Geology Controlling Factors of the Top Reservoir; Muara Laboh Geothermal System Case Studies

Mauliate Sihotang¹,², Suryantini², Herwin Azis², Jim Stimac³ and Marino Baroek³

¹Geothermal Engineering Master’s Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia
²PT. Supreme Energy, Menara Sentraya 23rd fl., Jl. Iskandar Syah Raya, Jakarta 12160
³Stimac Geothermal Consulting, 4210 Chaparral Rd., Santa Rosa, CA 95409

Email: mauliates@gmail.com
https://orcid.org/0000-0003-1390-2663

Abstract. Top of reservoir (TOR) determination is one of the resource keys features of the geothermal resource and significantly impacts the well's productivity (Casing Point Determination). It is defined from the conceptual model process and refined by the well temperature data. This paper will describe the geologic controls on the top of reservoir geometries of the Muara Laboh (ML). ML has located in step over-pull apart basins of the Great Sumatra Fault Zone segment. The features then accommodate the emplacement of quaternary to tertiary volcanic and intrusion. The geoscientific data from the existing conceptual model, well cuttings, cores, MeB test, and image log data were combined with the drilling parameter data (mud temperature & mud loses) to characterize the geology of the TOR. Drilling results show that wells in the NE sector have a shallower TOR. The TOR is located near the quaternary Patah Sembilan volcanic unit's contact with the undifferentiated silicic formation. The NE sector TOR corresponds with the change of alteration type from smectite rich argillic zone (<180°C) to the transitional zone (Chlorite, Chlorite-Illite, Chlorite-Smectite formed at 180°C to 240°C). The epidote – chlorite rich propylitic zone (>240°C) identified underlaying the NE reservoir sector's transition zone. MeB Index below 10 seems to be corresponding with the base of conductive of 5 Ohm, and the NE TOR location. The SW sectors TOR sits a deeper elevation (~300msl), lies within the intercalated dacite-andesite volcanic unit, higher temperature propylitic alteration zone, with epidote, epidote-adularia-quartz, and open space veins were observed below the TOR. Similar to the NE sector, the drop of the MeB index to less than ten, which is also related to the lithology contact, shows the possibility that the TOR has dropped in the SW sector. Below the low MeB zone, calcite infilled the fractures and sometimes encapsulated the pre-existing epidote vein; calcite then decreases with increasing epidote vein and epidote-adularia vein occurrence. The observation then suggests a rapid boiling process in the SW sectors due to the dropping of water levels, allowing the late-stage calcite vein to seal off the permeability within the shallow reservoir and not allowing the circulation of geothermal fluids within the interval.

1. Introduction

The top of the reservoir (TOR) identification is critical when conducting geothermal exploration and development drilling. This imaginary line separates the reservoir zone from the non-reservoir section
above it. Failure to define the TOR will result in an unproductive or decrease in the productivity of the well. The TOR is defined by multiple geoscientific studies and refined by well data. This paper will describe the geologic characteristic of the reservoir top geometries in the Muara Laboh (MLB) geothermal system. The Muara Laboh geothermal field is located at 1° 39', 38” Lat, 101 ° 07’38” Long (WGS 84), Solok Selatan Regency, and about 140 Km SE Padang, the capital city of West Sumatra Province. The geothermal concession covers 62,300 ha area at elevations from 450m to 2629m, bounded by the Kerinci Seblat National Park to the west and south. The geothermal system was identified based on the wide distribution of thermal manifestation, consisting of fumaroles, mud pools, and hot springs. The prospect is the first liquid-dominated geothermal field develop in West Sumatra, with a current installed capacity of 85 MWe.

1.1. Project exploration and development

The Muara Laboh geothermal system is recognized by the distribution of thermal manifestation that spreads from Balun spring in far NW to the Idung Mancung and Patah Sembilan crater to the SE. The reconnaissance survey of the field started by the Volcanological Survey of Indonesia (1972-1979), followed by a 3G (geology, geochemistry, and geophysical) survey conducted by PERTAMINA ITB in the early ‘90s. In 2008, Supreme Energy was appointed to conduct a pre-feasibility study and be awarded the geothermal working area license in 2010. The company then drill six explorations well (A1, B1, C1, E1, H1, H2), which proves a high-temperature resource of 235°C to 280 °C that could sustain 80 MWe dual flash power plant operation.

In 2017, the company conducted the development drilling campaign by drilling 11 new wells and two contingencies well. Furthermore, the campaign confirmed the predicted reservoir temperature and reservoir distribution toward S/SW that being described in the updated conceptual model and reservoir simulation model. In general, the resource can be divided into two sectors, the shallow NE reservoir (Pad A wells, H1, F1) and the deep SW reservoir sector.

Figure 1. Location of Muara Laboh Geothermal Field and two Sumatra fault zone segments
1.2. Geology Context

The Muara Laboh geothermal system is located within the stepover of the Great Sumatra fault (GSF) segments, namely the Suliti and Siluak segment [1]. This stepover then generates the pull-apart basins that accommodate the volcanism and magmatism activity related to the geothermal system. The pre-Tertiary Barisan formation, Siguntur formation, and Cretaceous granitic rock are outcropped in the E/NE of the geothermal system act as the pull-apart basin eastern margin basins and basement rocks. Overlaying uncomfortably in the basement is the Tertiary Painan formation, which consisted of mixed volcanic and sedimentary rock. The unit was exposed in the NW, covering the western margin of the pull-apart basins. The basement and Painan formation were intruded by the tertiary granodiorite-granite intrusion (Tgr, Tgdr). This intrusion and its contact act as the system SW reservoir host rock. This formation outcropped to the W/SW of the geothermal system. The Quaternary Undifferentiated -Silicic Volcanic (Quo and Qol) consisted of dacite, rhyodacite, rhyolite lava, and tuff, tuff-breccia, ignimbrite, and obsidian [2]. This formation outcropped in W/SW of the Muara Laboh Geothermal System. U-Pb zircon dating shows that the unit has a wide range of 0.5-3 Ma [3].

Underlying the silicic unit is the andesitic volcanic (Qyu), which consisted of andesitic lava, tuff, breccia, volcanic breccia, and sediments. The unit outcropped in the S/SE of the Muara Laboh system and as material infill within the Muara Laboh basin. Young quaternary volcanic products from Mt. Bangko, Mt. Patah Sembilan, Mt.Anak Patah Sembilan are andesitic in composition and mainly consisted of lava, tuff breccia, lahar, and debris flow deposits. These products cover most of the geothermal system's surface geology, age dating of the unit using C-14 yields an age range of 34 to 41 Ka [1]. The quaternary volcanic product act as the NE reservoir host rock. Manifestation is distributed mainly along with the Mt.Patah Sembilan volcanic product.

Surface observation wells data shows three major structural trends observed in the Muara Laboh geothermal system. The NS extension fracture, which parallels with the horst and graben trend within the pull-apart basins, the NW-SE that parallel with the GSF, and the NE-SW, which coincidently parallel with the conductive layer trend within Mt. Patah Sembilan western flank is interpreted as GSF antithetic [1,4]. Further observation shows that the trends of open fractures on the reservoir section are NW (parallel with GSF) and N/NE (dyke related) trending identified from wellbore fracture. Both trends are considered to control the permeability within the geothermal reservoir.
Figure 2. Geology of Muara Laboh Geothermal Field [1]

| Reference Ages | Regional Tectonic Stratigraphic Stages | Volcanic & Sediment Intrusive | Formational Volcanic Product & Lithology | Geohistorical Stratigraphy & Fault Structure | Stratigraphy & Geothermal System |
|----------------|--------------------------------------|------------------------------|------------------------------------------|---------------------------------------------|---------------------------------|
| Quaternary     | ACTIVE VOLCANISM AND BASINAL FILLING BY VOLCANIC PRODUCTS | | | Recent alluvium actively filling the valley and riverplain. | Hosts Reservoir Clay Cap |
|                | Reactivation Continually Active GSF | | | Mt. Kerinci, Mt. Kupur, Mt. Anak Patah Sembilan, Mt. Patal Sembilan, Mt. Bengko. | Shallow Reservoir |
| 2.4 Ma         | | | | Granite & Granodiorite, Pahian Formation: Volcanic (andesite to andesite) & Sedimentary (shale to tuff). | Intermediate Zone |
| Tertiary       | HORST AND GRABEN STAGE | | | Baalamite, volcanic tuffs, and associated volcanic sediment & tuff, intercalated with andesitic volcanic sequence. | Deep Reservoir |
| 55.5 Ma        | PRE-RIFT | | | Basalt intruders. | Outside Reservoir |
| 270 Ma         | Final stage of stable crust | | | Siputan Formation: Dunite, Bulit Barisan Formation: Phylite, slate, limestone, meta-graywacke. | |
1.3. Top of Reservoir Definition
The top of reservoir definition varies from one operator to another. It is likely related to the required energy, the minimum temperature, and permeability requirement. The line separates the reservoir section from the non-reservoir section above it, which consisted of a clay cap section and fresh volcanic. In the exploration stage, when no well data is available, the conceptual model developed from the combination of geoscientific data provides the first prediction of the top reservoir depth. This boundary then will be refined by drilling data, which include drilling cutting & cores geology observation, epidote (first occurrence and continues occurrence) which suggest temperature ~240°C MeB index which suggests the changes of temperature-sensitive clay (smectite content), mud temperature, mud loss record, and then well PTS analysis result as a final confirmation. The top of the reservoir is also being used for setting the production casing (PCS). The objective is to set the PCS close enough to the TOR that decreases the risk of cooler fluid influx that may affect the well productivity. The second objective is to prevent the well from punching through the reservoir section, making the cementing operation hard to conduct. In this paper, the top of the reservoir was defined based on a minimum productive temperature of 230°C and convective temperature profile. As shown in Figure 7, the top of the reservoir is located at around 800 masl and becomes deeper toward the SW sector ~300 masl to 500 masl (H2 and H4).

2. Muara Laboh Top of Reservoir

2.1. Top of Reservoir Lithology
Referring to the Muara Laboh well stratigraphy [3], the top of the reservoir in the NE sector wells is near the contact between the Patah Sembilan andesite unit undifferentiated silicic formation. A change from an andesitic composition of the Patah Sembilan volcanic product to more dacitic composition volcanic were observe on the cutting observation. The increasing GR-API value trend toward this unit confirms that the unit has a silicic component. Rock cutting analysis within the top of the reservoir shows intercalation between lava and tuff. Further thin section analyses at 640-643mMD & 651-654mMD (ML-A3) show that most of them consisted of andesitic lava cutting with secondary dacitic tuff rock occurrence. Electric image log interpretation of ML-A3 suggests that the top of reservoir located within the contact between brecciated lava, which underlays laminated tuff.

The SW wells of Pad H have a deeper top of the reservoir (300 to 500 masl) than the NE wells. The contact between Patah Sembilan andesite and undifferentiated silicic formation were observed in the shallower depth, following topography increase toward the pad. The SW sector's temperature profile still shows a conductive trend along with the two units, indicating its lower permeability compared to the NE sector. Convective temperature profile and permeable interval were observed within the intercalated andesitic to dacitic volcanic unit. The unit consisted of andesitic-dacitic lava, silicic tuff, and micro diorite at 1266m – 1269mMD (ML-H1). Electric image log observation shows that the interval is composed of intercalation between andesite to rhyolite lava/intrusion and ash-flow tuff (ML-H2OH).

2.2. Top of Reservoir Alteration
Muara Laboh alteration zone can be divided into four alteration zones, namely argillic alteration zone (smectite rich), transitional (mixed-layer clay and chlorite), phyllic (sericite, quartz, pyrite), and propylitic (epidote, chlorite, quartz, and pyrite). Figure 7 shows that the top of the transition zone corresponds with the conductive base of 5 Ohm (3D MT). It separates the clay cap with the potential reservoir top. The NE shallow TOR of Pad NE sector wells corresponds with the change of alteration type from smectite rich argillic zone (<180°C) to the transitional zone (Chlorite, Chlorite-IIIite, Chlorite-Smectite formed at 180°C to 240°C). Figure 3 shows that smectite clays decrease in the drilling rock cuttings indicated by the MeB index value lower than ten when approaching the top of the transition zone. Rare to minor epidote were observed within the zone and observed to be overprinted by later calcite-wairakite, that relative fits with the sector's measured temperature (230-238°C). The main vein
minerals are calcite, quartz, and wairakite (± euhedral), where wairakite and calcite were the latest vein episodes.

Figure 4 shows that the SW sector reservoir top is located within the propylitic alteration zone. The zone alteration minerals are fine to coarse grain epidote, chlorite, quartz, and pyrite identified in well H1, H2, and H4. Higher intensity, more euhedral, and open space epidote were found deeper in H4 and H2 wells (< 300 masl), suggesting higher temperature circulating fluids in the deep SW reservoir (Figure 7). The veins observed near the TOR composed of open space epidote vein, epidote-calcite, epidote-quartz, and epidote-sericite, where the latest vein episode are epidote and quartz. Within the shallow level of the SW sector, wells intersect similar lithology with the shallow NE reservoir but seem to be overprinted and sealed by the later stage of calcite, quartz, and quartz ± prehnite ± calcite [3]. In contrast to the shallow NE reservoir, the thin section analysis shows the absence of the modern wairakite and anhydrite vein at the shallow transition zone of SW sector wells.
Figure 3. ML-A3 well composite log with vein paragenetic and permeability indicators. The blue line represent the NE TOR refined by well PT data.
Figure 4. ML-H4 well composite log with vein paragenetic and permeability indicators. The blue line represent the SW TOR refined by well PT data.
Figure 5. Photomicrograph of Muara Laboh reservoir rocks, blue dye representing existing porosity (a,b) Photomicrograph of silicified andesite with quartz (Q) & chlorite vein at ML-A3 (618mMD) based on parallel and cross nicol observation; c,d) wairakite, calcite, and anhydrite in the NE steam reservoir at ML-A2(710.13mMD); e,f) epidote vein with minor open space with quartz and calcite encapsulation at ML-H3(1272mMD); g,h) epidote and minor quartz in open space, and late calcite infill at ML-H4 (2589.14mMD)
3. Permeability Indication
The NE wells encounter 1st permeability close to the TOR location at 760 to 800 masl, although the total loss circulation quite varies at 660 to 760 masl, and the shallowest feed zone located at 720 masl (A3) to 760 masl (A2). This indication seems to correspond with the convective temperature profile identified from PT survey. The SW wells have a deeper 1st lost location -540 to 60 masl in H2 & H4, total loss circulation quite varies within SW sector wells close to 200 masl at H1, as deep as -1180 masl at H4, and no TLC encountered in H2. The 1st feed zone within the SW sectors varies in elevation, H2 feed zone located at 200 msl compare to -700msl at H4. The thick gap between TOR with the permeability indicator on the SW sector suggest vertical permeability variation within the reservoir environment.

4. Discussion
TOR in the NE sector of the resource shows an excellent example of a classical top of reservoir determination where there is a shift from more smectite dominant clay cap towards becoming more of mixed-layer clay (chlorite-illite-smectite) transition alteration zone assemblage where the top of the reservoir located (~800 masl). The later stage wairakite vein suggests temperature higher than 220°C, which confirmed by PT result, calcite and anhydrite vein correspond with steam cap reservoir. No new epidote vein was observed from thin section analysis, it being overprinted by later vein species. Closer to the contact between Patah Sembilan andesite unit with the undifferentiated silicic formation, correspond with alteration zone changes and the distribution of BoC of 5 Ohm, and it's likely to provide more lateral permeability in the rock units where the TOR of the reservoir located. The permeability indicator such as convective temperature profile, first mud lost, TLC, and feed zones are distributed below the TOR within the NE sector.

A more complex indicator is used to determine the TOR in the SW sector. Although the wells intersect a similar unit with the shallow NE reservoir, permeability is located deeper. The propylitic alteration and epidote vein occurrence observed within intercalated dacite to andesite volcanic unit become the 1st indicator of the deep SW TOR. The permeability gap between the 5 Ohm BOC with the SW TOR indicating permeability restriction due to deposition of late-stage calcite, quartz, quartz ± prehnite ± calcite deposition that sealed the shallow top of the reservoir [3]. Permeability below the TOR varies within the sector, which may correspond with the young dyke/intrusion's existence [3].

The fact that the NE sector has a natural steam cap and the absence of the SW area zone may be related to the sector collapse event [3, 5]. This sector collapse then induced a rapid boiling process in the shallow reservoir of the SW sector, shown by the overprinting of the early propylitic zone (epidote vein) with the late calcite + quartz + sericite/illite + zeolite. This event also pushes the transition zone (no fresh epidote) and TOR deeper due to the permeability restriction of the TOR.
Figure 6. Muara Laboh well geology, mud loss location, shallowest feed zone, and TOR location
5. Summary

The Muara Laboh reservoir could be divided into two sectors, the shallow NE sector and the deep SW sectors. The NE sector of TOR was located at ~800 masl, precisely within the lower part of the Patah Sembilan andesite unit, and transition alteration zone (mixed layered clay-chlorite). The vein characteristic proximate to the NE TOR consisted of calcite-quartz-wairakite with major open space, which related with the steam cap existence within the sectors. Epidote vein observed being overprinted by later calcite-quartz-anhydrite vein, but still maintain sufficient permeability for fluid to circulate. The event may relate with the liquid level drop during the development of steam cap. The TOR correspond with 3D MT BOC of 5 Ohm which can be used as guidance for further drilling in this sector.

The SW sectors TOR located at 300msl to 500msl elevation, within the intercalated dacite and andesite volcanics unit. Although the wells on this sector observed similar unit with the NE sector, the TOR located deeper than the NE sector. Thicker transition alteration zone that move away from 5 Ohm BOC and the MeB index were observed SW sectors wells. Thin section analysis then suggests that the permeability within the shallow interval seems to be blocked by calcite-quartz-anhydrite mineral. It indicates that a rapid boiling process due to sector collapse event in the past [3,5]. At the TOR depth, the propylitic alteration assemblages with epidote and epidote-calcite-quartz-sericite vein were observed, this characteristic then being used as the 1st indicator of TOR in the sectors. Moving deeper towards feed zone and permeable area, open space epidote and porosity along vein become more intensive.
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