PROCEEDINGS, 47th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 7-9, 2022
SGP-TR-223

The Geology and Geothermal System of the Dieng Geothermal Field, Central Java, Indonesia

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Keywords: Dieng, geology, geothermal system, thermal manifestation

ABSTRACT

The Dieng Geothermal Field is currently the only geothermal system in Central Java that has been producing electricity. Previous studies suggest that the field consists of three prospect areas, namely Sileri, Sikidang, and Pakuwaja. Re-interpretation of volcanostratigraphy through DEMNAS and field checking has been done in our study. In general, volcanism in Dieng field, based on previous researches and our ground check - started since the volcanic activity of Mt. Prau in the eastern margin as the oldest phase of volcanism. A younger and smaller eruption centers then emerged in the SW part from NW to SE are, Pagerkandang, Pangonan-Merdada, and Pakuwaja. These NW-SE trending younger volcanic centers are spatially associated with the distribution of thermal manifestations which are dominated by solfataric and steam heated fluid discharges. The volcanism and the types and distribution of thermal manifestations may give hints of different geothermal systems within the area. When combined with the results of subsurface geologic data and supporting information from previous studies, it will be an important knowledge to better understand of the geology and geothermal system of the field.

1. INTRODUCTION

The Dieng Geothermal Field is located at about 80 km northwest of Yogyakarta, at an elevation of about 2,000 m asl. Dieng is a liquid-dominated field with reservoir temperature >300°C. It has 60 MWe installed capacity by 2019 managed by PT. Geo Dipa Energi. Up to 2019, 47 wells have been drilled, with some reaching depths of >3 km. The Dieng Geothermal Field is volcano-hosted which spatially associated with volcanic complex which consists of many volcanic eruption centers. Thermal manifestations lay at about 2,000 m asl. This study describes the geology and characteristics of the geothermal system of the field. Field work has been conducted supported by the results of subsurface study from 4 wells by the first author (Shalihin, et al., 2020) and geoscientific work of other workers. The study area is presented by Figure 1.

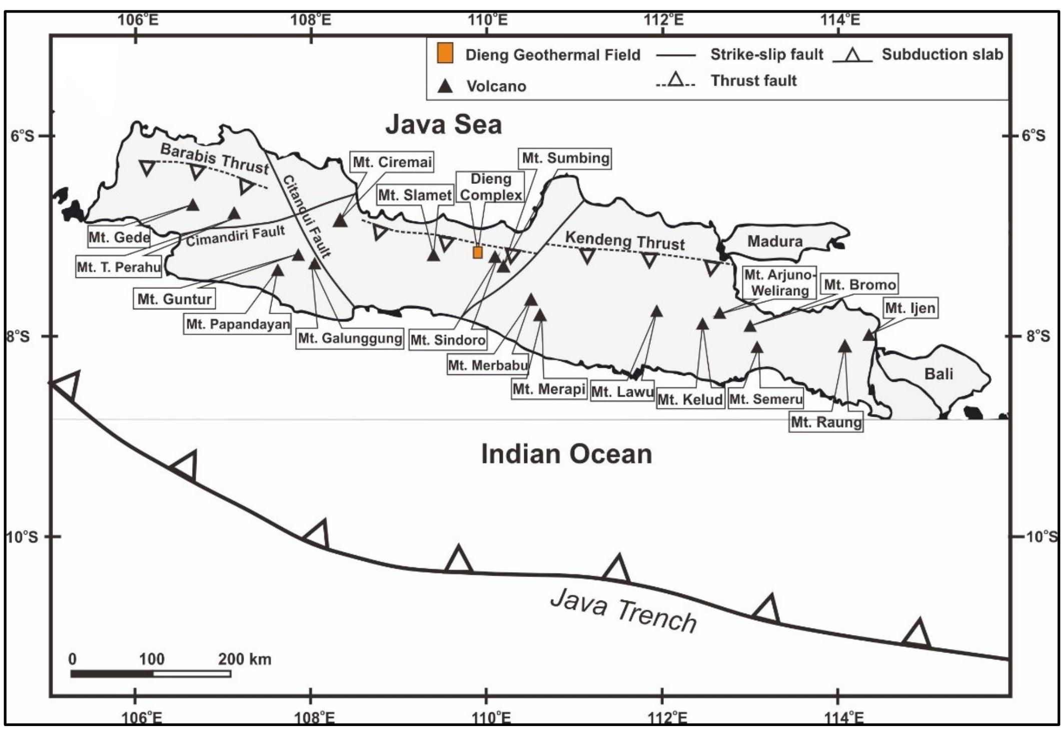

Figure 1: Location of the Dieng Geothermal Field within the simplified tectonic map of the Java Island in respect to major Quaternary volcanoes in Java (compiled from Simandjuntak and Barber, 1996).

2. GEOLOGY

2.1 Regional Setting

Physiographically the Dieng Geothermal Field is located within the North Serayu Range, and is part of the Quartenary Volcanoes of Java (van Bemmelen, 1949). The geology of Java is controlled by subduction of the Indian-Australian plates below the Eurasian continental plates (Hamilton, 1979; Simandjuntak and Barber, 1996). The island was affected by compressional forces associated with the Sunda orogeny in the late Neogen which produced plutonic intrusions and the uplift of the volcanic arc (Simandjuntak and Barber, 1996). Dieng field is part of the Dieng Volcanic Complex comprising part of the NW-SE trending Quartenary volcanic chain, including the younger cones of Mt. Sundoro and Sumbing (Allard, et al., 1989).

Accoding to Miller, et al. (1983), Dieng field is located in a plateu that has elevation ranging from 1,600 and 2,100 m asl, enclosed by volcanic peaks rising to 2,200-2,565 m asl. The Dieng field is composed by a complex of late Quartenary to recent volcanic strato-cones, parasitic vents, and explosion craters. However, recent study of age dating by Boedihardi, et al. (1991) showed an older age on Prahu volcanic products (3.6 Ma; late Pliocene) as the oldest volcanic activity which was reported by Sukhyar, et al. (1986) formed the margin of the Dieng volcanic complex. Allard, et al. (1989) also stated that the remnants of the ancient caldera of Mt. Prahu in the eastern margin marked the oldest phase of the volcanic complex. A smaller eruption centers then emerged inside the SW part of the ancient caldera. The eruption centers from NW to SE are, Pagerkandang, Pangonan-Merdada, and Pakuwaja.

2.2 Geomorphology

The morphological analysis of the Dieng field was conducted using DEMNAS image which has an 8 m spatial resolution. The division of geomorphological units were made based on landform classification by Brahmantyo and Bandono (2006) which are composed of:

a) Volcanic Ridge of Gajahmungkur, Prahu, Sembungan and Sikunang.
b) Volcanic Cone of Mt. Reban 1, Reban 2, Sigemplong, Jimat, Nagasari, Bisma, Sidede, Pagerkandang, Pangonan, Merdada, Igir binem, Watusumbul, Kendil, Prambanan, Pakuwaja, Sikunir, Seroja and Sikunang.
c) Crater, circular/semi-circular features associate with Mt. Nagasari, Bisma, Pagerkandang, Pangonan, Merdada, Pakuwaja, Seroja, include several small craters which are associated with active thermal manifestation in Sileri, Sikidang, and Telaga Warna.
d) Alluvial plain.

2.3 Stratigraphy

Based on identification of the volcanic centers and interpretation of the distribution of their products we conclude there at least 24 volcanic units in the Dieng field. The parameters which are used as the basis of interpretation include ridge line continuity, drainage patterns, eruption centers and the distribution of their products, texture, morphology, as well cross cutting relationships between each volcanic unit. Their stratigraphic relationship was also inferred according to radiometric dating by Boedihardi, et al. (1991) and Harijoko, et al. (2016). We also consider the works of Boedihardi, et al. (1991) and Nurpratama, et al. (2015) to better understand stratigraphic relationship of the field in more detail. Following the terms used by Sukhyar, et al. (1986) they are grouped into the volcanic products of Old Dieng, Middle-aged Dieng and Young Dieng.

a) Old Dieng: products of the late Tertiary to early Quaternary volcanic activity which is dominated by pyroclastics and lava occupy the outer margin of the field. They are composed by basaltic and andesitic rocks. K-Ar dating of some volcanic products in this group indicates their age with range 3.6 - 2.53 Ma or late Pliocene to early Pleistocene (Boedihardi, et al., 1991).
b) Middle-aged Dieng: products thought to develop after a major volcanic eruption of Prahu. They are dominated by andesite lavas and tuff breccia from some volcanic centers which occur in the central part inside the area of the oldest volcanoes. K-Ar dating from volcanic products of Mt. Pagerkandang and Mt. Pangonan-Merdada as the members of this group suggests an age 0.46 and 0.37 Ma (middle Pleistocene), respectively (Boedihardi, et al., 1991).
c) Young Dieng: products from the smaller volcanic centers in the SE part of the field. They are dominantly composed of biotite bearing andesite lavas. Ar-Ar dating of samples from this group, namely Mt Kendil and Pakuwaja suggest its age is 0.27 and 0.13 Ma (late Pleistocene), respectively (Harijoko, et al.., 2016).

2.4 Geological Structure

The primary evidences of undisturbed geological stuctures in the surface were difficult to recognize, due to the land use where the most of the research area has been terraced for agricultural purpose. Therefore, the geological structures were interpreted from DEMNAS. The main structures in the Dieng field are the NW-SE trending which is spatially associated with alignment of volcanic centers which are spatially associated with thermal manifestation areas. These structures may still function as permeability provider since the thermal associated with them are still active. Volcanic structures interpreted as crater rims are associated with Mts. Pagerkandang, Pangonan-Merdada, Pakuwaja, and Seroja. These structures may be connected with the subsurface, as indicated by the existence of some losses of circulation in drilling hole (Shalihin et al., 2020).

The geologic map of the Dieng field (Figure 2) is constructed based on our recent interpretation of the DEMNAS image and ground checked with reference from the work by Suhkyar, et al. (1986), Boedihardi, et al. (1991), and Nurpratama, et al. (2015). The age dates data were obtained by radiometric dating by Boedihardi, et al. (1991) and Harijoko, et al. (2016).

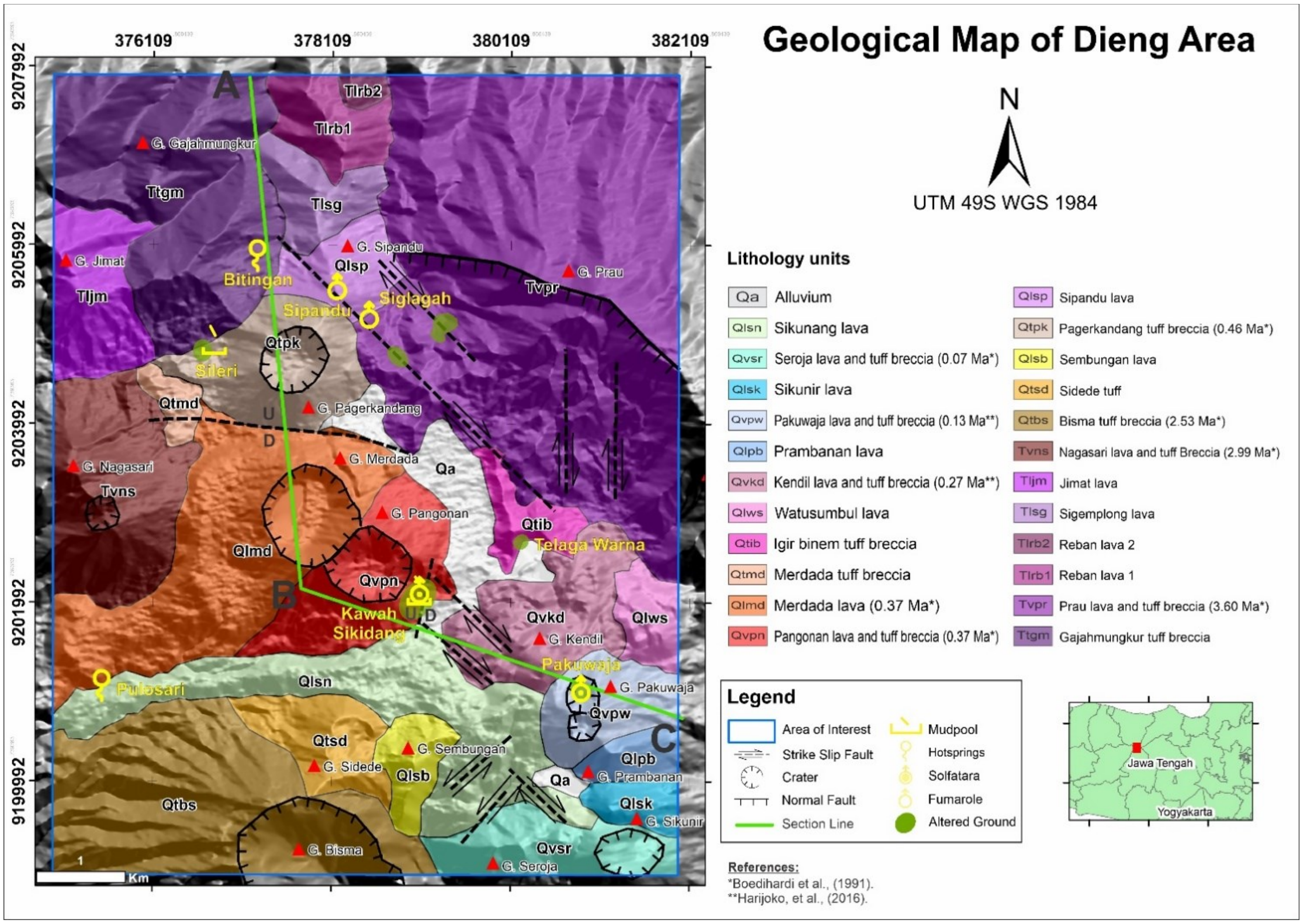

Figure 2: Geological Map of the Dieng Geothermal Field.

3. THERMAL MANIFESTATIONS

Sileri sector

Thermal manifestations in the Sileri sector are fumarolic and steam-heated type (Figure 3). Fumarolic discharges occur at the top and southeastern flank of Mt. Sipandu, namely Sipandu and Siglagah respectively, temperature measurement on the fumaroles is not conducted due to safety factors because they are located in the very steep area. The near neutral-pH hot spring (T=51°C) occurs in Sileri which is spatially associated with small crater structures in the western flank of Mt. Pagerkandang. The neutral-pH hot spring (T=52°C) is also discharges in Bitingan in the northern part of Mt. Pagerkandang. Ramadhan, et al. (2013) plotted the chemical composition of these thermal spring in the ternary diagram of Cl-SO_4-HCO_3 which shows thermal springs in Bitigan and Sileri are bicarbonate type (Figure 4).

Sikidang sector

Thermal manifestations in the Sikidang sector are of steam-heated and solfataric types (Figure 3). The largest thermal area is located in Sikidang and consists of mud pools, mud pots, acid hot spring (T=90-98°C), solfatara (T=90°C) with significant amount of sulfur deposits, gas vents, altered and steaming ground (T=82°C). Plot of the chemical composition of thermal spring by Ramadhan, et al. (2013) in the Cl-SO_4-HCO_3 ternary diagram shows the thermal manifestation in Sikidang are acid-sulfate type (Figure 4).

Pakuwaja sector

Thermal manifestations in the Pakuwaja sector are solfataric type includes solfatara, gas vents, altered and steaming ground (Figure 3). The manifestations are spatially concentrated in Mt. Pakuwaja which occur on its peak. There is no manifestation in the form of liquid, besides the location of the manifestations which are in a very steep location for sampling purpose. Therefore, the characteristic of the manifestations occurring in this area are poorly known due to the limited data.

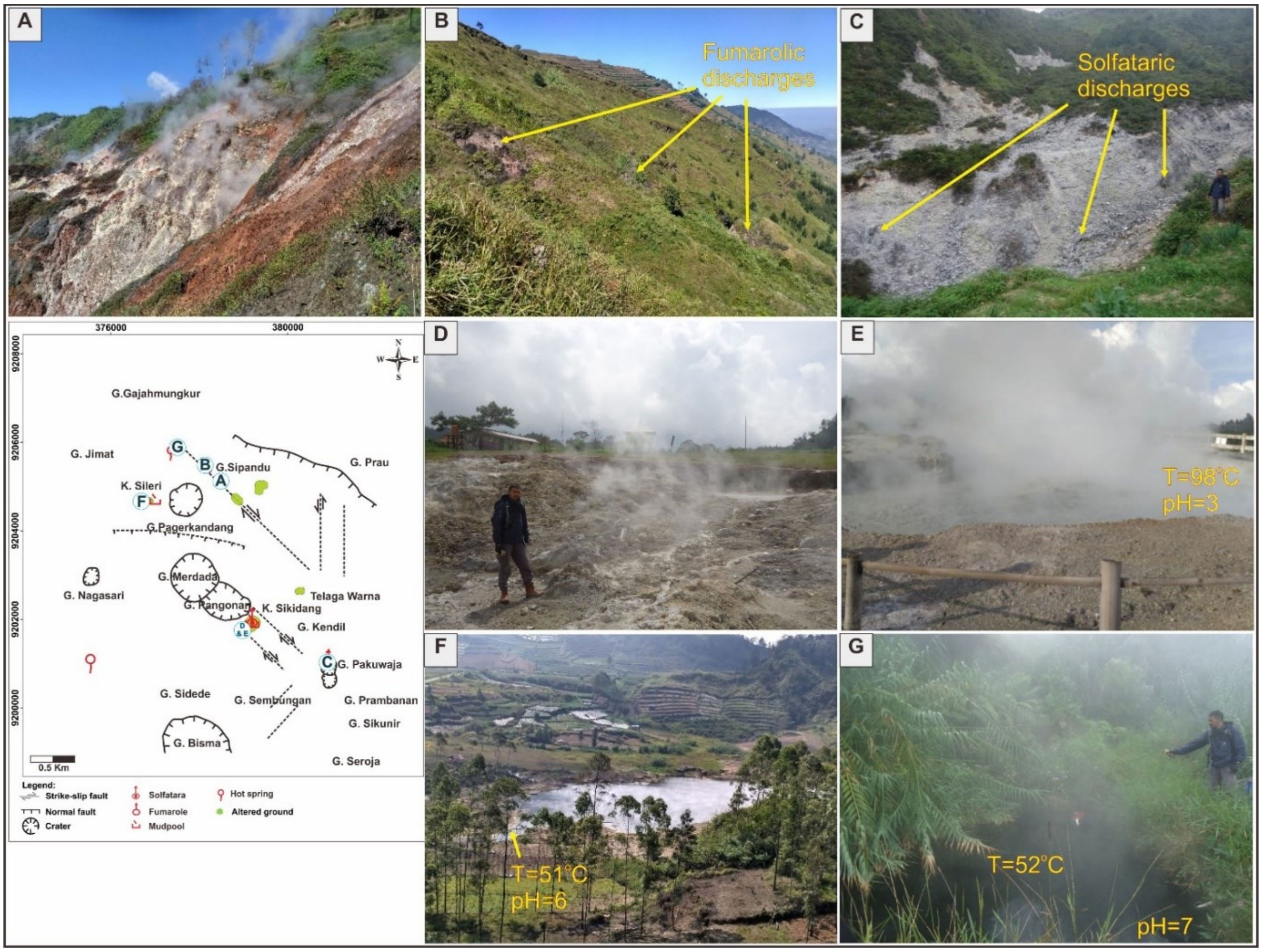

Figure 3: Photographs of representative thermal manifestations in the Dieng Geothermal Field and a location map. Circled letters in the map correspond to the photograph letters. A: Fumarolic discharge in Siglagah, in the southeastern flank of Mt. Sipandu; B: Fumarolic discharge at the top of Mt. Sipandu; C: Solfataric discharge and altered ground at the top of Mt. Pakuwaja; D: Solfataric gas vents, steaming ground, and altered ground in K. Sikidang; E: Boiling mud pools in the K. Sikidang; F: "Muddy" hot pool in the K. Sileri; G: Hot spring at Bitingan.

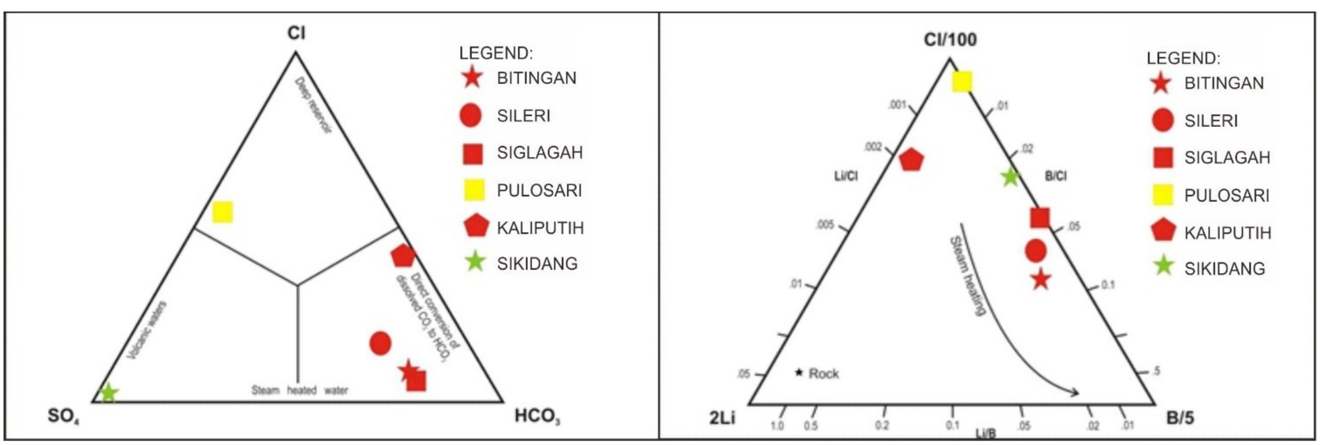

Figure 4: Plot of thermal spring in Dieng Geothermal field on Cl-SO_4-HCO_3 (left) and Cl-Li-B (right) ternary diagram (modified from Ramadhan, et al. 2013).

4. HYDROTHEMAL ALTERATION

The hydrothermal alteration in Dieng Geothermal Field were deduced from Shalihin, et al. (2020). The identity and the distribution of hydrothermal minerals gives clues about the past conditions of the system, including the changes in temperature, permeability, fluid composition, and the extent of activity.

Sileri sector

The subsurface hydrothermal mineral assemblage in the Sileri sector consists of epidote, wairakite, calcite, quartz, albite, and clays (smectite, chlorite, illite). They indicate the interactions of the rocks with near neutral pH-alkali chloride waters. These findings are also in accordance with Layman, et al. (2002) whose state that reservoir fluid in the Sileri sector is near neutral pH chloride waters. There is anhydrite in shallower part. The hydrothermal assemblages deposited in open spaces are generally similar to those replacing the primary phases in the wall rock, suggesting that they were formed from fluids of similar compositions.

Sikidang sector

In the Sikidang sector acidic mineral assemblage was encountered include pyrophyllite, native sulfur, and the presence of anhydrite to the deeper part. Leaching/dissolution texture is also occurred in the deeper parts of drilling well in the Sikidang sector (Shalihin, et al., 2020). This evidence indicating the possibility of acidic fluid input at depth within the area. There are also epidote and actinolite in the deeper part of the system which indicate temperature 250°C and >300°C, respectively. These minerals were formed from near neutral pH-alkali chloride waters. The relationship of the occurrence of both neutral and acidic fluid in the area are poorly constrained due to the absence of paragenesis study.

Pakuwaja sector

The subsurface hydrothermal minerals in the Pakuwaja sector include calcite, quartz, epidote, clinozoisite, actinolite, and clays (smectite, chlorite). These formed from near neutral pH-alkali chloride waters. Anhydrite and pyrite occur locally. Only a few of information which discusses the condition of the system in Pakuwaja sector. Pakuwaja sector has low permeability zone although the temperature is very high (Boedihardi, et al., 1991 and Layman, et al., 2002) as indicate by its hydrothermal mineral assemblage (Shalihin, et al., 2020). The information about fluid characteristic of the reservoir only deduced based on its associate of hydrothermal minerals.

5. CONCLUDING DISCUSSION

Previous studies suggest that geothermal system in the Dieng Geothermal field consists of three prospect areas, namely Sileri, Sikidang, and Pakuwaja. Boedihardi, et al. (1991) reported that there are two low permeability and low temperature barriers which separate Sikidang sector from the Sileri area in the north and Pakuwaja sector in the southeast. The geophysical data show that these barriers were defined by a gravity high and conductivity low which then confirmed by well drilling. Recent study of MT model by PT. Geo Dipa Energi (*vide in* MEMR, 2017) and gravity model by Rosid (2021) also supporting the existence of the barriers between the sectors which are presented by Figure 5 and Figure 6, respectively.

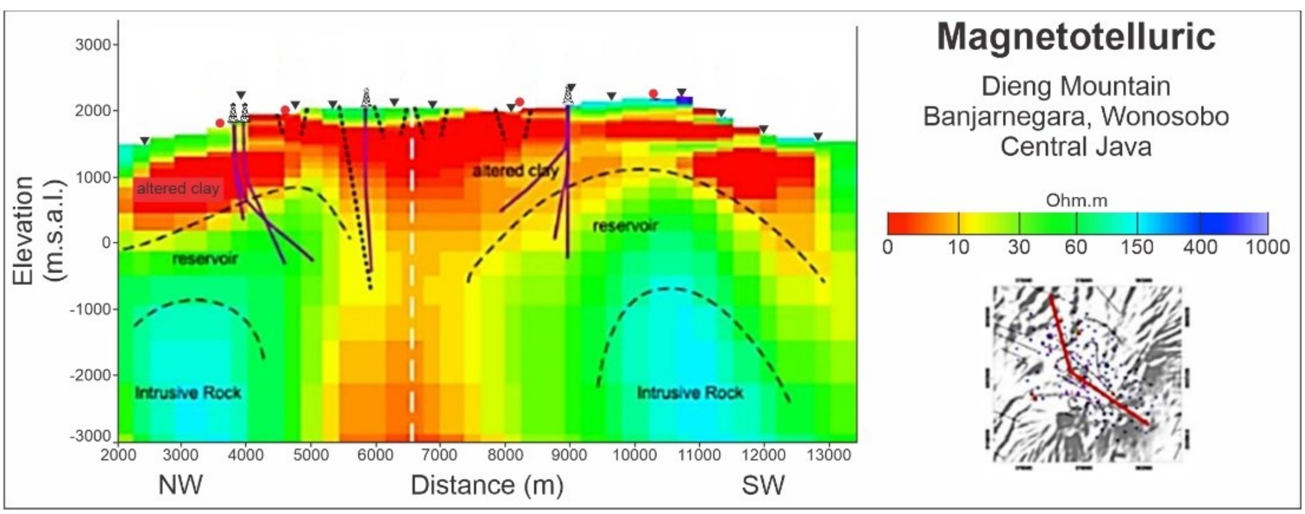

Figure 5: 2D MT inversion model of the Dieng Geothermal Field (PT. Geo Dipa Energi in MEMR, 2017).

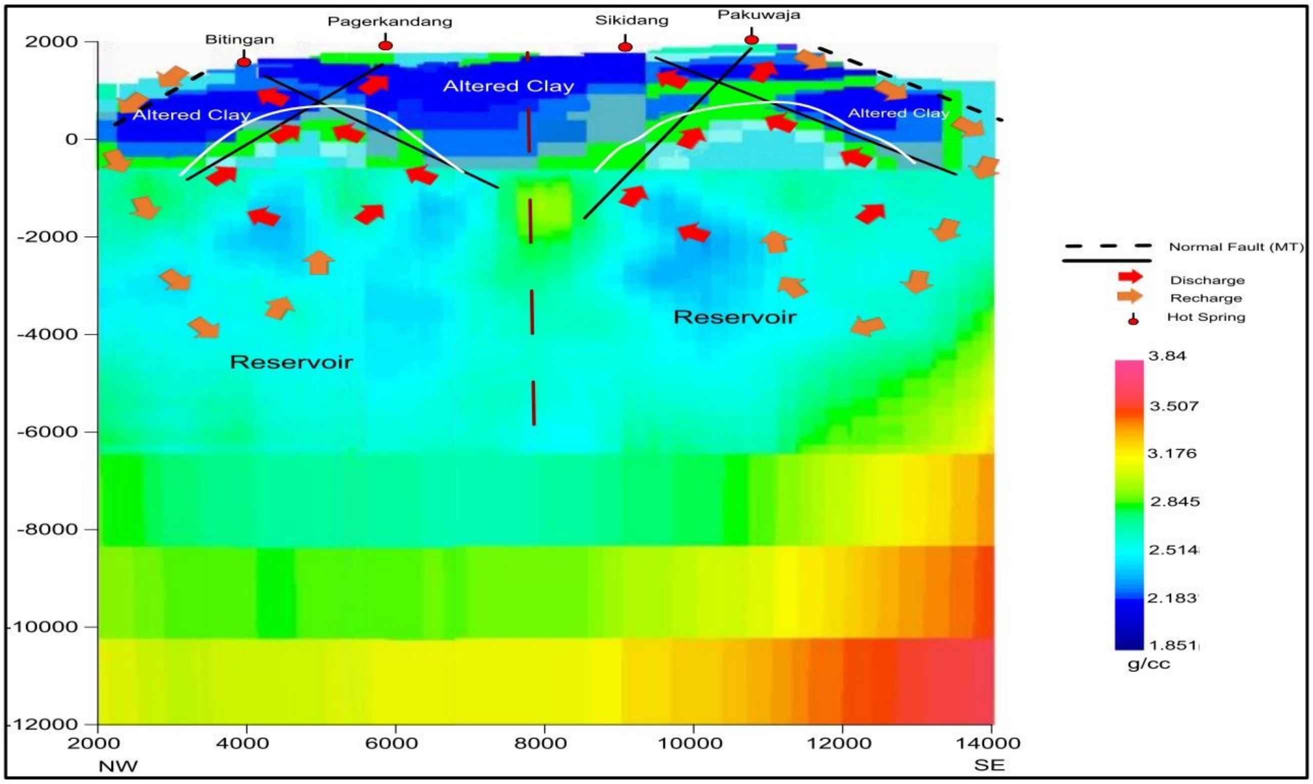

Figure 6: Gravity model of the Dieng geothermal field (Rosid, 2021).

The geothermal system in each sector of the Dieng field may have different characteristic one to another. Sileri sector that associate with Mt. Pagerkandang is the oldest system within the area compared to other sectors (Sikidang and Pakuwaja). Wohletz and Heiken (1992) explained that the age of the of volcano or volcanic activity is one of important factor to estimate whether the heat from magma emplaced at the dept is still preserved and the hydrothermal system has been well developed.

Based on Hochstein and Browne (2000), in the hydrothermal and volcanic system, surface discharge are the only directly observable expressions of geothermal systems. The manifestations very widely in their appearance, often reflecting the type of geothermal reservoir from which their discharged fluids derive. Sileri sector is the oldest system in the Dieng field, which is associate with Mt. Pagerkandang (0.46 Ma). In the Sileri sector the occurrence of geothermal system manifests in the form of fumarolic discharges which occupy the high relief terrain of Mt. Sipandu. Fumarolic discharges also reported occur around Mt. Pagerkandang crater (Boedihardi, et al., 1991; Ramadhan, et al., 2013). However, when ground checking was conducted in 2018 this manifestation is no longer there.

Neutral-pH bicarbonate hot springs discharge in Bitingan and *Kawah* (crater) Sileri, in the west flank of Mt. Sipandu and Mt. Pagerkandang, respectively. Some indications of the presence of reactive fluids, such as rock leaching were found around the manifestations. In Kawah Sileri the occurrence of reactive fluids is characterized by "muddy" hot pools. These features may record former thermal activity as the present-day thermal manifestations have neutral pH condition (pH=6-7).

Fumarolic discharges may act as the location of an upflow zone in the Sileri sector. Shalihin, et al. (2020) illustrate upflowing pattern beneath Mt. Pagerkandang, where well MG-1 drilled toward beneath the volcano showed high temperatures (≥300°C). In general, the distribution of hydrothermal minerals in this well were formed by near neutral pH-alkali chloride waters. Anhydrite was found locally to intermediate depth, and there is no evidence about influx of magmatic fluids in this sector. These findings give an impression typical of mature hydrothermal system where steam-condensate and magmatic fluids become neutralized and diluted, as reported by Reyes (2000) for some magmatic-hydrothermal system in the Philippines.

Geothermal system in Sikidang sector has a younger age than in Sileri, it associates with Mt. Pangonan (0.37 Ma). The geothermal system is expressed by solfataras with significant amount of sulfur deposits, mud pools, mud pots, acid hot springs, altered and steaming ground that is centered at *Kawah* (crater) Sikidang in the SE of Pangonan crater. The presence of these solfataric-type discharges suggest that the system may receive some contribution of volcanic waters. Kawah Sikidang area is inferred to be the marker of the upflow zone in the Sikidang sector. Well MG-3 drilled within this sector presented high temperatures (>300°C) but showed some evidence of minerals which formed by the acidic fluid such as pyrophyllite, native sulfur and anhydrite to the deeper part (Shalihin, et al., 2020). The deep part of Sikidang-Merdada area may have received magmatic fluids contribution as reported by Layman, et al. (2002) that there is a corrosive steam zone in Sikidang area, as characterized by very high H_2S/CO_2 ratio in the gas, and presence of gaseous HCl.

Pakuwaja sector has a youngest geothermal system in the Dieng field. It associates with Mt. Pakuwaja with an age about 0.13 Ma. The knowledge about geothermal system within this sector is poorly understand due to limited of available data. The only manifestation occurs at the top of Mt. Pakuwaja in the form of solfataras that deposit significant amount of sulfur. Boedihardi, et al. (1991) reported the wells drilled at Pakuwaja showed low reservoir permeability. The young age of the system may cause the convection cell within the geothermal system in this sector is not yet well developed that prevents any significant mass outflow to the surface. Well MG-4 drilled within this sector showed temperature which lower (<300°C) than in Sileri and Sikidang sectors.

Figure 7 shows the schematic model of the field according to the cross-section line A-B-C on Figure 2. The thermal structure is interpreted and modified based on the stable temperatures of the selected wells in Shalihin, et al. (2020) as well the igneous intrusion, then the hydrology is interpreted from geochemistry data of Ramadhan, et al. (2013).

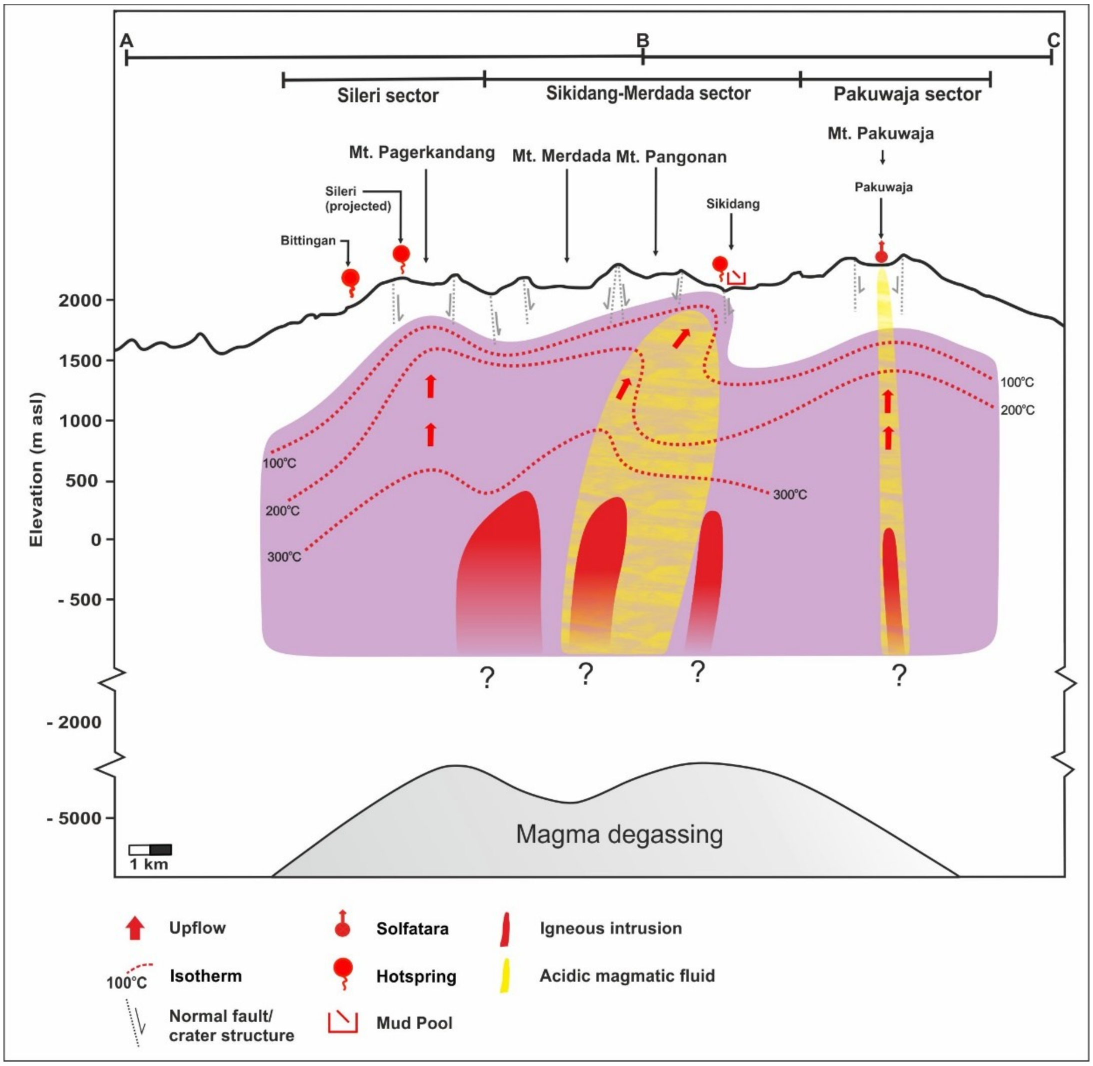

Figure 7: Schematic model showing the volcanic centers, thermal and hydrological structures of the Dieng geothermal field.

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