VOLCANOSTRATIGRAPHY OF HULULAIS GEOTHERMAL FIELD, BENGKULU, INDONESIA

Graniko Reza Pratama[1], Vivi Dewi Mardiana Nusantara[1] , Sapto Trianggo Nurseto[1], Muhammad Tajul Arifin[1], Mochamad Husni Thamrin[1]

[1]PT. Pertamina Geothermal Energy (PGE), Indonesia

graniko.p@pertamina.com

Keywords: *Hululais, Sumatra, geothermal, volcanostratigraphy, volcanic facies*

ABSTRACT

Hululais geothermal field is one of the exploration geothermal fields operated by PT Pertamina Geothermal Energy (PGE). It is located in Rejang Lebong district, Bengkulu province, Sumatra Island, Indonesia. Regionally, this field situated within Bukit Barisan Mountain range on the western side of an overlapping of two major fault segments. They are called Ketahun and Musi Segment. These are two segments of the Great Sumatran Fault complex.

In 2018, geological mapping was carried out to update the data of Hululais volcanostratigraphy by PT PGE. 24 wells were successfully drilled to complete the exploration and development drilling stage on this field. Based on data from surface geological mapping, subsurface (borehole data such as cuttings, cores and borehole image), remote sensing, and some updated modification reports from the previous researchers, Hululais field is part of the quaternary Hululais Volcanic Complex (HVC) from quaternary.

The field comprises six main units (Bukit Resam, Suban Agung, Bukit Beriti, Bukit Gedang, Bukit Lumut and Bukit Pabuar) with associated primary/secondary deposits.

1. INTRODUCTION

Hululais geothermal field is located in Rejang Lebong district, Bengkulu province, Sumatra Island, Indonesia. The field is one of the geothermal working areas operated by Pertamina Geothermal Energy (PGE). It is 6 hours' drive from Bengkulu City towards the mountainous Barisan Range in the north (Figure 1).

Geoscience studies in Hululais and surrounding areas have been carried out by Pertamina and other institutions since 1992. The earliest publication in the study area focuses on the regional geological mapping of Bengkulu with a scale of 1:100.000 (Gafoer, et al., 1992). The more detailed geological mapping in the study area was done internally by Pertamina (Budiardjo, 1994) which preceded the earliest geothermal resource assessment of Hululais. Since then, various geoscience publications have been made but few that discuss the structural and volcanism aspects of Hululais. In 2018, geological mapping was carried out to update the data of Hululais volcanostratigraphy by PT PGE.

Figure 1. Location map of the Hululais geothermal field (Topography taken from maps.google.com, 2020)

2. TECTONIC SETTING & STRUCTURAL GEOLOGY

2.1 Tectonic Setting

Sumatra Island is affected by the convergence of two plates, the northward movement of Indian Plate beneath the Eurasian Plate. The convergence of these two plates is accommodated by oblique subduction. The result of oblique subduction occurs on the surface by the Northwest-Southeast dextral strike-slip of Sumatran Fault System (SFS). The fault zone forms the NW-SE Barisan Range of Sumatra Island that

separates the back-arc basin to the east and forearc basin to the west.

Along its 1900 kilometers (km) long, the Sumatra Fault Zone has 20 major segmentations separated mostly by valleys and lakes that form as dilational jogs. The dilational jogs length might vary from about 35 km to 200 km (Natawidjaja, 2018). The movement of SFS also provides pathways for magma that is resulted from partial melting as the product of the oblique subduction. Therefore, most major volcanoes in Sumatra Island is located parallel to SFS and near from the fault zone. (Figure 2).

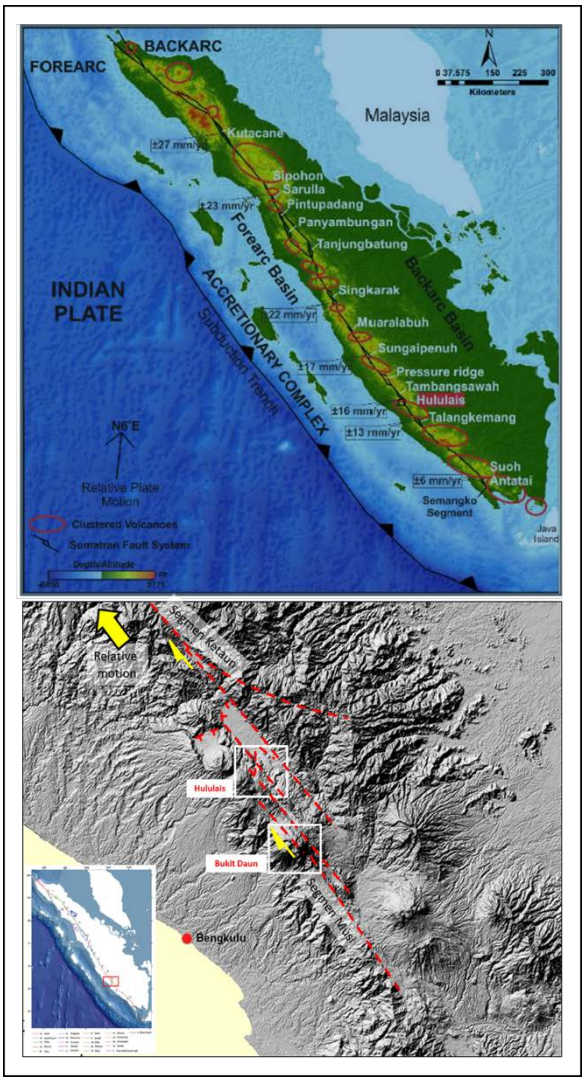


Figure 2. Tectonic map of Sumatra showing the location of Hululais geothermal field and the clustered volcanoes within the Sumatra Fault System (SFS) (modified from Muraoka, et al., 2010, Barber, et al., 2005, Darman & Sidi, 2000, Sieh & Natawidjaja, 2000) of Nurseto et al., 2020. Hululais is located at the overlap of the Ketahun and Musi Segments.

Hululais is located between two segments of the Sumatra Fault System (SFS) with a NW-SE direction, namely the Ketaun Segment (north) and the Musi Segment (south). There are two main depressions at the northwestern of the Musi Segment, namely the Muara Aman tectonic depression which extends at the intersection of the Musi and Ketaun Segments. The Tabahbaru volcanotectonic depression that appears at the northwestern distal of Mt. Lumut.

The Ketaun segment has one main straight segment and it curves eastward at its southeast. The Musi segment overlapps with the Ketaun segment in the Muara Aman depression area. The northwestern tip of the Musi Segment is present as several overlapping segments to the southwest, forming a wide transitional strain zone. The Musi Segment lies 70 km from the Air Keruh pull-apart basin in the southeast and has slip rate of 11 mm/yr. It is also interpreted continue beneath the Hululais and Bukit Lumut mountain. Ketahun Segment has 85 km in length and at the southern tip of the segment, it ends at the 6-8 km wide dilatational step over onto the Musi Segment (Sieh and Natawidjaja, 2000).

The two depressions are relatively parallel and adjacent. This indicates that the western block of the Sumatra Fault is actively moving to the northwest in dextral shifts, while the eastern block is relatively more static. This condition is considered to control the local geological conditions in the Hululais area.

2.2 Structural Geology

The geological structure of Hululais is analyzed from various surface and subsurface data. Lineament analysis from remote sensing (LiDAR), field data (extension fracture, shear fracture, sheeting joint, and possible fault surfaces measurement), geophysical data (gravity) and fracture orientation from borehole log data. There are three structure orientations in Hululais, NNW-SSE or relative N-S, NE-SW and NW-SE. (Figure 3).

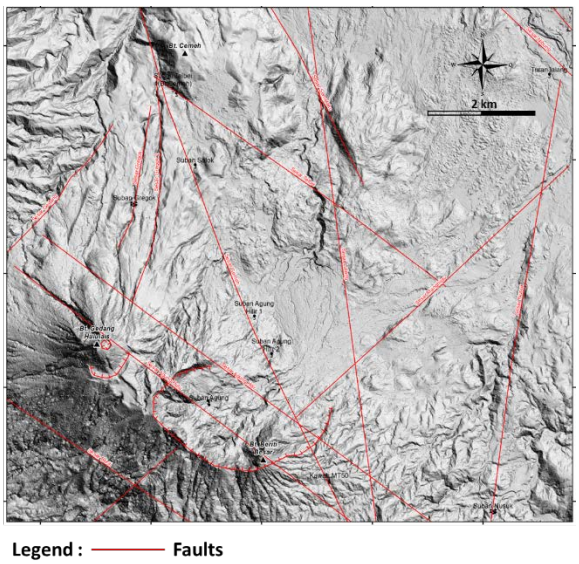


Figure 3. Structural geology map of Hululais geothermal field (PGE, 2018).

The NW – SE direction is similar to that of the SFS. These faults control the permeability and fluid flow of the Hululais geothermal field.

Based on well drilling data obtained from borehole images, it shows that the productive faults are NW-SE direction faults (Suban Agung Hulu Fault, Suban Agung Hilir Fault and Cemeh Faults)

3. VOLCANOSTRATIGRAPHY OF HULULAIS

3.1 Volcanism of Hululais

The updating of surface geological data in the Hululais field was carried out in 2018 with an independent detailed volcanostratigraphic survey by the exploration division of PT Pertamina Geothermal Energy (PGE). There are at least three main volcanic phases during the quaternary which are known to develop and play an important role in the geothermal system of the Hululais field, mentioned from old to young, namely Bt. Suban Agung volcanism, Bt. Beriti Besar and Beriti Kecil volcanism, then the youngest is the volcanism of Bt. Gedang Tua and Gedang. These last two still show undisturbed central cone morphology.

Suban Agung hill volcanism is the oldest and largest quaternary volcanism in the active geothermal zone of Hululais. K-Ar analysis of andesite samples taken in the crater of the Suban Agung hill showed that the age of the rocks was around 0.907 ± 0.25 million years ago (Budiardjo, 1994).

Based on the results of observations, it is known that the Suban Agung caldera that seen now, is the product of volcanic activity and giant colluvial activities from the ancient Mount Suban Agung. Large landslides that have occurred in the past, indicated by the hummock complex which is 8 km away in the northern part of the Bt. Suban Agung body. The hummock complex is a collection of chunks of rock composed of cataclastic andesite facies. The hummock complex is depicted on the geological map as the Non-epiclast / pyroclast unit of the Bukit Nibung deposit and the Debris avalanche Suban Agung Purba 1 and 2. The collapse of old Suban Agung could use the 1980's Mt. St. Helens eruption as the recent analog based on its outcrops, the morphology of amphitheater rim and the hummocky topography on the surface

The volcanism of the big and small hills of Beriti is distinguished by the morphology of the volcanic cones that form on the surface at the present time. K-Ar dating analysis was carried out using andesite samples from the Bukit Beriti Kecil Lava & pyroclastic unit showing that the age of the rocks ranged from 2.28 ± 0.47 million years ago (Budiardjo, 1994). The youngest volcanism in the Hululais field is the Old and Young Gedang. The morphology of these two formations forms a parasitic cone flank that develops on the northwest side of the hill body of Suban Agung.

Nurseto et al., 2020 explain in detail about the volcanism history of Hululais and surrounding area could be illustrated as follows (Figure 4):

1. Construction phase of Suban Agung, the volcanoes comprised of andesite lava and pyroclastic with an elevation about 3000 masl. Musi Segment Fault as a part of Great Sumatran Fault provides the conduit for magma to emerge from beneath
2. As the GSF is active, it may trigger a potential slope failure due to frequent earthquakes.
3. Destruction phase of Suban Agung might be triggered by lava dome that plugged at the top of the crater. The eruption along with a potential slope failure on the volcano body is favourable to have a debris avalanche and a collapsed crater. The ejected material could reach to more than 8 km.
4. As the area has an active geologic structures thus provides pathways for magma to emerge, the parasitic cone of Bukit Beriti and Bukit Gedang Tua was formed on the both flank. The Bukit Beriti and Bukit Gedang products cover to the NE and N from its eruption centre.
5. The volcanism continues to form latter Bukit Beriti hummock units and Bukit Gedang Muda lava dome on top of the eruption centre.
6. Recently, heat below Suban Agung has become the heat source for Hululais geothermal system. The active geologic structures from Musi Segment Fault and volcanic structures provide the permeability for the hydrothermal fluids to circulate.

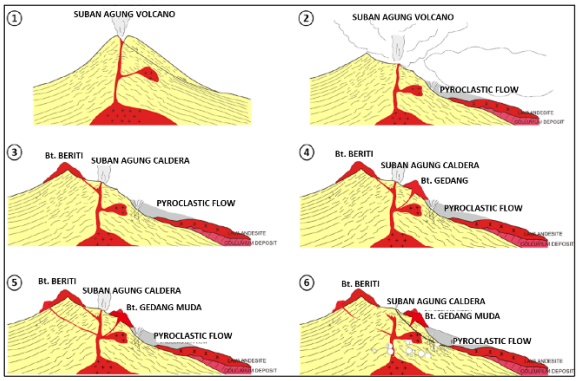


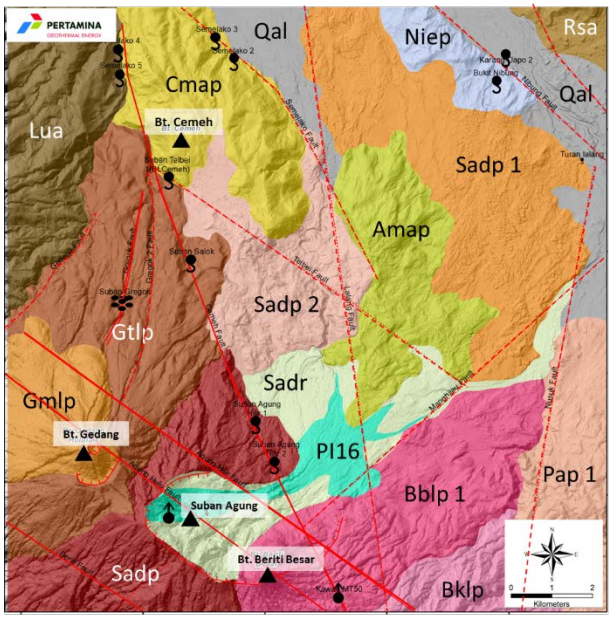
Figure 4. Volcanism of Suban Agung, Bukit Beriti and Bukit Gedang (Nurseto et al., 2020)

3.2. Surface Volcanostratigraphy of Hululais

Volcanostratigraphy of Hululais follows the guidelines on Sandi Stratigrafi Indonesia (1996) and Bronto, et al., (2016) where each unit is divided based on the volcanic source, description and the genesis (Figure 6). The sequence of each unit is determined directly from observation in the field and indirectly from remote sensing analysis and also from previous researches (Gafoer, et al., 1992, Budiardjo., 1994, PGE., 2014, PGE-UGM joint study., 2014 and PGE., 2018).

The research in 2008 produced an update geological map that describes the order of volcanism and surface stratigraphy in more detail. The distribution of rock units on the surface in the Hululais field is shown by the geological map below (Figure 5).

The rows of volcanic facies of the Bt. Suban Agung, Bt. Beriti Besar & Kecil, and Bt. Gedang Tua & Muda develop in a northwest - southeast direction as a row of quarterly old hills. It is believed that this row of quaternary volcanic hills is one of the manifestations of an active under-surface heat source in the form of a feeder moving to the surface as an intrusion. A detailed explanation of the character of surface rock formations in the Hululais field which is depicted on the Hululais geological map in 2018, is explained from young to old.



Epoch	Age Dating (Budiardjo, 1994)	Crown	Hummock	Primary Deposit	Secondary Deposit
Holocene	Recent				Alluvial deposit (Qal)
					2016 product (PI16)
					Suban Agung Debris Avalanche (Sadr)
	1100 ya	Bukit Pabuar		Bukit Pabuar 3 Lava and Pyroclastic (Palp3)	
				Bukit Pabuar 1 Pyroclastic (Pap1)	
Pleistocene	0.907 mya	Bukit Gedang	Bukit Gedang Muda	Bukit Gedang Muda Lava and Pyroclastic (Gmlp)	
			Bukit Gedang Tua	Bukit Gedang Tua Lava and Pyroclastic (Gtlp)	
		Bukit Beriti	Beriti Besar	Beriti Besar 1 Lava and Pyroclastic (Bblp1)	
			Beriti Kecil	Bukit Beriti Kecil Lava and Pyroclastic (Bklp)	
		Suban Agung		Ancient Suban Agung Debris Avalanche 2 (Sadp2)	
			Air Mubai (?)	Air Mubai Andesite and pyroclastic (Amap)	
				Ancient Suban Agung Debris Avalanche 1 (Sadp1)	
					Non-epiclastic/pyroclastic deposit (Niep)
			Bukit Cemeh (?)	Bukit Cemeh Andesite and pyroclastic (Cmap)	
				Suban Agung Lava and Pyroclastic (Salp)	
	0.893 mya?	Bukit Lumut		Bukit Lumut Andesite (Lua)	
	1.220 mya	Bukit Resam		Bukit Resam Andesite (Rsa)	

Figure 5. Geological map and volcanostratigraphy of Hululais geothermal field (PT PGE, 2018)

3.2.1. Alluvial deposit (Qal)

Alluvial deposits are located in the north-northeast part of the Hululais field. It consists of unconsolidated material in the size of boulders, gravel, sand, silt and clay, some of which are also mixed with materials carried by flash floods from Hululais.

3.2.2. Suban Agung Debris Avalanche (Sadr)

Debris avalanche Suban Agung spread from the Rim Suban Agung to the northeast. It is an unconsolidated-semiconsolidated material such as breccia which is composed of fresh-altered rock fragments with a partially altered matrix. The source of material for debris avalanche is interpreted to come from Suban Agung. (Figure 6)

Figure 6. The product of Suban Agung Debris Avalance, consisting of an unconsolidated-semiconsolidated material such as breccia which is composed of fresh-altered rock fragments.

3.2.3. Pabuar volcanic (Pap)

Occupies the east-southeast part of the Hululais field. Composed of lapilli tuffs, some of the lapilli tuffs have a layer structure such as graded bedding and partially altered. 14C dating has been carried out on a sample of charcoal from Pabuar tuff and aged 1100 years ago. There are obsidian flows that are found above the Bayuak Andesite, but this unit cannot be ascertained where the location is (Pertamina internal report, 1994).

3.2.4. Gedang muda volcanic (Gmlp)

This is the youngest volcanic product from Bukit Gedang, occupying the top of Gedang Hill to the middle of the mountain body to the west. Composed of andesite with massive structure and sheeting joints, andesite lava breccias, andesite fragments dominated by andesite fragments partly matrix supported, and found lava breccias that are affected by the activity of hydrothermal fluids with a low pH which is characterized by the presence of kaolinite with andesite fragments that have a slit texture due to leaching. (Figure 7)

Figure 7. The product of Gedang Muda volcanic, consisting of andesite lava with sheeting joints structure.

3.2.5. Gedang tua volcanic (Gtlp)

Old volcanic products from Bukit Gedang, occupy from the top to the bottom of the body of Bukit Gedang. Composed of andesite with a massive structure and sheeting joints, lava

breccias are predominantly andesite fragments and partly fragmented obsidian.

3.2.6. Beriti Besar Volcanic (Bblp)
This unit is the constituent of Bukit Beriti Besar in the southeastern part of Suban Agung's body. Consists of andesite lava with a sheeting joint structure and partly massive, elsewhere composed of lava breccia, tuff, and hydrothermal deposits in the form of altered clay material containing organic material (Figure 8).

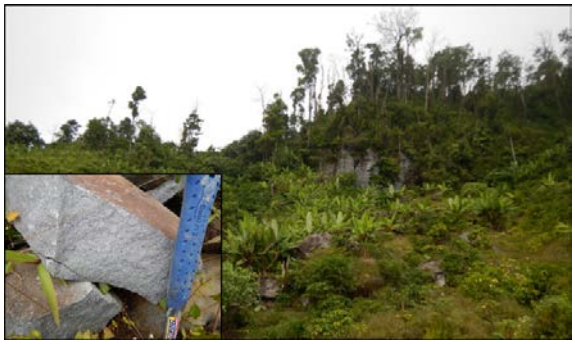


Figure 8. The product of Beriti besar volcanic, consisting of andesite lava.

3.2.7. Beriti Kecil Volcanic (Bklp)
It is a constituent of Bukit Beriti Kecil in the southeast and is volcanostratigraphically relatively older than the Beriti Besar Volcanic. It consists of andesite lava with a sheeting joint structure, lava breccias and tuff.

3.2.8. Ancient Suban Agung Debris Avalanche 2 (Sadp2)
Is a product of ancient avalanche debris scattered in the northern part of Rim Suban Agung. The ancient avalanche debris product deposits from Suban Agung are characterized by the relief on LIDAR such as hummock (Figure 9). Consisting of andesite boulders, in several places the sheeting joint structure of the andesite boulders was observed and tuff-breccia outcrops were observed, some of which were intensively altered.

Figure 9. The product of Ancient Suban Agung Debris Avalanche 2, consisting of andesite boulders.

3.2.9. Air Mubai Volcanic (Amap)
Occupies the middle of the Hululais field. Polymic breccia cliffs, matrix supported with altered matrix, were observed on the cliffs in the Kotok water river. There were also boulders of rock which were partly altered and partly fresh.

3.2.10. Ancient Suban Agung Debris Avalanche 1 (Sadp1)
It is located in the north-northeast part of the Hululais field which is characterized by a low, rough and ruffled relief on LIDAR. This is the oldest avalanche debris product from Suban Agung. Consisting of boulders of andesite, xenoliths were observed in the andesite fragments which indicated the product near the vent facies and cataclastic structure indicating the products of large avalanches of ancient volcanoes.

3.2.11. Nibung non epiclastic-pyroclastic deposits (Niep)
Located in the north-northeast part of the Hululais field, it consists of pyroclastic and nonepyclastic deposition materials. Pyroclastic deposits of coarse-crust sand, with andesite fragments, partly scoria. The nonepiclastic deposit is an ignimbrite chip product, with pumice and andesite fragments, 1-10 centimeters (cm) in size and has a layering structure.

3.2.12. Cemeh Volcanic (Cmap)
Located in the northern part of the Hululais field, composed of fine-coarse-sized tuff of dust where this unit is above andesite or lava breccia (?). Either exposed or in the form of andesite blocks in the area around Semelako.

3.2.13. Young Suban Agung Volcanic (Salp)
Is a constituent of the body of the youngest Suban Agung. In the Suban Agung crater, lava and pyroclastic layers are observed, which constitute the lithology of Suban Agung. Also observed altered rocks around the Suban Agung crater due to the presence of manifestations.

3.2.14. Lumut Andesite (Lua)
The Bt. Lumut Andesite Rocks are the constituent of Bukit Lumut which is located in the northwestern part of Bt. Gedang. Bukit Lumut has an open crater or collapsed crater that leads to the north. This unit rock is composed of alternating basaltic andesite lava with breccias and tuff breccias can be found locally. The results of K / Ar dating on andesite pyroxene samples from Sungai Aman showed that the age was 0.89 million (?) (Pertamina internal report, 1994).

3.3. Sub-Surface Volcanostratigraphy of Hululais

Stratigraphy in the Hululais field was concluded by combining data on the distribution of rock on the surface and subsurface. The distribution of rocks on the surface refers to the geological map in 2018 which has been updated by the geologist team of PT PGE. The subsurface volcanostratigraphy of Hululais geothermal field obtained from the correlation well drilling data is depicted in the following section (Figure 10).

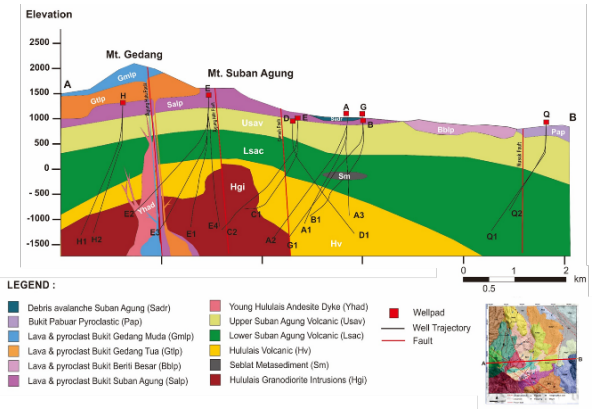


Figure 10. Subsurface volcanostratigraphy cross section of Hululais geothermal field (PGE, 2020)

The subsurface rocks obtained from the subsurface data, as follow:

3.3.1. Upper Suban Agung Volcanic (USAV)

The Upper Suban Agung Volcanic Formation (USAV) was identified and defined from drilling data. This formation is not exposed on the surface and is only found in the depth range of 100 - 750 meters in the production wells (wellpad A, C, E). The further away from this zone, this formation is getting thicker and is found in the range of 200 to 1700 meters (wellpad H and P) (figure 11).

The lithology that makes up the formation of the large volcanic upper Suban is dominated by tuff pyroclastic rocks and tuff breccias (figure 12) around wellpad B, P, and Q. While andesite breccias dominate around wellpad A, C, E, and H. These three types of lithology have relatively clay content. As a member of this formation, lenses of epiclastic lava deposits are found with a conglomeratic composition of tuff and silicified wood.

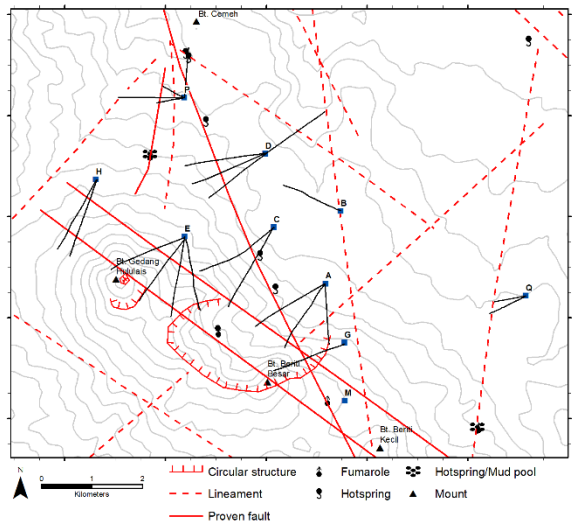


Figure 11. Well distribution map of Hululais geothermal field.

Figure 12. Binocular image of the tuff and tuff breccias that compose the formation of the upper suban agung volcanic.

3.3.2. Lower Suban Agung Volcanic (LSAV)

The lower suban agung volcanic formation was found to be shallower (top formation at ± 800 m) around the Suban Agung and Beriti. Meanwhile, in the Bt. Gedang and around the injection wellpad, this layer is found to be deeper (± 1400 m top formation). This is controlled by the thickness of the upper layer of the great volcanic upper suban agung, and is associated with the claycap zone.

This formation is composed of intercalated layers of andesite lava, andesite breccias, tuff breccias, and lithic tuffs. Based on the character of the dominant minerals, this formation can also be referred to as a "clean volcanic product" formation, where the mineral markers of the reservoir begin to be found and the characteristic minerals of the clay cap begin to disappear.

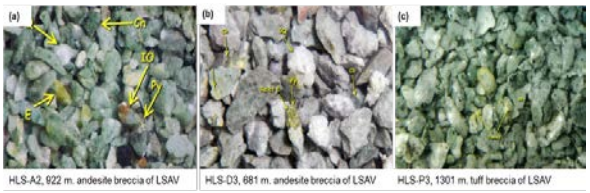


Figure 13. Physical appearance of andesite breccias and tuff breccias cutting members of LSAV.

3.3.3. Hululais volcanic (HV)

The Hululais volcanic (HV) formation is the zone where the Hululais field reservoir is generally found. Thus, this formation is also known as the "productive reservoir zone". The lithology of this formation is identified from drilling data. The lithology is andesite lava, characterized by a trachytic structure.

The main composition that distinguishes the volcanic hululais formation from the upper LSAV formation is the presence of less clay content in the volcanic hululais layer than in the LSAV.

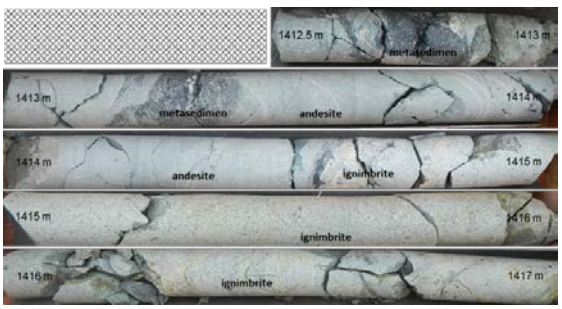


Figure 14. The cores that show this formation are composed of pyroclastic rocks ignimbrite, andesite, and metasediment inserts from the Seblat formation.

3.3.4. Hululais granodiorite intrusion (HGI)

Hululais granodiorit intrusion (HGI) is a batolite body beneath suban agung, gedang and beriti volcanism, in the hululais field. The rocks that compose this formation have been identified as plutonic rocks of the granodiorite type. (Figures 13). Its presence is found in cutting and core samples in wells in wellpad A, C and H.

The presence of intrusion granodiorite hululais formation indicates a nearby heat source, under the suban agung, beriti, and gedang. This formation is assumed to be of miocene age and is associated with the diorite formation of the Bt.Cogong which is exposed and raised on the south side of the hilly ranges of suban agung, gedang, and beriti. This assumption is also supported by regional geological data where the basement rocks around the Hululais field and the Tambang Sawah are composed of diorite to granodiorite lithology.

Figure 15. Sidewall core sample from drilling well at 2300 m showing granodiorite lithology (Nusantara, 2020).

3.3.5. Seblat metasedimen (Sm)

Seblat metasedimen is a non-volcanic rock found from drilling rock samples. This formation is found in the wells of wellpad A, D, P, and Q. Megascopic, this rock is referred to as a slate, with a dark gray to black color, with a strong foliation structure. (Figure 14). Petrographically, this rock shows a biogenic content with a clastic texture of wackestone (Dunham, 1962). Based on his petrological observations, the description approximates the physical properties of the limestone of the Seblat formation, which is the oldest tertiary sedimentary rock in the Bengkulu Basin.

Figure 16. sidewall core from drilling well at 2300 m showing metasediment rock (Nusantara, 2020)

Stratigraphy in the Hululais field was concluded by combining the distribution of rock data on the surface and subsurface. (Figure 16). The distribution of rocks on the surface refers to the geological map that was updated in 2018. Meanwhile, the distribution of rocks below the surface is interpreted from the correlation of data from drilling wells that have been processed and evaluated.

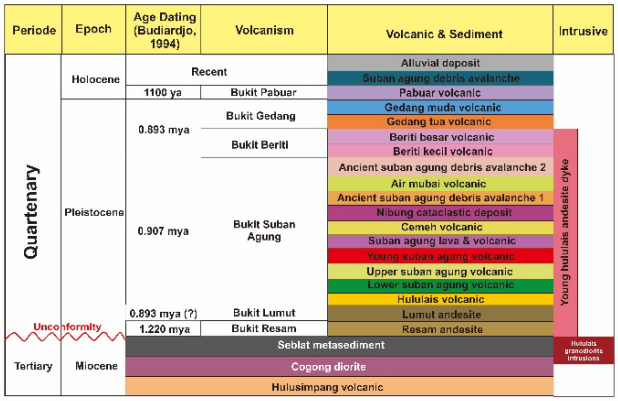


Figure 17. Volcanostratigraphy of Hululais (PGE, 2020)

4. CONCLUSION

There are 3 main periods? of volcanism that compose the volcanostratigraphy of the Hululais geothermal field, from old to young, namely Bt. Suban Agung, Bt. Beriti, and Bt. Gedang. The volcanic product of the Suban Agung is the main lithology found in the Hululais geothermal system which acts as a reservoir and cap rock. The lithology of the reservoir in Hululais is the lava and pyroclastic formation of the Lower Suban Agung (LSAV), the Volcanic Hululais (HV), and the Hululais Granodiorit Instrusion (HGI) formation.

ACKNOWLEDGEMENTS

The authors would like to thank PT PGE for allowing the publication of this paper. Thank you to the all team who contributed to the data acquisition and writing of this work. This paper would not have been possible without the encouragement and support of M. Husni Thamrin as our Manager.

REFERENCES

Bronto, S., 2010, Geologi Gunung Api Purba Publikasi Khusus, Badan Geologi Kementerian Energi dan Sumber Daya Mineral, Bandung.

Budiardjo, B., et al., 1994, Scientific Model of the Hululais Geothermal Resource, Internal Report, Eksplorasi Operasi Divisi Panasbumi Pertamina, Jakarta (unpublished)

Darman, H., and Sidi, F.H., 2000, An Outline of the Geology of Indonesia, Indonesian Association of Geologists, Jakarta, 192pp.Ibrahim, R.I., Sukhyar, R., Kuncahyo, R.: Future of geothermal development in Indonesia. *Proc. World Geothermal Congress 2005*, Antalya, Turkey. (2005).

Gafoer, S., Amin, T. C., and Pardede, R., 1992, Peta Geologi Lembar Bengkulu, Sumatra, skala 1: 100.000, Direktorat Geologi, Bandung.

Google Inc, 2020, Google Maps (http://maps.google.com/).

Koestono, H., Prasetyo, I.M., Nusantara, V.D.M., Thamrin, M.H., Kamah, M.Y, 2015, Hydrothermal Alteration Mineralogy of Well HLS-C, Hululais Geothermal Field, Bengkulu, Indonesia, Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April. Waitangi, New Zealand. (2020).

Nurseto,S.T., et al: Structural Geology and Volcanism in Hululais Geothermal Area, Bengkulu, Indonesia. *Proc. 9th ITB International Geothermal Workshop 2020*, ITB Bandung, Indonesia. (2020).

Nusantara, V.D.M., Pratama, G.R., Nurseto, S.T., Arifin, M.T., and Thamrin, M.H.: Characterization of Hululais subsurface rock formation and ts implication to strato volcano facies model Hululais geothermal field, Indonesia. *Proc. 42th New Zealand Geothermal Workshop 2020*. Waitangi, New Zealand. (2020).

Pertamina Geothermal Energy, 2020, Laporan Evaluasi Petrologi & Alterasi Hidrotermal Lapangan Hululais,Internal Report, Fungsi Exploration – Region I, Direktorat Perencanaan dan Pengembangan, Jakarta (unpublished)

Sieh, K. and Natawidjaja, D.H., 2000, Neotectonics of the Sumatran fault, Indonesia. Journal of Geophysical Research, v.105, no.b12, p.28,295-28,326