**Figure 3**). Rhyolitic tuffs found in almost all wells were used as a marker bed to aid in well correlation across the field.

Fieldwide stratigraphy in Muara Laboh includes a silicic intrusion complex at the bottom of wells composed of granite, granodiorite and diorite (**Figure 3**). U-Pb age dating of zircon shows these altered and deformed intrusions have Late Cretaceous (96.1 Ma) and early Miocene (20.8 Ma) ages (Stimac et al., 2019b). This intrusive complex is overlain by, and possibly intruding, a lower basalt-andesite and a lower rhyolite that is likely a Pre-Painan Formation with predicted ages of Tertiary-Oligocene. This formation was then covered by mixed andesite and dacite volcanics of the Painan Formation (23.7 to 14.3 Ma). Overlying the Painan Formation is the younger Undifferentiated Silicic Formation (USF), which appears to have been deposited from ~3 to 0.5 Ma.

In Rantau Dedap, similar to Muara Laboh, an intrusive complex was found near the bottom of most deep wells ranging in composition from granite to granodiorite (**Figure 3**). These intrusions show significantly less intense alteration and deformation textures than those at Muara Laboh, suggesting that they were emplaced more recently. Dacite porphyry intrusions are also locally present. This plutonic complex is overlain by, and possibly intruding, the Lower Andesite and Rhyolite units that are interpreted as Kikim Formation. Overlying this formation is a thick silicic volcanic sequence including mixed Sediment and Tuff, Upper Dacite and Rhyolite Tuffs and a sub-aqueous debris flow sequence of bulk andesitic to dacitic composition, interpreted as the Hulusimpang Formation. Covering this formation are more subaqueous andesite to dacite lavas, tuff, and hyaloclastites deposited in water interpreted as the Posumah Formation. Andesitic volcanic deposits of the Mt. Bukit Besar complex are found covering the older silicic sequences. Currently we lack absolute ages constraints on the Rantau Dedap well stratigraphy, but U-Pb zircon dating is planned.

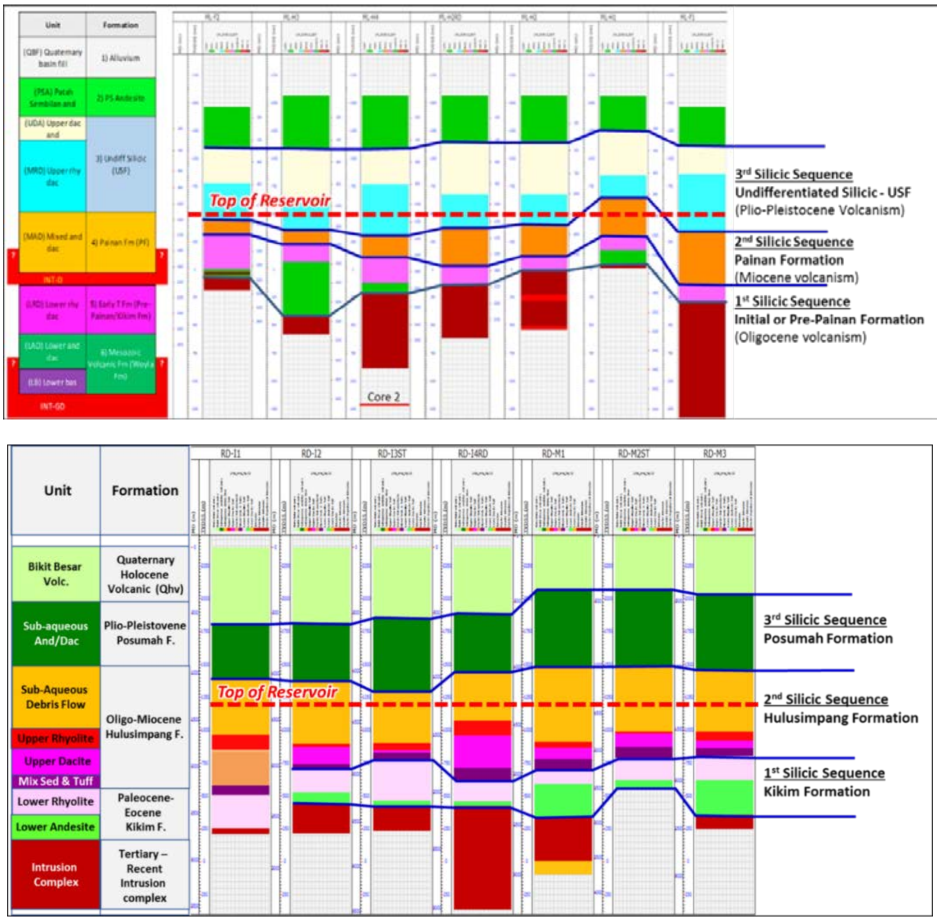


**Figure 3: Well stratigraphic units and correlated regional formations in Muara Laboh (Top) (from Stimac et al., 2019b) and Rantau Dedap (Bottom).**

In a surface exposure, a sequence of young fallout tuffs overlying the Bukit Besar Andesite was carbon dated, but the ages indicated that it was older than the resolution of method (>40 ka).

## 4. SILICIC VOLCANIC SEQUENCES CHARACTERISTICS IN THE RESERVOIR

### 4.1 Major Episodes of Silicic Volcanism

Silicic volcanic sequences in both Muara Laboh and Rantau Dedap occur in at least three major episodes of silicic volcanism (**Figure 3**). The first and second sequences host the geothermal reservoir, while the third sequence is associated with the transition alteration zone which is part of the reservoir caprock. In Muara Laboh, these silicic sequences mainly fill the west and east Muara Laboh Basin with thicknesses reaching about 400 to 1000 meters (**Figure 5 & 6**). In Rantau Dedap, they were interpreted as caldera fill deposits with the thicknesses of far more than 1000 m.

### 4.2 Macroscopic Description

Silicic volcanic rocks in Muara Laboh and Rantau Dedap can be recognized by characteristic mineralogy, textures, and hydrothermal alteration. Under the binocular microscope the rocks cuttings are mainly white or gray to tan in color with plagioclase, pyroxene, quartz, feldspar, and accessory biotite and hornblende as phenocrysts. The tuffs are mainly very fine-grained, containing lithic fragments of andesite lava and dioritic to granitic intrusives. In core and large cuttings partially welded ash-flow textures (flattened shards and pumice) can be identified. In the reservoir section phyllic or propylitic alteration with illite and quartz more abundant than epidote or chlorite is common, while in the overlying transition zone, the silicic rocks contain abundant quartz and mixed layer clays which give moderately low MeB Index values (10 to <5).

### 4.3 Petrography

#### 4.3.1 Silicic Tuffs

Under the petrographic microscope, silicic tuffs at Muara Laboh are characterized by clastic textures, with very fine-grained ash containing lithics; andesite and intrusive rocks (dioritic-granitic), and crystals; plagioclase, pyroxene, and quartz in volcanic glass shard matrix (**Figure 4**). In some parts tuffs are welded with devitrified spherulitic or granophyric textures. Zircon is a common accessory mineral.

In Rantau Dedap silicic tuffs consist of partially flattened pumice of green to tan color, lithics (5 to 20%), and crystals in an ash matrix. Plagioclase is the dominant phenocryst, while quartz is relatively small and sparse. The mafic phenocrysts are generally not preserved but were probably mostly pyroxene based on the shape of pseudomorphs. Plagioclase phenocrysts show a range of alteration and dissolution, with some samples showing substantial dissolution cavities that indicate enhancement of rock porosity (**Figure 4**).

In the reservoir zone, the silicic tuffs in both fields are typically altered to a propylitic (epidote-chlorite-quartz-pyrite) to phyllic (illite-quartz-pyrite) assemblage with illite typically more abundant than epidote. The intensity of veining is generally lower at Rantau Dedap than at Muara Laboh, suggesting a lower intensity of distributed fractures in that area.

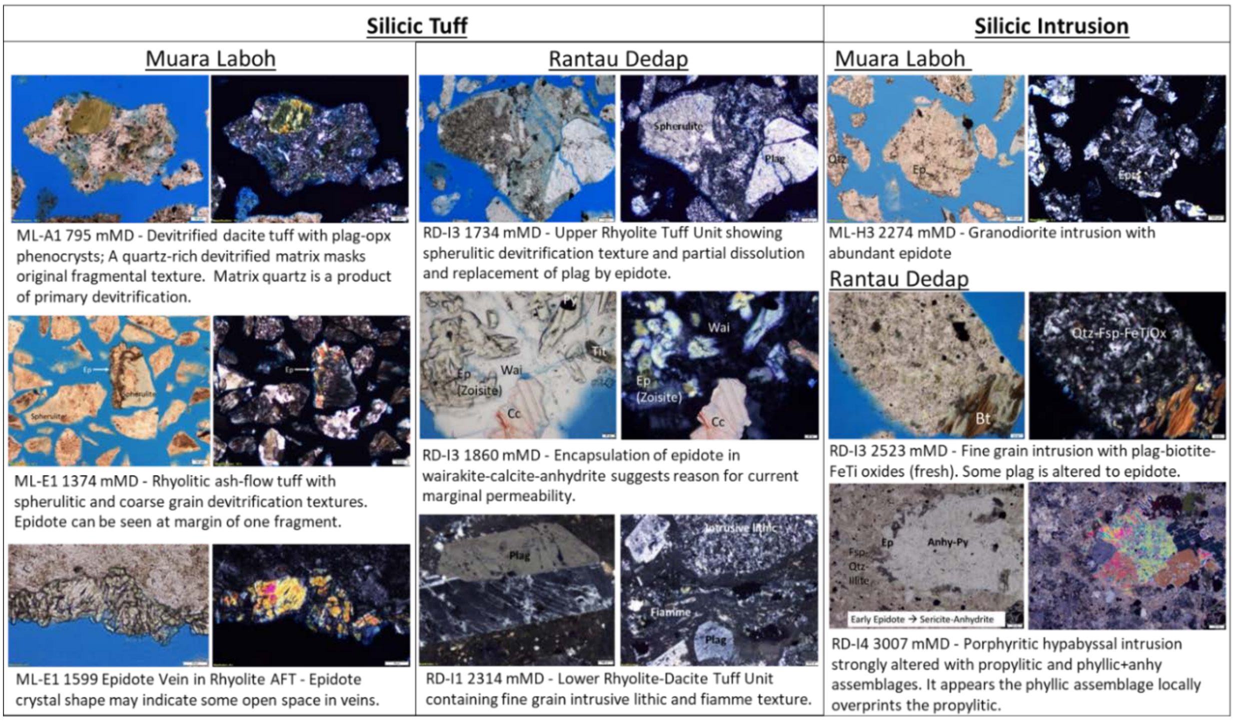


**Figure 4: Petrography of silicic tuffs and intrusions from Muara Laboh and Rantau Dedap cutting samples. Parallel nicols at left and cross polarized at right.**

### 4.3.2 Silicic Intrusions

In Muara Laboh, rocks hosting the deep SW reservoir are mainly older volcanic sequences of dacitic to basaltic composition cut by a variety of intrusions (Baroek et al., 2018, Stimac et al, 2019b) (**Figure 6**). The rocks are mainly granite and granodiorite with plagioclase, quartz, k-feldspar, and biotite as major minerals and apatite, zircon, and FeTi-oxides as accessory minerals (**Figure 4**). Medium grained diorite with hornblende, biotite and pyroxene in addition to plagioclase and quartz, accessory titanite, apatite and zircon. Locally sheared with minor open space and alterations around fractures. The darker part of the rock has a higher percentage of biotite and amphibole. This rock is much less altered and deformed than the granodiorite.

Finer-grained granitic to dioritic intrusions show less alteration and deformation and are more likely mid-Tertiary or younger. Secondary amphibole and lesser garnet are common vein minerals in these intrusions. A few fine-grained intrusions contain fresh plagioclase and pyroxene that indicate they were emplaced recently, after the bulk of hydrothermal alteration took place.

In the SW reservoir zone, there is a significant interval of the upper propylitic zone that is currently less permeable than would be expected. This appears to be related mainly to infilling of early-formed epidote ± adularia veins with later quartz ± prehnite ± wairakite or calcite ± quartz, sealing once permeable fractures. Calcite is particularly abundant in the sealed interval. Calcite in filling is dominant in the upper most propylitic zone with quartz ± prehnite becoming more abundant with depth (Mussofan et al., 2018). Late-stage veins filled exclusively by calcite are also common in the SW. These paragenetic relationships are consistent with extensive boiling, accompanied and followed by ingress of cooler bicarbonate-rich waters (Baroek et al., 2018).

Deep intrusive rock was also observed in Rantau Dedap wells. Mineral assemblages include quartz, k-feldspar with accessory fine-grained biotite, plagioclase, and FeTi-oxides. Rocks have a homogeneous/non-fragmental texture, possibly a chill margin that suggests a dike or stock contact zone. The intrusion contains some fresh plagioclase and rare biotite phenocrysts (**Figure 4**). This shows that the rock is only altered along fractures and consistent with low permeability, correlating with the change to a more conductive thermal gradient as measured in well temperature profiles. The deep intrusions are relatively undeformed, implying young, potentially active heat sources.

A porphyritic hypabyssal intrusion is strongly altered to propylitic and phyllic (illite-anhyrite-quartz-pyrite) assemblages. It appears the phyllic assemblage locally overprints the propylitic one. Alteration assemblages of this intrusion consist of sericite, sericite-quartz ± pyrite ± anhydrite and minor epidote (**Figure 4**). Minor epidote veining with micro-open space also occured in this rock. Minor epidote in plagioclase deuteric alteration suggests limited circulation of meteoric water (low permeability). The epidote was observed replaced by wairakite - prehnite ± carbonate. In the later stage carbonate-anhydrite-sericite ± pyrite was deposited after wairakite-prehnite.

### 4.4 Log Characteristics

Silicic volcanics in Muara Laboh and Rantau Dedap can be recognized by high gamma ray (GR) counts and moderate to high resistivity in image logs. The silicic tuff texture observed in image logs is massive with a matrix supported fabric and moderately abundant (5 to 20%) small (<15 cm) clasts interpreted as lithic fragments and pumice in very fine-grained ashy materials. Sometimes the welded texture can be discerned. The texture is mainly homogenous, unbedded and ungraded on the meter-scale, but sometimes contains more abundant lithic fragments in discrete intervals. These silicic units can be easily distinguished by high GR counts 65 to 200 API in both fields (**Figure 5**). Fractures are identified with varying abundance. Fractures are relatively sparse in very thick and homogenous silicic tuff layers while high fracture density is found in highly welded tuff sequences.

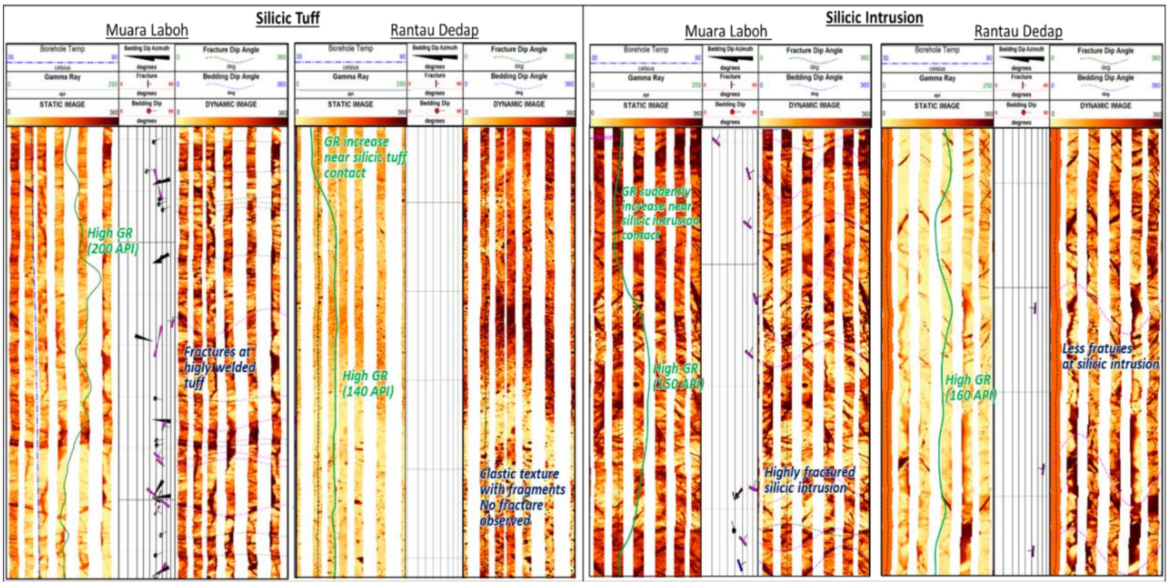


**Figure 5: Representative image log of silicic tuffs and intrusions from Muara Laboh and Rantau Dedap wells. Silicic tuff unit is characterized by fine grain texture, light, high resistive, and high GR counts (65 to 200 API). Mainly silicic tuff is massive, homogenous and poorly fracture and have fragmental texture. Partial conductive fractures and bedding are found in highly welded tuff interval (purple sinusoidal line). Silicic intrusion unit is characterized by massive, light, high resistive, high GR counts (100 to 200 API). Silicic intrusion in Muara Laboh is highly fractured, however in Rantau Dedap it is less fractured.**

In image logs silicic intrusives are massive, light colored, highly resistive and have high GR counts (100 to 200 API). In Muara Laboh, the silicic intrusions are highly fractured while in Rantau Dedap they are less so. In some cases, it is difficult to distinguish densely welded tuffs from lavas or intrusions. The similarity in texture for both intrusive and tuff sequence requires the image log to be combined with core or cuttings petrography for a high confidence lithologic interpretation.

## 5. SILICIC RESERVOIR FORMATIONS AND THEIR RELATIONSHIP TO PERMEABILITY DISTRIBUTION

Silicic volcanic formations in Muara Laboh and Rantau Dedap exert variable stratigraphic control on reservoir architecture and permeability. This may be caused by formation thickness and rock properties that are influenced by rock-homogeneity, degree of welding and devitrification, and degree of faulting and fracturing.

In Muara Laboh, feed zones primarily occur at the margin of the deep silicic intrusives in the SW sector (Pad H and F wells) and within the shallow silicic tuff in the NE reservoir sector (Pad A wells) (**Figure 6**). Deep permeability in the upflow of the SW reservoir sector mainly occurs at the margins of the sheared and intensely altered intrusive complex, associated with proximity to the Siulak master fault segment GSF. In the NE area, faulting and fracturing in a horst structure of a shallow silicic welded ash-flow tuff provides secondary permeability. These tuffs also host a natural state steam zone. However, at reinjection wells at Pads D and E the permeability is limited within the thick silicic sequence.

At Rantau Dedap, a thin shallow welded silicic tuff stratigraphically control the outflow of the system from the production area towards the outflow chloride hot springs and appears to have some characteristics of an aquifer (**Figure 7**). Additionally, feed zones within silicic sequences are associated with discrete structures (e.g., RD-I1). Feed zones are also located near the contact of the silicic intrusive complex with dikes and Lower Andesite Formation.

## 6. DISCUSSION

It has generally been found that densely welded, monotonous caldera-filling tuffs make low permeability reservoir rocks except where cut by relatively recent faulting near caldera margins (Garden et al., 2017). Examples where low permeability has been encountered in intracaldera tuffs include the Valles Caldera (USA) and Los Humeros (Mexico) calderas. Some systems such as the Valles Caldera may have had more vigorous hydrothermal circulation in the past and presently be waning (Goff and Gardner, 1994). Such pervasively devitrified and welded tuffs have low porosity and lack anisotropy that may foster or enhance complex fracturing. Thinner outflow sheets are more likely to develop zones of welding and pseudo-columnar jointing that contribute to anisotropy within extensive rock layers. Reactivation of joint systems, high matrix porosity in originally vapor-phase altered zones, and layer continuity can potentially translate into aquifer-style permeability of silicic tuff sheet. Fields where silicic tuffs sequences likely representing outflow sheets appear to have locally enhanced permeability relative to the dominant andesitic rock mass include Bulalo (Vicedo et al., 2008) and Salak (Stimac et al., 2008).

As noted earlier, there is evidence for an extensive, possibly Sumatra-wide episode of silicic volcanism mainly during the Miocene to Plio-Pleistocene time, and locally continuing to the present. Evidence from Muara Laboh and Rantau Dedap indicates that ash-flow tuffs are by far the most important rock type in the silicic sequence, suggesting an "ignimbrite flair-up". Examples of ignimbrite flair-ups have been well documented in the western U.S. and NW Mexico (McDowell and Clabaugh, 1979; McDowell and Mauger, 1994; Best et al., 2016), the Altiplano-Puna, South America (Best et al., 2016); and the Taupo Volcanic Zone, New Zealand (Gravley et al., 2016). With further study, we expect Sumatra will also qualify as hosting one or more ignimbrite flair-up events during Tertiary and Quaternary Time.

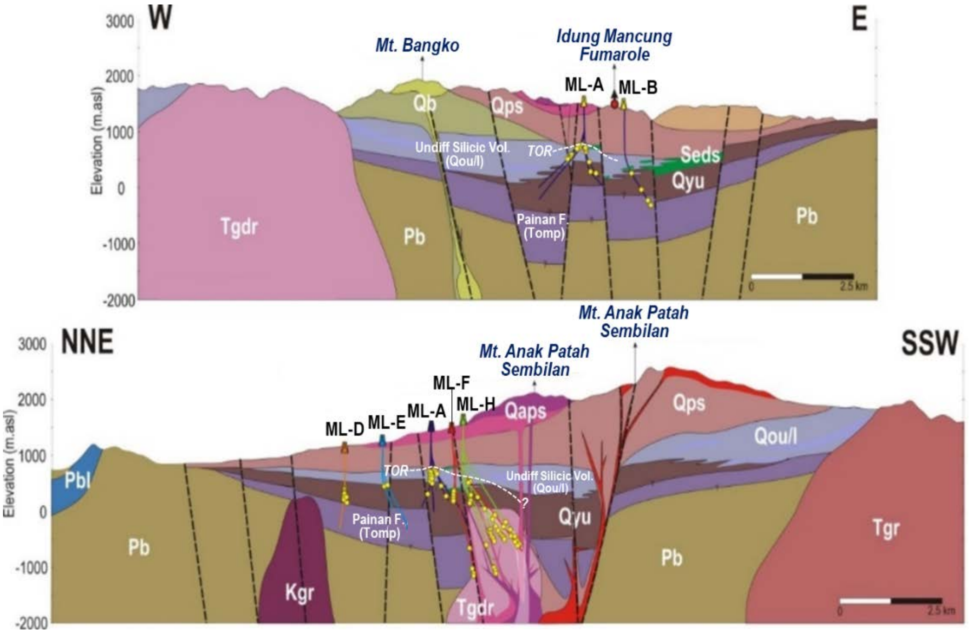


Figure 6: Muara Laboh geologic cross sections showing the stratigraphy and distribution of feed zones (yellow dots). Within the silicic sequence, feed zones are found only at Pad A wells due to highly fractured horst structure in this area. While in other wells feed zones are located mainly at contacts of the intrusive complex with dikes and andesitic volcanics (see Figure 2 for section line).

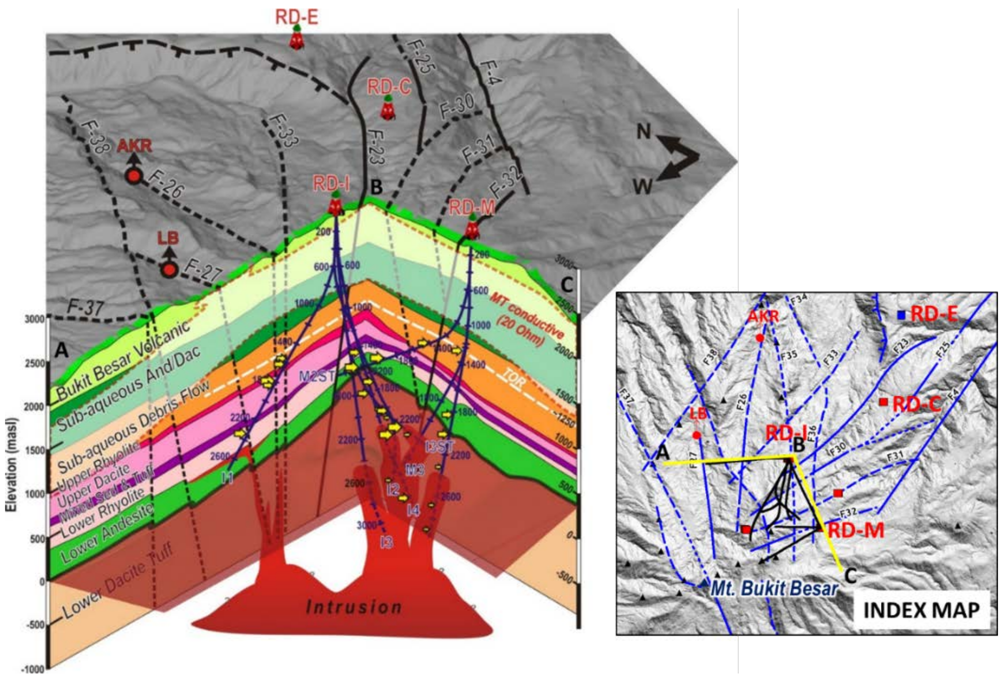


Figure 7: 3D view of Rantau Dedap geologic cross sections that showing the stratigraphy and distribution of feed zones locations (yellow arrows).

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