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The Potential of Sukadana Basalt Province as a New Geothermal Resources in The Back Arc of Sumatra: A New Insight from Petrology and Geochemistry

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Abstract

Geothermal resources are currently obtained from areas within volcanic arcs, such as the Pertamina Ulu Belu and Supreme Energy Rajabasa Geothermal Fields. However, this understanding may change in the future, as the Quaternary Sukadana Basalt Province (SBP), located in the back arc, is believed to have potential as a future geothermal energy resource. This research aims to explore the various factors that contribute to the high heat flow in the SBP region and generate a new perspective on geothermal energy particularly in the Lampung province. The methods used integrate previous research findings, such as heat flow data, regional tectonics, and geological structures, with new petrography-whole rock geochemistry. The whole rock geochemistry was determined using X-Ray Fluorescence (XRF), Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The SBP was formed by the Paleogene northwest-southeast striking fault and influenced by the Quaternary northeast-southwest striking fault, which may serve as conduits for hydrothermal fluid in addition to their vesicular structures. Geochemical analysis suggests the presence of both mantle plume and subduction-related processes. The magmatism linked to subduction-plume tectonic mechanisms and the thinning of the crust due to pull-apart motion caused by the movement of two large faults (Sumatra Fault Zone and Bangka Shear) can increase regional heat flow to 100±10 mW/m^2. As a result, the SBP has significant potential as a source of geothermal energy for electricity generation in the future.

Keywords:
Sukadana basalt, Lampung, renewable energy, mantle plume, back arc

1. Introduction

The Sukadana Basalt Province (SBP) is part of Sundaland, the continental promontory of the Eurasian plate in SE Asia (Hall & Morley, 2004). This continental region is surrounded by active and complex tectonic boundaries, with oceanic Indo-Australian plate subduction in the south under the continental Eurasian plate (Abdurrachman et al., 2018; Pramumijoyo & Sebrier, 1991). This oceanic plate undergoes partial melting at a depth range of 150–300 km and rises to the surface as magma (Ringwood, 1990). SBP has similarities with continental flood basalt, as both are short-duration eruptions dominated by mafic minerals (Coffin & Eldholm, 1994; Ketchum et al., 2013). The age of SBP is estimated to be about 0.8 Ma (Nishimura et al., 1986) or 1.2 Ma (Soeria-Atmaja et al., 1986), indicating that it is a Quaternary and short-duration eruption. Its age is similar to Mount Rajabasa (Hasibuan et al., 2020;

Mangga et al., 1993). Despite this, the presence of SBP remains an anomaly, such as its geometry and appearance in the back arc.

The SBP area is characterized by a significant amount of heat flow, which can be attributed to the fact that Sundaland is a region with a high surface heat flow, exceeding 80 mW/m^2, based on global data (Artemieva & Mooney, 2001). Nevertheless, upon closer identification, the SBP region displays a higher heat flow compared to other regions located in the back arc. According to research conducted by Hall and Morley (2004), the heat flow zone passes through Mount Rajabasa, the location of Rajabasa Supreme Energy. The high heat flow observed in the region is likely due to subduction-related arc magmatism (partial melting) in Sumatra and Java (Hall & Morley, 2004; Hall & Spakman, 2015). However, there are other factors contributing to the elevated heat flow in the region.

This study aims to explore the various factors that contribute to the high heat flow in the SBP region and generate a new perspective on geothermal energy exploration. Exploration and exploitation efforts in Sumatra have been largely confined to the volcano arc region. However, this poses a challenge to future development potential because volcanoes are situated close to or within national parks, such as Bukit Barisan National Park and Kerinci Seblat National Park, which raises environmental concerns. Hence, all stakeholders should explore alternative ways to obtain the geothermal potential outside of the regular volcano arc. This study used heat flow data from Hall & Morley (2004) as one of the information sources. This is a significant study since previous research by Gasparon (1993) did not consider geothermal data. The study proposes a new perspective that the back arc region has equal potential as a source of geothermal energy. The research methods involve a combination of published and new petrographic and whole-rock geochemical data to obtain novel insights. The goal is to reveal the geothermal potential in the SBP region based on rock petrography and geochemistry, with an additional analysis of geological structures to explain the appearance of SBP on the surface.

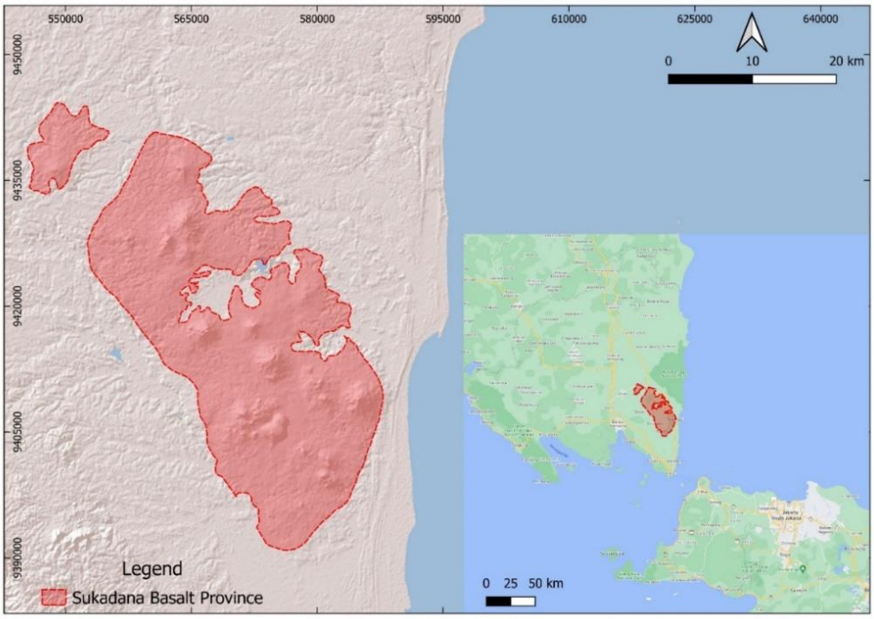

Figure 1. The Sukadana Basalt Province (SBP) is located in Lampung, Sumatra Island, and is characterized by small hills formed by basalt extrusion.

2. Method

This study utilized both published data and the latest collected petrographic and whole-rock geochemical data to evaluate the potential of the Sukadana Basalt Province as a future geothermal resource. The whole rock geochemical data were used to determine the tectonic setting, while the petrographic data was used to identify primary structures. The published data were obtained from several sources, including Nishimura et al. (1986), Mangga (1993), Sribudiyani (2003), and Hall & Morley (2004). Nishimura et al. (1986) discussed regional structures in the Northeast-Southwest (NE-

SW) direction, while Mangga (1993) focused on Quaternary fault structures. Sribudiyani (2003) indirectly stated that the Bangka Shear and Sumatra Fault Zone structures coincided during the Paleogene period. Finally, Hall & Morley (2004) discussed the high heat flow in the Sundaland area.

The Major and Trace elements (the whole rock geochemical) data were collected from three rocks, which were sampled from three observation points (1.1, 1.2, and 1.3) (Figure 7). Petrography analysis was conducted on the rocks sampled from 1.2. All the samples were taken from the Goa Pandan Area, which is considered the best outcrop from SBP and sufficiently representative of its tectonic setting. Geochemical analysis samples were processed at Intertek Jakarta Office using X-Ray Fluorescence (XRF), Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) to obtain the geochemical data. Meanwhile, the sample from 1.2 was processed at the Center of Research and Development of Mineral and Coal Technology in Bandung, West Java, to obtain petrography data.

The previous maps and concepts were re-evaluated and then integrated with the whole rock geochemical and petrographic data. Most maps used in this paper were processed using QGIS 3.16 with the Coordinate Reference System (CRS) WGS 84/UTM zone 48S and Digital Elevation Model (DEM) data from ESRI. The images were processed using the Inkscape program.

3. Results and Discussions

3.1 Regional Tectonics

The area surrounding SBP includes Lampung mainland and Sunda Strait (as shown in Figure 2). According to Nishimura et al. (1986) and Harjono et al. (1991), there is a lineament of islands that runs Northeast-Southwest (NE-SW) spanning from SBP, Mount Rajabasa, through Sebuku, Sebesi, Mount Anak Krakatau, to Panaitan Island. This lineament is related to the Quaternary structure, which is the primary controller of several volcanoes in the Sunda Strait and surrounding areas, including SBP. This argument is supported by the age of several volcanoes from previous research. Nishimura et al. (1986) and Soeria-Atmaja et al. (1986) explicitly concluded that SBP and Mount Rajabasa are Quaternary, as supported by research by Hasibuan et al. (2020) and Mangga et al. (1993). Mount Anak Krakatau, which is still active to this day, can also be classified as Quaternary (Abdurrachman et al., 2018). Additionally, the presence of this structure is supported by the relatively high intensity of earthquakes in the last 100 years within the shaded area in Figure 2. Earthquakes of the Quaternary age are typically associated with the development of active fault structures (Muksin et al., 2014; Panjaitan, 2015). In addition to the NE-SW striking structure, the Panjang fault also developed around SBP, which is closely related to the Sumatra fault system (Pramumijoyo & Sebrier, 1991).

The emergence of SBP was influenced by the development of two major fault structures, which are the Bangka Shear and Sumatra Fault Zone (SFZ), located approximately 350 km apart. These faults were indirectly formed due to the collision between India and Eurasia Plates, and they have similarities such as their direction and fault type (dextral strike-slip faults and NW-SE orientation) (Figure 3B). The movement of these two strike-slip faults also impacts the development of Late Cretaceous to Early Tertiary North-South (N-S) direction basins (Sribudiyani et al., 2003). Based on a review of the geometry of SBP, the formation of structures follows a pull-apart mechanism as a consequence of the movement of Bangka Shear and SFZ (Figure 4). This mechanism makes the crust's thickness thinner than its surrounding. As an example of this mechanism, the thinning underneath Mount Anak Krakatau, which has a thickness of only 22 km due to the pull-apart mechanism in the Sunda Strait (Mandeville et al., 1996; Susilohadi et al., 2009), shows a close relationship between the pull-apart mechanism and magma activity (Girard & van Wyk de Vries, 2005). As seen in Figure 4, the geometry of SBP tends to be NW-SE direction, which is due to the dominance of SFZ over the influence of Bangka Shear.

The evolution of structures formed in the SBP and surrounding areas results from the geological dynamics of Sundaland. Fault structures associated with SBP can be divided into two patterns: NE-SW and NW-SE. These structures can be the main conduit of hydrothermal flows to the surface and production wells (if drilled) (Früh-green et al., 2022; Rybach, 2019; Zheng et al., 2019).

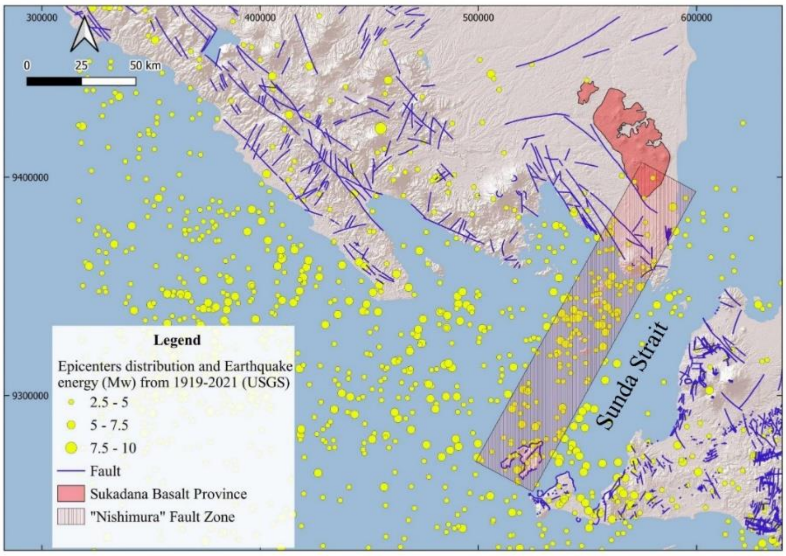

Figure 2. Distribution of earthquake epicenters with energy (USGS), Quaternary faults (blue lines), and the "Nishimura" Fault Zone (shaded area) according to Nishimura (1986). The "Nishimura" Fault Zone is identifiable due to the high intensity of earthquakes within the area.

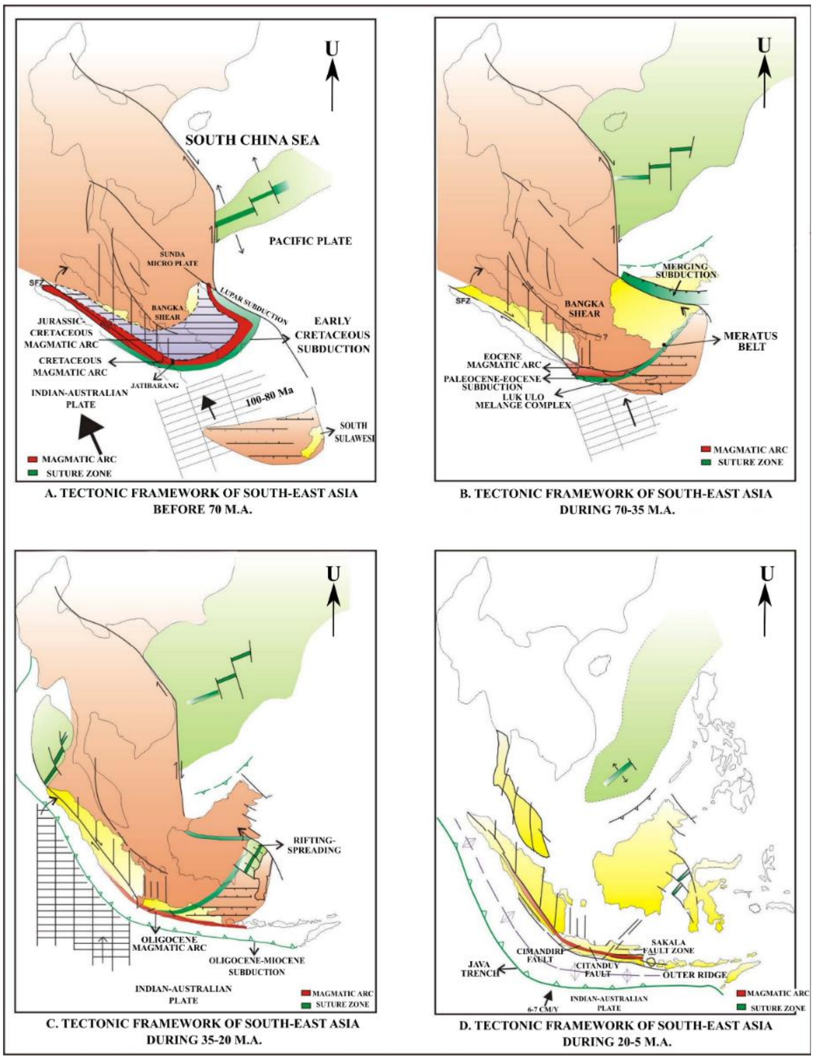

Figure 3. Tectonic evolution of western Indonesia (Sribudiyani et al., 2003).

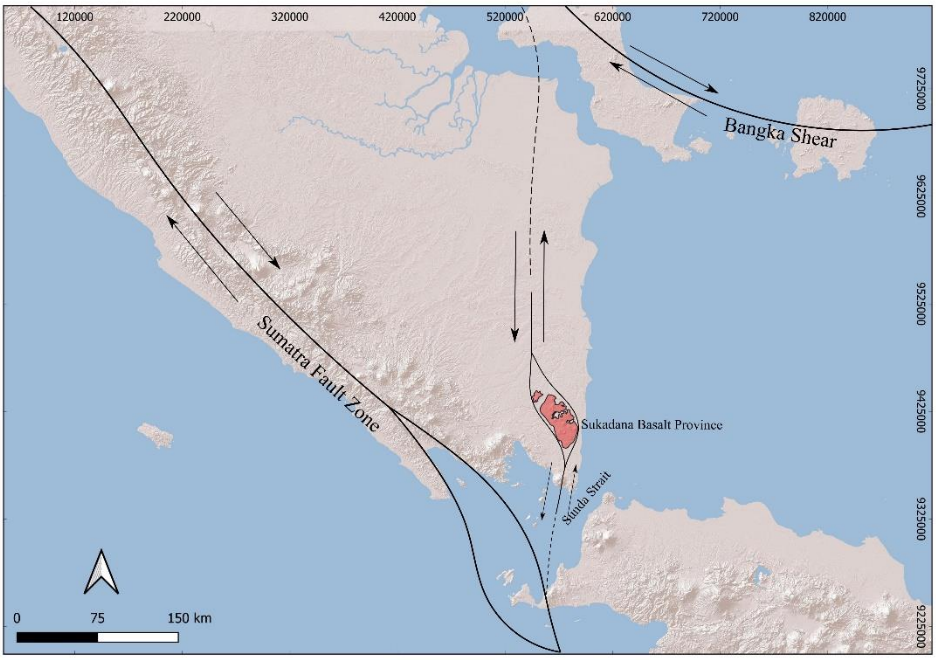

Figure 4. The development of SBP was triggered by a pull-apart mechanism caused by the movement of the Sumatra Fault Zone and Bangka Shear between 70-35 Ma (Sribudiyani et al., 2003).

3.2 Regional Heat Flow

Sundaland is well-known for its high heat flow regions based on existing data. The value of heat flow surfaces is over 80 mW/m^2 (Artemieva & Mooney, 2001). Heat flow is related to magmatism-related subduction (Hall & Morley, 2004; Hall & Spakman, 2015). Even in the interior of Sundaland, heat flow comes from granite radiation and its erosional products (Hall & Morley, 2004). Figure 5 shows the distribution of heat flow in the Sundaland region. High heat flow in Sumatra Island is seen in more detail, especially in the back arc where the SBP is located. This figure shows a heat flow value of 100±10 mW/m^2 in the SBP region. This heat flow is continuously passing through Mount Rajabasa to the Sunda Strait (Figure 5). In addition to subduction, the high heat flow value is also caused by the continental plate's thickness, which ranges between 50–60 km in the back arc (Figure 6; Curie & Hyndman, 2006). The relationship between crust thickness and heat flow value is that the thinner the crust, the higher the heat flow value. This is because the heat from the mantle is increasingly dominant. According to previous research, the crust thickness of Sumatra varies from 27–35 km (Bora et al., 2016). Referring to Curie & Hyndman (2006), the thickness estimation of the crust in SBP is about 27 km. There is a possibility that the thickness of the lithosphere underneath SBP is thinner than 50 km. This geological condition makes SBP has excellent potential as a source of geothermal power generation in the future. The SBP area might have a heat flow value that is the highest in the world among the regions in another back arc in the world (Table 1).

Table 1. Summary of observations for the present-day and former back arcs in the compilation. The Lampung back arc, where SBP is located, has the highest surface heat flow among the other region. Modified from Curie & Hyndman (2006).

Region (Arc-Back arc)	Back Arc Width (km)	Surface Heat Flow (mW/m2)
Cascadia–SW Canada	500	75±15
South America–South Chile/Argentina	>400	
South America–central Andes	400	85±16
South America–Peru (flat slab)		~50
Mexico	>250	72±17

Alaska-Bearing Shelf/continental Alaska	>800	
Aleutian-Bering Sea	>900	75±15
Kamchatka-Sea of Okhotsk	>700	70±18
Ryukyu-Korea	>600	69±16
Sunda-Borneo,	>800	76±18
Lampung Back Arc	**>100**	**100±10**
Northern Canadian	600	76±21
Cordillera		
Appalachians		50-60
Archean craton (average)		42±10

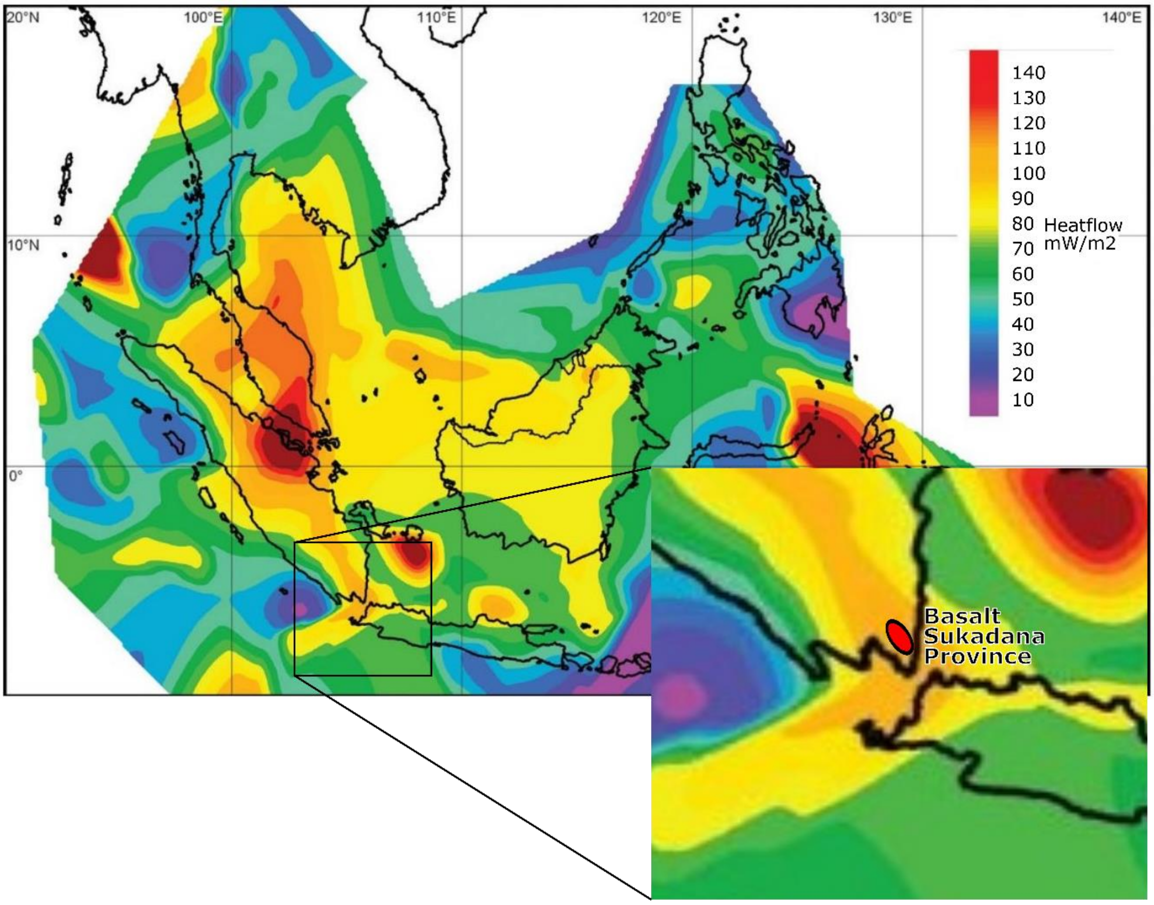

Figure 5. The distribution of surface heat flows within Sundaland. The SBP is located within orange color, equal to 100±10 mW/m^2 (Hall & Morley, 2004).

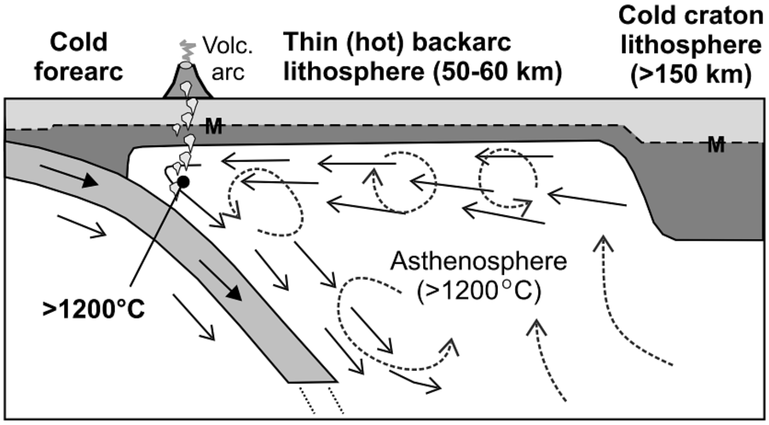

Figure 6. Schematic cross-section through a continental subduction zone (Curie & Hyndman, 2006).

3.3 Petrography and Geochemical

There are three observation points for rock's physical characteristics identification. The three observation points are 1.1, 1.2, and 1.3 (Figure 7a). Specifically for petrography analysis, the sample is only taken from point 1.2. In general, the three rock samples observed from the three observation points had the same physical characteristics, namely black brownish to black for the weathered color, bright gray for fresh color, aphanitic texture, and vesicular structure (Figure 7b). The petrography shows that the SBP is characterized by the dominance of vesicular structures, indicating a high potential for fluid flow (Figure 7c). This vesicular structure indicates that magma contains a massive amount of gas, specifically H_2O, CO_2, and S (Nukman & Moeck, 2013; Winter, 2009).

Table 2 presents the result of the geochemical analysis. These values of major and trace elements were plotted into Na_2O +K_2O vs. SiO_2, Ba/Nb vs. La/Nb, Nb/La vs. La/Yb, and Th/Nb vs. La/Yb. The Na_2O +K_2O vs. SiO_2 diagram shows the composition of the samples from basalt to basaltic andesite (Figure 8a; Le Bas et al., 1986). The geochemical data was plotted into Ba/Nb vs. La/Nb, Nb/La vs. La/Yb, and Th/Nb vs. La/Yb diagrams to investigate tectonic positions in more detail. The Ba/Nb vs. La/Nb diagram shows that SBP is affected by the Oceanic Island Basalt (OIB) mechanism (Figure 8b; Sun & McDonough, 1989). In the other diagram from Hollocher et al. (2012), SBP is closely related to the tectonic positions of oceanic islands and continental arcs (Figures 8c and 8d). OIB is associated with mantle plume tectonics (Safonova et al., 2015). This is further supported by the geological history of SBP, which indicates that one of the characteristics of mantle plumes is the eruption of magma in a short duration. Furthermore, this indicates that there is a mantle plume tectonic that occurs concurrently with subduction tectonics. A mantle plume means the magma ascends from the lower mantle. The magma affinity indicates that SBP is divided into two groups: Calc-Alcaline and Tholeiitic (Figure 9; Irvine & Baragar, 1971). This also shows that SBP is related to the subduction process and OIB (plume-type) (Garnero et al., 2007; Mattei et al., 2014). Plume tectonics occurred in the Quaternary period, therefore the remaining heat from this tectonic activity still exists (Figure 10). There is a possibility the slab window is located on a subducted oceanic plate, allowing the mantle plume to ascend to the surface.

Table 2. The whole rock geochemical for this study.

No. samples	**1.1**	**1.2**	**1.3**
Lithology	Basalt	Basalt	Basaltic andesite
Major element (%)			
SiO_2	48.23	51.54	52.12
Na_2O	2.95	3.63	3.27
K_2O	0.78	0.75	0.56
Trace Element (ppm)			
Ba	197.0	101.0	80.0
Nb	14.80	10.90	7.4
La	11.6	7.0	5.7
Yb	1.5	1.1	1.0
Th	2.54	1.5	1.21

3.4 Correlation with Other Studies

The tectonic evolution of SBP is identical to The Buyuk Menderes Basin, Turkey. The lithologies in the Buyuk Menderes Basin consist of schist and dolomitic marbles overlaid by sedimentary deposits. Evolutionary tectonics consists of metamorphism, magmatism, and deformation of the main rock formations (Yamanlar et al., 2020). The developing structures are Miocene North-South and Lower Pliocene East-West striking normal faults (Yilmaz, 2002). The intersections of these faults have created a favorable fractured medium for the formation of geothermal systems in the area. In this basin, there are 34 (21 proven and 13 probable occurrences) geothermal fields having medium to high temperature ($T \geq 100$ °C) values (Yamanlar et al., 2020). The similarity of SBP tectonics with the Buyuk Menders

Basin was undergoing a magmatism process and the formation of normal fault structures due to intensive tectonic processes. Based on this data, then SBP may have the same geothermal resource potential as the Buyuk Menderes Basin.

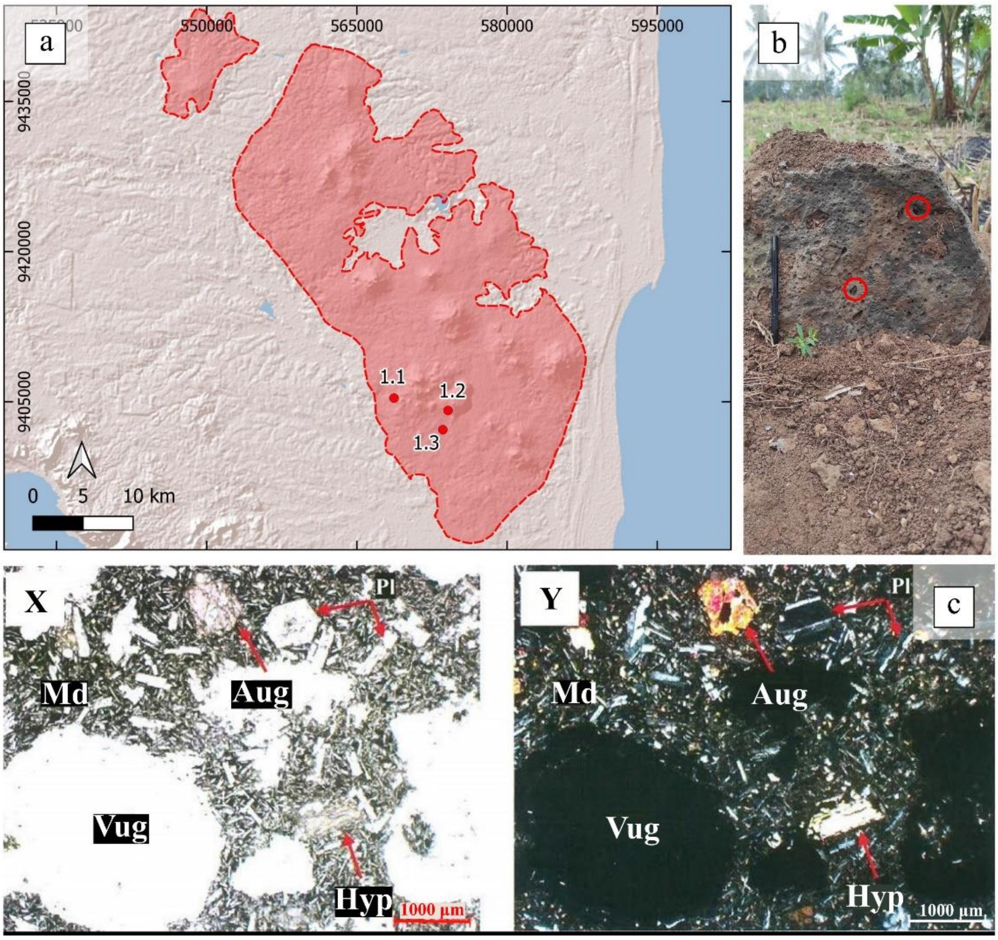

Figure 7. a. The location of observation points 1.1, 1.2, and 1.3. b. The physical characteristic of rock from observation point 1.1 shows vesicular structures (red circle). c. The thin optical section shows the vuggy structure is very dominant. X=Open Nicol ; Y=Cross Nicol. Aug= Augit, Hyp= Hipersten, Pl= Plagioklas, Md=Massadasar (Groundmass), Vug= Vuggy.

The same geological conditions are comparable in the northern part of Oman. The complexity of faults and joint structures in the northern part of Oman is likely to be present also in the SBP. These structures are of special interest for geothermal exploitation. Extensional tectonic processes from the Cretaceous to Paleogene created large-scale normal faults. This mechanism also occurs in SBP because SBP has been created through a pull-apart mechanism. The pull-apart mechanism creates normal fault bending (Fossen, 2010). Data from two groundwater wells show that Calculated temperature gradients (T-gradients) represent conductive conditions as 18.7 and 19.5 °C/km, corresponding to about 70–90 °C at 2000–3000 m depth (Schütz et al., 2018). This indicates the geothermal potential that could be utilized for high-energy uses like cooling or water desalination. In addition, from the T-logs and calculated thermal conductivity values in these wells, surface heat-flow values of 46.4 and 47.9 mW/m^2 were calculated (Schütz et al., 2018). Compared to the SBP estimated to have 100±10 mW/m^2, the heat flow in the northern part of Oman is relatively small. Therefore, the utilization of SBP's geothermal potential may exceed the geothermal utilization in the northern part of Oman.

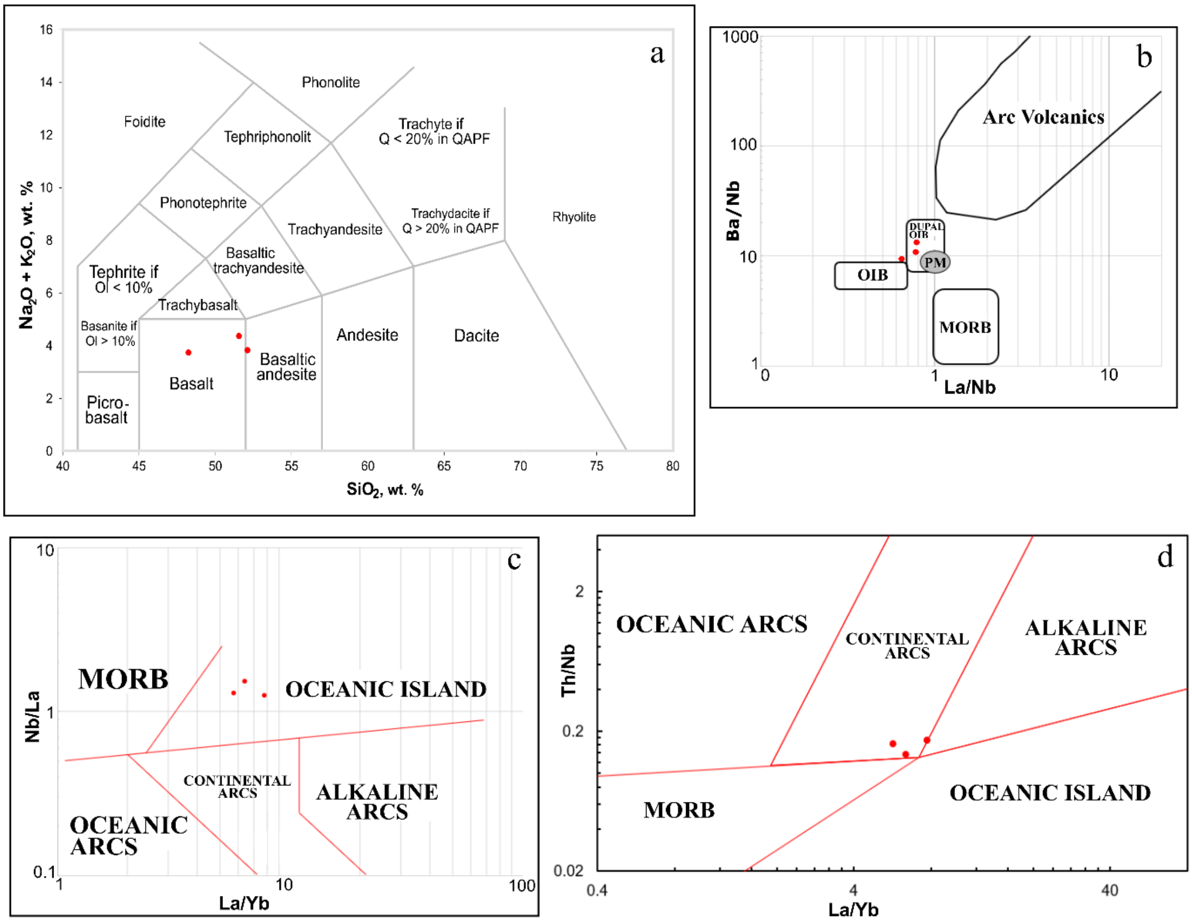

Figure 8. a. The plotting results in the diagram Na_2O+K_2O vs. SiO_2 show the composition from Basalt to basaltic andesite (Le Bas et al., 1986). b. The Ba/Nb vs. La/Nb diagram shows that SBP is influenced by a mantle plume tectonic (Sun & McDonough, 1989). c and d. Diagrams from Hollocher et al. (2012) show that SBP is closely related to the tectonic position of oceanic islands and continental arcs.

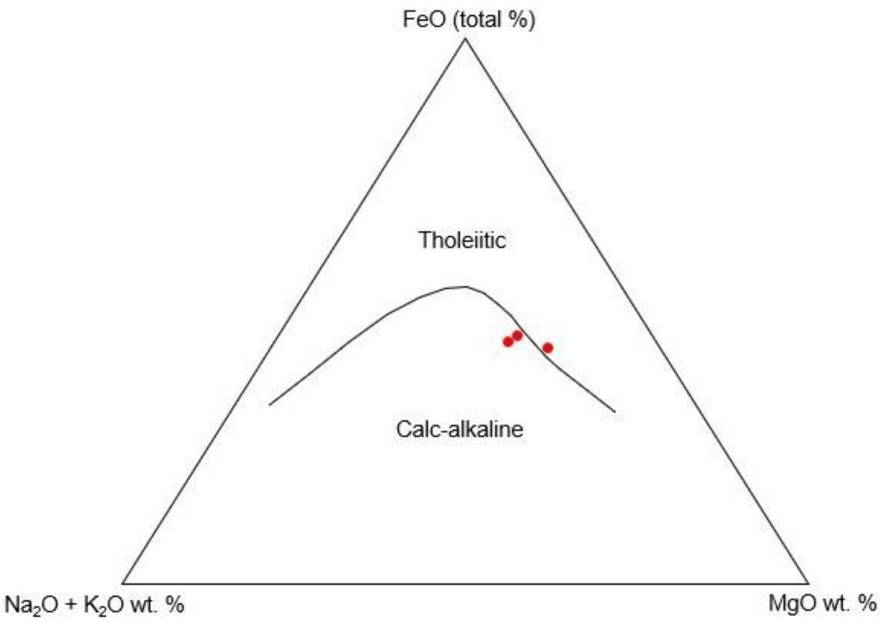

Figure 9. The diagram from Irvine & Baragar (1971) shows SBP is divided into two groups: Calc-Alcaline and Tholeiitic.

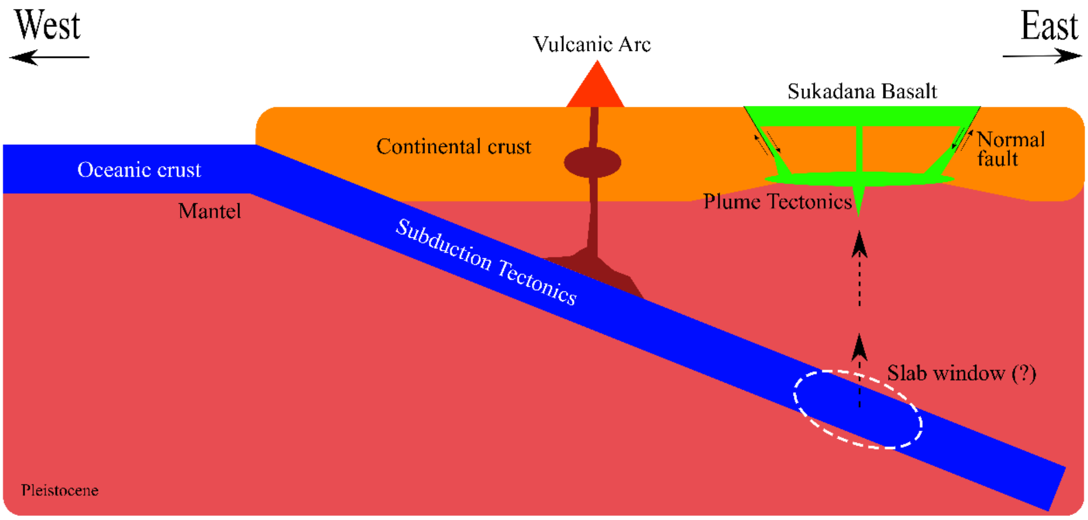

Figure 10. The appearance of Sukadana Basalt resulted from plume tectonics that occurred in the Quaternary period. The figure is not to scale.

4. Conclusions

The presence of Sukadana Basalt Province (SBP) on the surface is unique because of its position in the back arc. SBP has formed through the pull-apart mechanism from two large regional faults: Sumatra Fault Zone and Bangka Shear. These faults have caused the crust's thickness in this area to be thinner than the surrounding area. The geochemical data plotted into Nb/La vs. La/Yb, Th/Nb vs. La/Yb, Ba/Nb vs. La/Nb, and Na_2O+K_2O-MgO-FeO diagram show that there is a mantle plume tectonic influence in the SBP genesis. The interaction between the mantle plume and subduction tectonics in this area results in high heat flow, which can reach up to 100±10 mW/m^2. The Late Cretaceous to Early Tertiary (NW-SE) and Quaternary (NE-SW) geological structures make SBP very interesting to be explored further. The structural complexities make the fluids pass well. This is also supported by petrography data that indicates highly developed vesicular structures. Compared to other studies in The Buyuk Menderes Basin, Turkey, and the northern part of Oman, SBP has a higher potential for utilization. Therefore, SBP has the potential to be developed in the future, and more detailed exploration is needed to reveal the specific area for drilling.

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