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The Role of The Hulusimpang Formation in Well-Scale Permeability of The Central-Southern Sumatra Geothermal Fields

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ABSTRACT

Permeability is one of the most critical objects that dictates a geothermal field success story. In Sumatra's hydrothermal system, most of them are believed controlled by fault or fractures, either due to tectonic or volcanic structure. The combination of crystalline and brittle lithology associated with a local extensional mechanism is common and underlain this hypothesis. In this paper, we address the evidence of the other option for hydrothermal fluid to flow: the relatively lateral matrix permeability through an extensive and thickest Paleogene - Neogene volcanic formation in central and southern Sumatra, the Hulusimpang formation. The evidence was synthesized from the comprehensive analysis through available field data including Sungai Penuh, Bukit Daun and Ulubelu which was guided by the regional geological data.

The finding of this paper is the distribution of the Hulusimpang formation across central to southern Sumatra in the subsurface and also its sufficient contribution to the well-scale permeability. Hulusimpang formation is characterized by the thick layer of volcanic breccia and ignimbrite, interlayered with lava flow products such as andesite and basalt, which are found fairly distributed and extensively from wells in the geothermal fields mentioned above. The proof is derived from the detailed analysis of borehole data integration such as core and image log and supported by the thin section analysis, where the stratigraphy unit of these lithologies is fit if refer to the regional Hulusimpang formation. By using the spinner data, we also revealed that most of the shallower feedzones in the southern Sumatra geothermal fields reservoir are associated with the less-fractured Hulusimpang formation zone which is dominantly composed of pyroclastic deposits such as volcanic breccia and ignimbrite. The primary permeability in this lithology might come from its vesicular, open veins and microfractures, as shown by the image log and petrography analysis. Their contribution to the well's productivity is massive, ranging from 30 to 60% of the total injectivity index, which concludes that the Hulusimpang formation is favourable to consider in the well-targeting strategy.

1. INTRODUCTION

Sumatra Island is widely known as one of the most productive geothermal power production areas in Indonesia. The geothermal development in Sumatra rapidly grows year by year due to the abundance of geothermal fields which are promising and economically worth to developed. With approximately 3.5 GW possible of resources and 774 installed geothermal capacity (Geological Agency, 2021), Sumatra still has a big opportunity to gain more electricity generated from geothermal energy and fulfil the country's energy target by accelerating Sumatra's green fields exploration and development.

The geothermal activity in Sumatra is mostly concentrated in central and southern Sumatra, although some of the well-developed fields are also located in North Sumatra, for instance, Sibayak, Sorik Merapi, and Sarula fields. Most of Sumatra's geothermal fields are typical of volcanic-hosted geothermal fields, whereas those volcanoes, and also its geothermal system, are mostly associated with the pull-apart basin or extensional regime as the result of the Sumatra Fault System (SFS) stepover zones and splay-associated (Muraoka et al, 2010). Some references are addressed the role of these extensional structures in Sumatra's geothermal system permeability. Mussofan et al. (2018) suggested the critical role of N-S extensional structure in Muara Laboh field permeability yielded by the interaction between Siulak and Suliti segments. Ikhwan (2020) suggested the Bukit Daun geothermal field permeability, that pinched between Ketahun and Musi segments, is influenced by the Tertiary N-S forearc Bengkulu Basin structural framework. Arifin et al. (2020) concluded that the permeability of the Ulubelu geothermal field is mostly associated with the NW-SE fault trend which parallels the SFS trend. While most authors focus on the role of the secondary permeability control in Sumatra's geothermal system, only a few considered the matrix permeability or formation contribution in Sumatra geothermal reservoir. Ikhwan et al. (2021) reveal the permeable volcanic breccia unit in Bukit Daun field and Nusantara et al (2020) suggested the role of the ignimbrite unit in Ulubelu geothermal field. The impact of these units on the wells injectivity index is significant but unfortunately, less discussed comprehensively.

In this paper, we deliver the evidence of formation-hosted feedzones focusing on the central-southern Sumatra geothermal fields including Sungai Penuh, Bukit Daun and Ulubelu. The data is conducted by Pertamina Geothermal Energy (PGE) drilling activity, and the discussion of this paper focuses on the borehole image log and thin section analysis. We correlate the well-scale formation permeability finding with the massive regional volcanic formation called The Hulusimpang formation. The Hulusimpang formation lying extensively from central to southern-end Sumatra is commonly used to be the epithermal explorations target (Barber et al., 2000). We conducted the well-scale feedzone identification by integrating the borehole image analysis with the pressure-temperature spinner (PTS) injection data, supported by available cutting, core, and fossil analysis data, to suspect the formation-hosted feedzone (FZ) in the reservoir. This type of FZ is justified with the subsurface lithology type that might correlate with a major volcanic explosion event in the area which results in a pyroclastic product, for example, the Hulusimpang formation. As the fracture is well-known as the main permeable zone geothermal reservoir, the matrix permeability influence is interpreted where the fractures are absent or not well-developed in identified FZ interval from the spinner data. This finding gives us a better understanding of the control of fluid flow in the well-scale and sharpens our insight into the future well target clarity, both in geothermal exploration and exploitation stages in central-southern Sumatra.

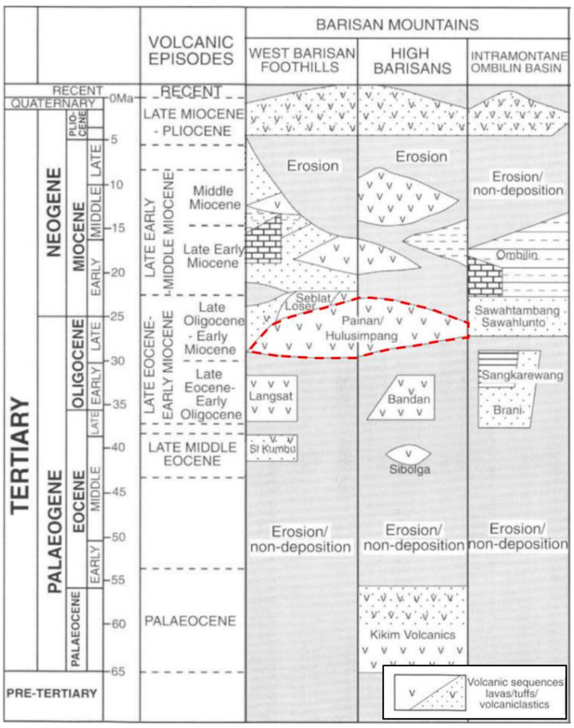
2. REGIONAL GEOLOGY OF SUMATRA

In general, Sumatra consists of several groups of basement rocks (age range: Precambrian (?), Late Devonian to mid-Cretaceous) that are intruded by Miocene plutonic rocks and covered by Paleogene-Neogene and Quaternary volcaniclastic and epiclastic deposits (Barber et al., 2000). Basement rocks are mostly exposed in northern and central Sumatra and have been intersected in south Sumatra by commercial drilling activity. The occurrence of xenoliths of metamorphic rock on the western part of North Sumatra attests to a deep-seated Precambrian basement in that area. The late Oligocene to early Miocene is marked by unconformities. These represent a change of tectonic setting from Eocene to the Oligocene extension, which produces the horst and graben architecture predominant in basement rocks, to contraction as a consequence of subduction, also known as tectonic inversion. This resulting the orogenic period that is well-recorded in central to southern Sumatra. The latter period also resulted in the initiation of the right-lateral strike-slip SFS, uplift, and arc volcanism.

3. REGIONAL OF HULUSIMPANG FORMATION

Most of the Tertiary volcanic and volcaniclastic formations in Sumatra were identified in the Geological Maps published by the Geological Research and Development Centre. McCourt *et al.* (1993) and Kusnama *et al.* (1993) summarized the stratigraphy of Southern Sumatra, including the volcanic units. The Hulusimpang formation is one of the Tertiary volcanic products in Sumatra, deposited from the late Oligocene to early Miocene, which made it the oldest volcanic product mapped in central to southern Sumatra (Gafoer et al., 1992). Generally, it extensively lies from West Sumatra province, which is also known as the Painan formation, to South Sumatra and remarked the Bukit Barisan stratigraphy along the northeast to southwest Sumatra (De Smet, 1992) (Table 1.)

Table 1. Tertiary volcanic episodes and phases and their distribution in selected depositional and erosional environments in Sumatra (De Smet, 1992). Hulusimpang formation bounded by red dashed line



The Hulusimpang formation is a part of the proto-Barisan mountain which marks a major tectonic event in Sumatra (Barber et al., 2005). The proto-Barisan mountain represents a volcanic arc that separated the forearc and backarc basins. During this period, maximum transgression occurred in the forearc, resulting in a major sedimentary influence on the Hulusimpang formation (Kusnama et al., 1993). Hulusimpang formation was affected by tectonism as the SFS initiated in the late Miocene and tectonically sliced the Hulusimpang formation along NW-SE strike-slip faults, some of which may have localised on inherited rift faults (Barber et al., 2005).

The Hulusimpang formation is dominated by 700m andesite breccia and tuff, together with the lava flow product such as andesite and basalt, as it was formed by an explosive eruption from a collapsed lava dome, which distributed block and ash flow around the volcanic centre. The focus of such volcanism is unclear because a large volume of Quaternary deposits masks diagnostic features. However, it is suggested that the Hulusimpang Formation results from more than one volcanic source (Barber et al., 2005).

In regional geological maps of the three study areas in this paper include the Hulusimpang formation (Figure 1). The Sungai Penuh is the field located in the Sungai Penuh and Ketaun quadrangle (Kusnama et al., 1992), the Bukit Daun field is located in the Bengkulu quadrangle (Gafoer et al.,1992), and the Ulubelu field located in the Kota Agung quadrangle (Amin et al., 1993). These maps extensively mapped the distribution of the Hulusimpang formation and, in a certain way, it reflected how the Hulusimpang formation was impacted by the SFS. Although the Bukit Barisan surface is currently dominated by the Quaternary volcanic deposits, the Hulusimpang formation was always mapped whether it was exposed due to the orogenic uplifting during Plio-Pleistocene (Ikhwan, 2020), surface erosion or uncovered by the younger deposits. Therefore, we can conclude that how the Hulusimpang formation dominantly lies under the surface and should potentially be encountered by deep drilling activity.

4. HULUSIMPANG FORMATION ON THE SURFACE

Due to the massive distribution of the Hulusimpang formation across central to southern Sumatra, the geological survey can be an effective method to describe its rock and mineral composition. The Hulusimpang formation characteristic is commonly found in those three fields of study. Collected hands specimens are mostly described as pyroclastic deposits such as lapilli and tuff. This paper only discusses two surface outcrops that represent the Hulusumpang formation distributed in the three field studies. In general, all the collected surface Hulusimpang's formation outcrop from Kerinci, Bukit Daun, and Ulubelu fields feature relatively similar petrography and petrology characteristics, which are dominated by tuff or lapilli tuff (Figure 2A). The tuff on the surface is highly weathered, characterized by reddish-white colour, in some spots quartz and obsidian fragments are dominant (Figure 2B, C). It is also deposited together with laharic and andesitic boulders. From petrography analysis, the tuff sample shows clastic and welded textures, supported by <0.03-1.4 mm matrix composed by the glass. Some fragments identified are plagioclase, clinopyroxene and opaque minerals. Another sample of the tuff outcrop is almost completely altered into clay, sericite and opaque minerals yet quartz is still identifiable as the primary mineral (Figure 2D, E).

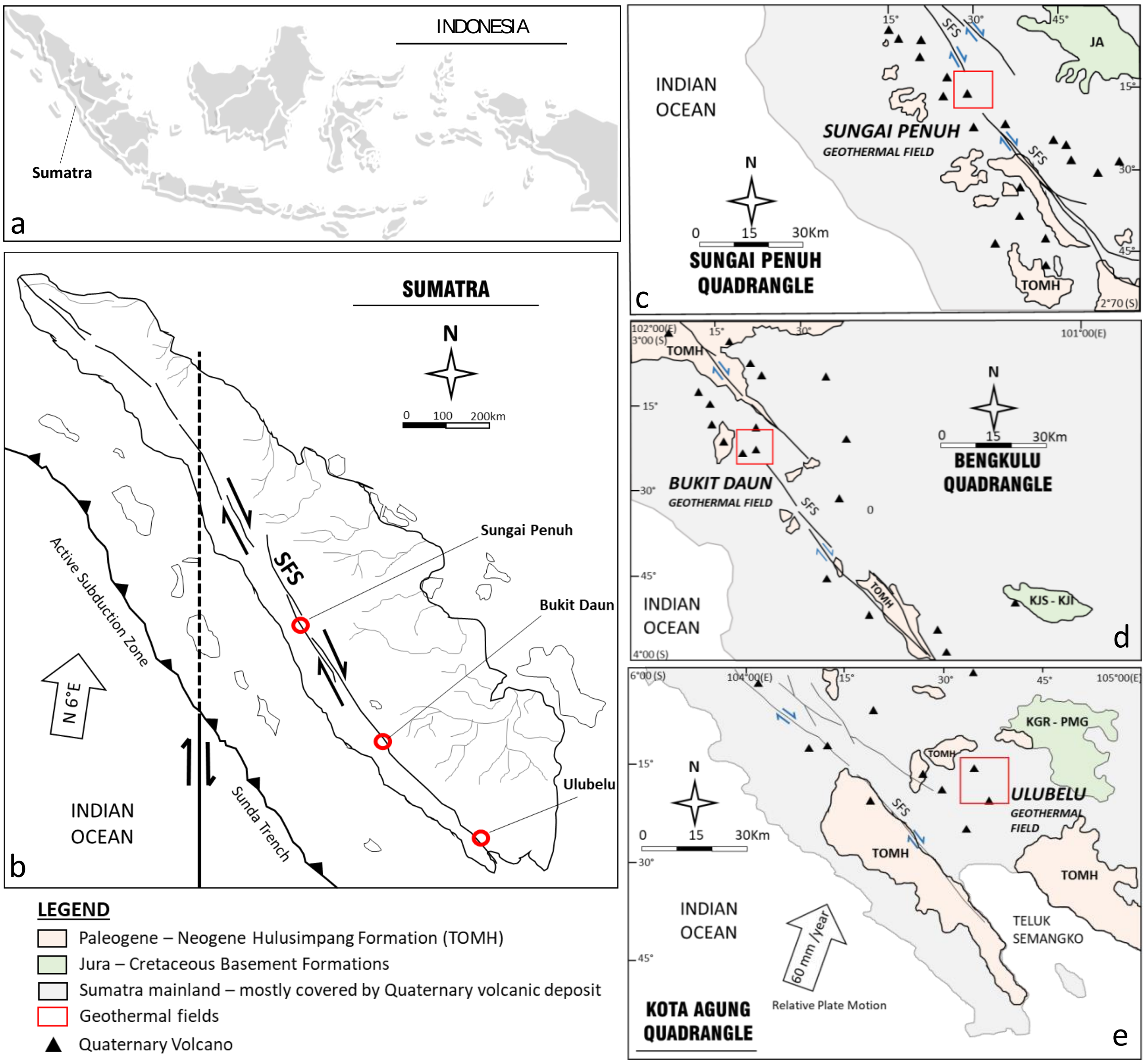


Figure 1: A) The Sumatra island map. B) Physiography regional of Sumatra. C) The simplified Sungai Penuh geological map quadrangle. D) The simplified Bengkulu geological map quadrangle E) The simplified Kota Agung geological map quadrangle.

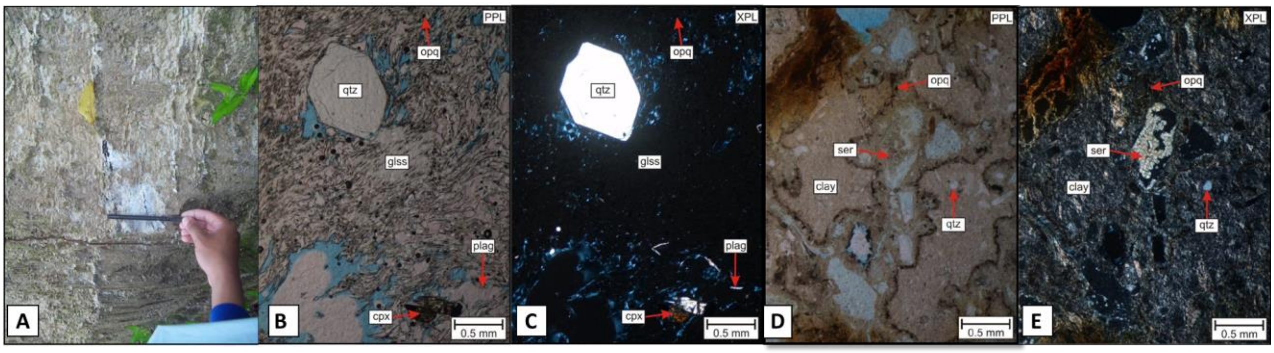


Figure 2: The surface outcrop and sample of a unit in The Hulusimpang formation. A) The lapilli tuff outcrop mapped in Bukit Daun as the unit in the Hulusimpang formation. B & C) PPl and XPL of the lapilli tuff sample. D & E) PPL and XPL of the weathered tuff sample mapped in Sungai Penuh as a part of Hulusimpang formation. Cpx = Clinopyroxene, Opq = Opaque, Glss = Glass, Plag = Plagioclase, Ser = Sericite, Qtz = Quartz.

5. HULUSIMPANG FORMATION IN WELL-SCALE

The Hulusimpang formation in the specified fields was revealed from the drilling activity, based on the drilling parameter, cutting, and image log data. In this paper, we compare the image log, focused on the feedzone interval, and thin section analysis to confirm the distribution of the Hulusimpang formation across the wells and fields. All the wells included in this study are relatively good in permeability magnitude. The interpreted Hulusimpang formation on all wells mostly shows similar image log texture and thin section analysis. The Hulusimpang formation interval mostly consisted of volcanic breccia, pyroclastic and lava. (Figure 3). The interpreted matrix-controlled feedzone is associated with pyroclastic or volcanic breccia, with gamma-rays ranging from 25 to 60 API. The elevation of this type of feedzone is distributed evenly on the SFS step-over zone controlled fields such as Sungai Penuh and Bukit Daun, where it measured between 217 to 250 mRSL.In Ulubelu, Hulusimpang formation drilled relatively deeper which might cause by the tectonic setting in this area that more controlled by depression.

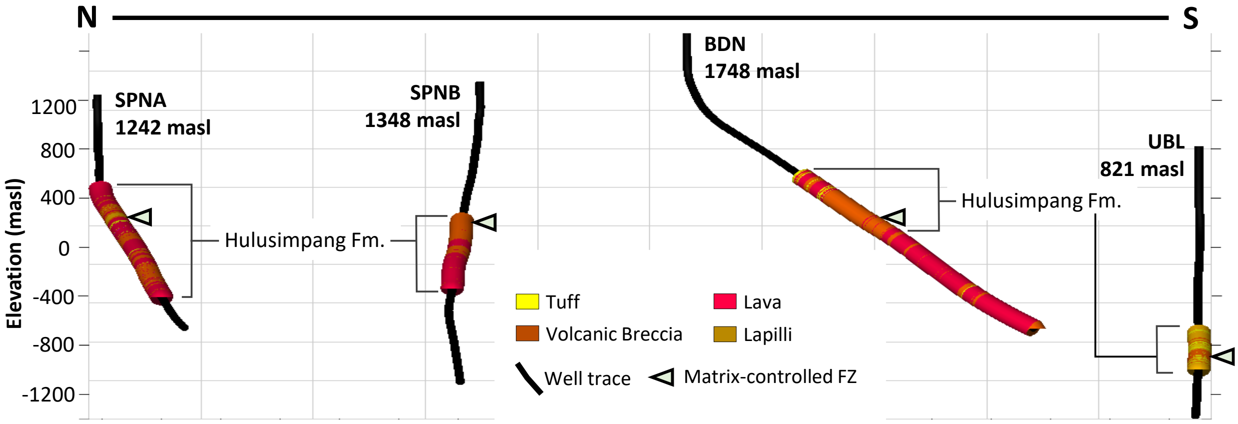


Figure 3: The vertical section of the well included in this study, is derived from three geothermal fields. All the wells are directional and big-hole size. The stratigraphy unit is composed of image log analysis supported by cutting and core samples.

5.1 Borehole Image Log Characteristics

All the image log data shown here are electrical image log data (pad-based borehole image log tools) that show not only the fracture distribution but also detailed lithology texture that easier the formation evaluation and identification. Below is the summary of the stratigraphy interpreted from the borehole image log with their associated feedzone lithology and flow contribution.

Table 2: The contribution of the Hulusimpang pyroclastic unit to the well's productivity, quantify from PTS log measurement.

Well	Hulusimpang Fm. Interval (mMD)	Matrix-controlled Feedzone Interval (mMD)	Feedzones Lithology from Image log data	Flow contribution of total Injectivity Index
SPNA	1303 - 2197	1302 - 1402	Volcanic Breccia	43%
SPNB	801 - 2203	1250 - 1400	Volcanic Breccia - Conglomerate	40%
BDN	1300 - 1960	1824 - 1955	Volcanic Breccia	60%
UBL	1616 - 2003	1900	Volcanic Breccia	28%

<u>Sungai Penuh</u>

Sungai Penuh field is situated in the central area of Sumatra. Hulusimpang Formation (Tomh) in Sungai Penuh field, which is also called as Painan Formation in some literature, was confidently synthesized from two wells that contain the image log data; SPNA and SPNB. It is characterized by various volcanic products including andesite lava, volcanic breccia, tuff and also metasedimentary units. Mostly the Hulusimpang formation mapped abundantly on the western part of the prospect area (Figure 1C). It is believed that they are mostly hidden by the younger Quaternary volcanic product deposit which lay extensively on the surface, as the Sungai Penuh field tectonically formed as a depression area due to the interaction between two strike-slip faults (Fahrudin et al., 2018)

All of the image log interval data available in the SPNA well are interpreted as the Hulusimpang formation, ranging from 1303 to 2197 mMD. This interval is dominated by volcanic breccia interlayered with tuff and lava (Figure 4). Several feedzones were recorded from spinner measurement which was divided into two zones, upper and lower feedzones. The lower feedzones are strongly controlled by the fractures zone while the upper feedzones interval, which begins at 1302 to 1402 mMD, is interpreted as controlled by matrix porosity of the volcanic breccia or pyroclastic (Figure 4). There is no strong sinusoid or fracture evidence on the image log in this 100-meter production interval, which leads to the formation permeability suspect that influences the spinner response and contributes to 43% of the total permeability of SPNA.

The SPNB separated 1.5km to the north of SPNA. The whole image log data available in SPNB well also interpreted as the Hulusimpang formation, measured from 801 to 2203 mMD. The lithology mostly consists of volcanic breccia and lava (Figure 4). Feedzones in the SPNB are dominated by fracture zones except for the upper feedzones which range from 1250 to 1400 mMD and contribute to 40% permeability. This interval has minor fracture occurrence and lithology is dominated by volcanic breccia or conglomerate with very resistive fragments (Figure). Both of the image lo data in the SPNA and SPNB show relatively similar gamma-rays which range from 10 – 50 API.

Bukit Daun

Bukit Daun field is one of the southeast trending geothermal field series in the Bengkulu province, southern Sumatra. Tectonically, it is most likely similar to the Sungai Penuh where the geothermal potential occurs in an extensional zone due to interaction between SFS segments (Ikhwan, 2020). Hulusimpang Formation (Tomh) in Bukit Daun intersected from drilling activity is characterized by various volcanic products, including andesite lava, volcanic breccia, lahar deposit, tuffs, lapilli, metasedimentary units, and rare dacite. Metasedimentary units intersected by drilling indicate that this formation was deposited during an active sedimentation process in a transgressive environment (Kusnama, et al. 1992). Hulusimpang formation is the latest Paleogene-Neogene formation identified from drilling although some younger Neogene deposits are described on the surface. They are mapped abundantly and mostly concentrated on the west and northern part of the prospect area (Figure 1D). It is believed that they are mostly hidden by the younger Quaternary volcanic product deposit which lay extensively on the surface.

Hulusimpang formation in Bukit Daun has proven significantly contribute to the fluid flow, especially on the well-scale. The BDN image log analysis confirms the ~ 130m feedzone interval with nearly 60% contribution of the total permeability extracted from the Hulusimpang formation (Figure 4). The image texture analysis shows the volcanic breccia lithology, with some fragments imaged resistive which is interpreted as andesitic or silicic fragments. The fracture distribution on this interval is minor, thus the feedzone interpreted might be controlled by matrix porosity of the volcanic breccia or microfractures. Moreover, the image also shows some conductive porous features or vuggy that also possible contain the fluid flow. The gamma-rays on this lithology mostly range from 10 to 65 API

Ulubelu

Ulubelu geothermal field is located about 100 km west of Bandar Lampung, Lampung Province, southern Sumatra (Figure 1E). It lays as a half-graben structures related to tensional stress from SFS inside the post-caldera depression of Mt. Sula. Nusantara et al. (2020) have summarized the subsurface stratigraphy of the Ulubelu field which is composed of lava and pyroclastic products of Mt.Rendingan, mixed volcaniclastics breccia associated with carbonates lenses, ignimbrite as the reservoir facies of the system, and carbonaceous rocks as the deepest layer penetrated by numerous wells at an elevation around -1100 masl. As a sequence of graben filling formation inside of a depression system, the formation lateral distribution is spread evenly aligned with the basin topography. It is proven by borehole data in every well inside the depression that the dipping of this sequence of lithology is tilted to the east.

The Hulusimpang Formation (Tomh) in Ulubelu is represented by the UBL well (Figure 4). The image log in this well is only available from 1616 to 2003 mMD. The lithology in the image log is dominated by interlayers of pyroclastic products such as volcanic breccia, tuff and lapilli and overall shows a relatively high resistive image. The matrix-controlled feedzone in this well occurs at 1900 mMD and contributes ~28% of total well permeability. The lithology in the feedzone interval is a highly resistive volcanic breccia, with some conductive and resistive fragments, and also conductive vuggy in some spots. Fracture’s sinusoid in this interval is minor, leading to an interpretation that the feedzone is more controlled by the matrix porosity from the volcanic breccia.

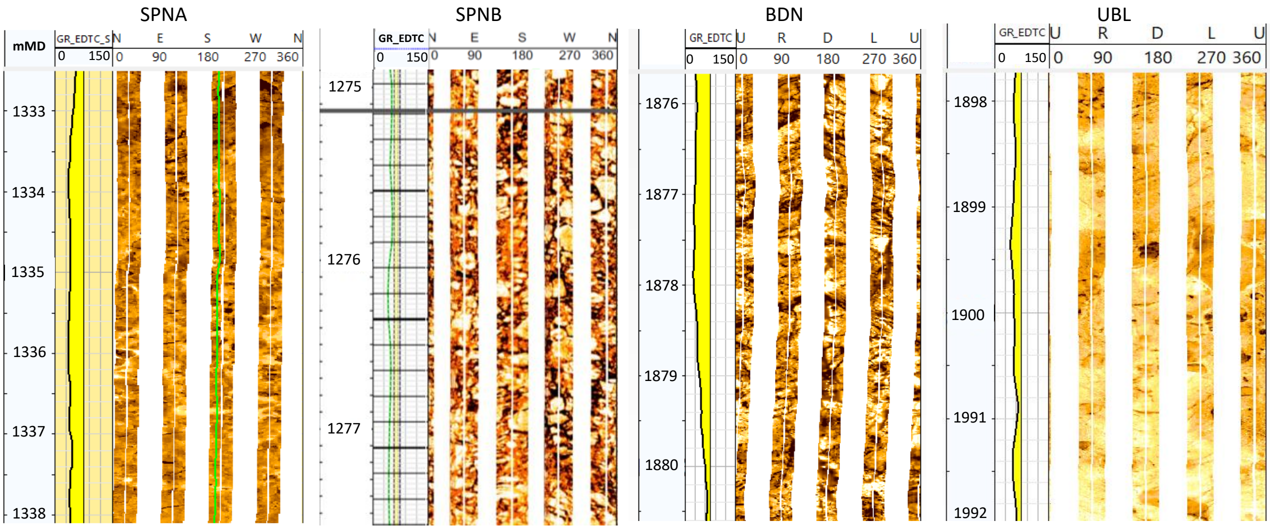


Figure 4: Dynamic image that covered the interval feedzones of each well in this study. The image consists of measured depth, gamma ray and dynamic log. All of the feedzones intervals show relatively similar rock textures, which is composed by matrix and fragments.

5.2 Thin Section Analysis

Thin section analysis confirms the detailed rock composition from the suspected matrix-controlled feedzone formation interval. All of the samples were derived from core samples. The purpose is to compare the composition of each reservoir formation, and to conclude their similarity to the Hulusimpang formation. The megascopic analysis from the core sample concluded that all the samples were interpreted as polymic volcanic breccia. The matrix is mostly composed of tuff and the fragment varies from altered andesite and lithic tuff. For the thin section analysis here, only the matrix was used to fairly compare each sample from different wells.

The mineral composition of all samples analyzed confidently indicated lapilli tuff or ignimbrite. It has fragmental texture, matrix-supported, felsic colour with vesicular structure filled by secondary mineral. The ignimbrite consists of volcanic glass as groundmass, fine size plagioclase and primary quartz as phenocryst. Some glass shard textures can be found in fully altered conditions. The intensity of alteration in these facies is 0.6 IA or very intense. Ignimbrite is strongly altered in groundmass and phenocryst to secondary minerals such as actinolite, alunite, smectite, chlorite, quartz and epidote. The secondary minerals also fill the vein and grain contact in rock bodies, for example, pyrite and calcite. Primary permeability in this lithology might come from its vesicular, open veins and microfractures.

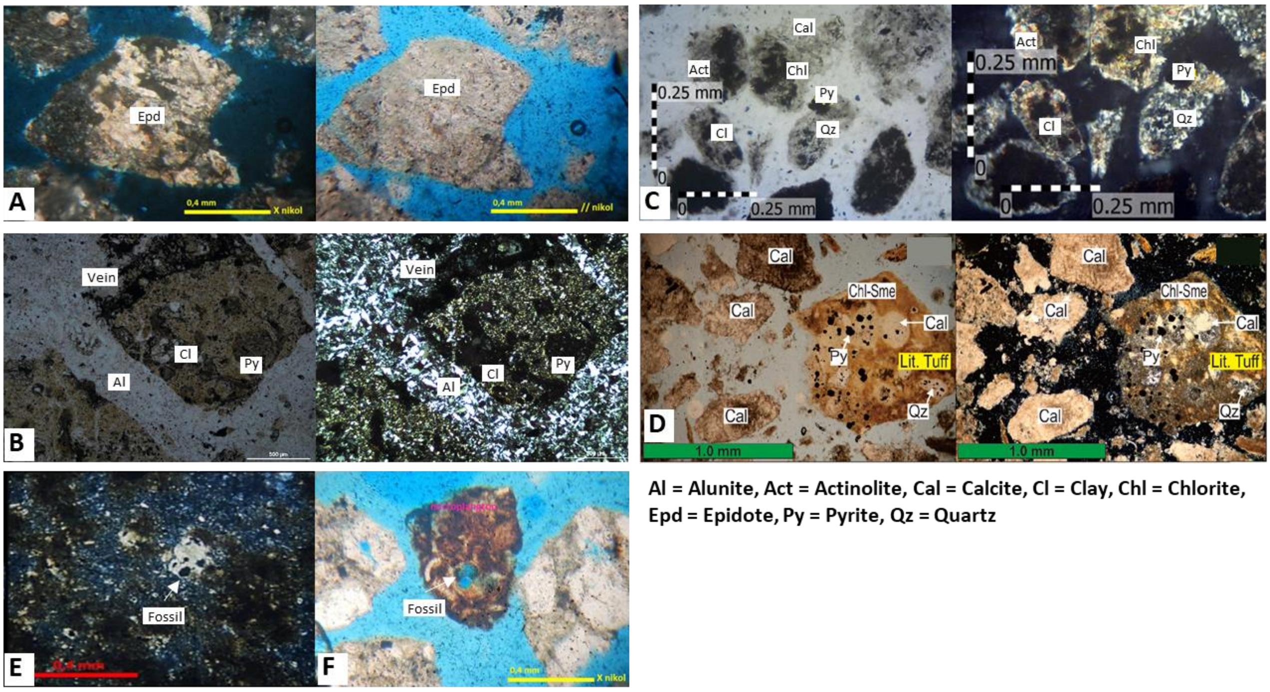


Figure 5: The thin section analysis of several core samples. A) Thin section from SPNA feedzone at 1325 mMD. B). Thin section from SPNB feedzone at 1252 mMD. C) Thin section from BDN feedzone at 1839 mMD. D) Thin section from UBL feedzone at 1899 mMD. E) Fossil contained in BDN at 1500 mMD. F) Fossil contained in SPNA at 1400 to 1500 mMD.

Another remarkable characteristic of the Hulusimpang formation is the containment of the metasedimentary unit as the representative of the maximum transgression period during the formation depositional process. The Hulusimpang formation is a part of the proto-Barisan mountain which marks a major tectonic event in Sumatra (Barber, 2005). The proto-Barisan mountain represents a volcanic arc that separated the forearc and backarc basins. During this period, maximum transgression occurred in the forearc, resulting in a major sedimentary influence on the Hulusimpang formation (Kusnama et al., 1992). Therefore, 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).

The metasedimentary units are occurred in the SPNA and BDN, as the microfossil seen through the thin section analysis in the Hulusimpang formation interval samples. In BDN, cutting samples containing abundant fossils within metasedimentary material were found at 1500 mMD. Fossils analysis was conducted by the PGE team (PGE unpublished report, 2015). It is Globigerinoides primordius species, were recognised based on characteristics defined by Postuma (1971), which indicates an age range that matches the suggested Hulusimpang formation age where it was found (late Oligocene to early Miocene). The occurrence of volcanoclastic lithology was found in the SPNA cutting sample with abundant microfossil at 1400 to 1600 mMD. The most abundant microfossil was found at 1529 mMD as 8% of the total cutting percentage. Unfortunately, the fossil analysis has not been done yet so its relative age is still undefined.

5. CONCLUSION & DISCUSSION

Hulusimpang formation believed as a massive volcanic product during Paleogene and Neogene, extensively distributed in central and southern Sumatra. Geothermal drilling activities in several fields in Sumatra encountered this formation and found its significant role in the permeability and well's productivity. The Hulusimpang formation is dominated by volcanic breccia and ignimbrite that control the matrix permeability as proved by the image log analysis and spinner data. It has generally been found that porous ignimbrite can generate a good permeability in the reservoir. Some examples where high permeability ignimbrite has been encountered in geothermal drilling include the Mokai (Bignall et al., 2010), Ngatamariki (Cant et al., (2018) (New Zealand) and Tompaso (Ikhwan et al., 2021) (Indonesia) as a caldera-hosted geothermal system. Other geothermal fields in Sumatra, for example, Muara Laboh and Rantau Dadap, also report the role of the Hulusimpang or Painan formation on their reservoir, which is mostly composed of silicic tuff or ignimbrite (Mussofan et al., 2019). Moreover, the silicic product, such as dacitic intrusion and rhyolitic tuff is also encountered in Bukit Daun and Ulubelu fields, which could be 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 those fields 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, the Altiplano-Puna, South America, and the Taupo Volcanic Zone, New Zealand. With further study, we expect Sumatra will also qualify as hosting one or more ignimbrite flair-up events during Tertiary and Quarternary time. Thus, targeting this formation could be highly considered in the next well targeting strategy especially in Sumatra's geothermal field.

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