



# Modeling of subsurface structure by using magnetic methods in the area of Mt. Pandan, Indonesia

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## Abstract

Mount Pandan is an active volcano with geothermal phenomena and is located in tectonically active East Java, Indonesia. We conducted a geomagnetic study around Mount Pandan to obtain further information about fault structures and geothermal prospects. We established 245 geomagnetic observation stations covering an area of 20 km<sup>2</sup>. We calculated the magnetic anomalies, applied upward continuation and reduction to the pole, and calculated the improved normalized horizontal tilt angle to interpret the area. Furthermore, modeling was performed that included previous research. Our study identified NW–SE-, SW–NE-, and W–E-trending structures that might be affected by the Kendeng thrust fault and act as pathways for geothermal fluid flow. This geothermal fluid is estimated to flow from the southern area between Mount Pandan and Mount Wilis toward the north. There are several hot springs around Mount Pandan and Tirtohusodo hot spring near Mount Wilis. Thus, the heat source may be located in the area between Mount Pandan and Mount Wilis and supply heat for the geothermal systems of both volcanoes. The modeling results show the intrusion of andesite-type bodies at the summit of Mount Pandan and in the northern part of the study area. We found low magnetic anomalies that might indicate a heated region as a potential geothermal area. The reservoir of the geothermal system in Mount Pandan is interpreted to be tuffaceous sandstone from the Kalibeng Formation with claystone from the Klitik Formation as a clay caprock.

**Keywords** Magnetic anomaly · Volcano · Geothermal · Fault structure · Forward modeling

## Introduction

Mount Pandan is a volcano located on the administrative border between 3 cities in East Java, Indonesia: Nganjuk, Madiun, and Bojonegoro. Mount Pandan is located 40 km north of Madiun city (Santoso et al. 2017). According to the Center for Volcanology and Geological Hazard Mitigation of Indonesia (PVMBG), Mount Pandan is a dormant volcano (Santoso et al. 2018). Based on research conducted

by Setijadji (2010), the Mount Pandan area was identified as one of eleven geothermal prospects in East Java. Additionally, based on seismic information, the Mount Pandan area is still tectonically active. This is evidenced by the presence of small earthquakes that occur around Mount Pandan. The Meteorological, Climatological, and Geophysical Agency (BMKG) (2016) stated that during successive earthquakes in Nganjuk, the 897 m-high slab of land beneath Mount Pandan, which was lava, was thought to have experienced movement, causing vibrations recorded by BMKG's seismic radar. Therefore, further research is needed in the Mount Pandan area to determine the potential for disasters and the prospects for the existing geothermal system.

Several geological, geochemical, and geophysical studies have been carried out on Mount Pandan. Based on an analysis of fluids in several hot springs around Mount Pandan, Lekatompessy et al. (2019) showed that the area is an outflow zone with a rhyolite or an andesite lithological formation environment in the basaltic region. The temperature of the reservoir is estimated to range from

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153 to 222 °C. Studies related to seismicity conducted by Muttaqy et al. (2019) and Nugraha et al. (2016) indicate that the seismicity in the Gunung Pandan area has a shallow source and is controlled by an inland fault. Santoso et al. (2018) stated that seismicity in the Mount Pandan area was controlled by Kendeng thrust fault activity or by magmatic activity from Mount Wilis or a combination. The gravity study conducted by Aji et al. (2018) revealed a high gravity anomaly around the peak of Mount Pandan, which was modeled as an intrusion of andesitic igneous rock. In this research, geophysical investigations were carried out using geomagnetic methods to obtain further information regarding the subsurface conditions of Mount Pandan. The results of the geomagnetic study are then integrated with information related to Mount Pandan based on previous research, so that improved information will be obtained about the subsurface conditions of the Mount Pandan area.

## Regional geology

The Java subduction zone is the most active plate boundary in the world, stretching ~ 1700 km from the Sunda Strait to eastern Indonesia (Koulali et al. 2017). Subduction from the Indo-Australian Plate beneath the Eurasian Plate has occurred from the middle Eocene to the present day (Hall 2002). As a consequence of subduction since the early Cenozoic, Java Island has become a volcanic island with both active and ancient volcanism (Smyth et al. 2005). Currently, the Southern Mountains no longer experience active volcanism. Meanwhile, the modern Sunda Arc has been active from the late Miocene to the present. The modern Sunda Arc is located 50 km on the north side of the Southern Mountains. The characteristics of the eruption products from the modern Sunda Arc are basaltic to intermediate. The modern Sunda Arc consists of a series of volcanoes and active volcanoes in Java today.

Mount Pandan is one of the volcanoes in the modern Sunda Arc; with an elevation of 800 m, this volcano formed in the early Pleistocene (Thoha et al. 2014). Mount Pandan is located above the Kendeng zone, a depositional area containing volcanogenic material and sediments with a thickness of up to 8000 m (Smyth et al. 2005). Sediment thickness in the Kendeng zone is reflected in a very strong negative Bouguer anomaly value (Smyth et al. 2008). The volcanic constituents of Mount Pandan are andesite breccias and andesite intrusions (Thoha et al. 2014). According to Thoha et al. (2014), several structures in the Mount Pandan area trend northeast-southwest and

northwest-southeast. The location of Mount Pandan can be seen in Fig. 1.

## Data and methodology

The geomagnetic survey was carried out in the Mount Pandan area, East Java, Indonesia, from January 24, 2020 to January 29, 2020, covering an area of 4 km × 4 km. We used a proton precession magnetometer GSM-19 T (produced by GEM Systems, Inc.) to acquire magnetic data. In total, geomagnetic observation points were measured at 245 stations along the tracking route with distances between stations of 50 m and 150 m. Quality control of the field measurement data was carried out by reading the total magnetic field value 3 to 5 times at the same point with the 99% signal-to-noise ratio. Statistically, the data from the field measurements had a standard deviation in the range of 0.006 to 8.126. The results of magnetic field measurements using a proton magnetometer produced the total magnetic field value (Kearey et al. 2002). Therefore, diurnal correction and IGRF correction were applied to the data to obtain the total magnetic anomaly. We use the kriging technique with 50-m spacing to produce a map of the total magnetic anomaly in the research area. Topographic maps and maps of total magnetic anomalies from the results of measurements can be seen in Fig. 2.

We applied filtering techniques such as upward continuation and reduction to the pole (RTP) to help the interpretation process. The mathematical calculation of upward continuation process referred to the equation from Robinson (1970). We applied upward continuation filter at various depths to understand the regional pattern. The result showed the anomaly pattern was relatively stable at elevations of 500 m and above. Reduction to the pole helped to identify the anomaly more easily because the anomaly became monopole. Furthermore, we performed anomaly separation by using a moving average filter to understand the regional pattern and the residual anomaly caused by shallow subsurface conditions.

Regionally, similar trends can be observed in the anomaly map resulting from the upward continuation of magnetic data that has been reduced to the pole, shown in Fig. 3a and a regional gravity anomaly map from Aji et al. (2018) shown in Fig. 3b. On the southern side of the study area, there is a negative regional anomaly trend from both magnetic and gravity data. The north the observation, the higher the anomaly is. Regional anomalies describe subsurface conditions for relatively deep depths. The relatively low anomaly trend means that the rock conditions in the area have low magnetic properties and low density. These features can be caused by the condition of the rocks, which are still hot. In addition, we interpret that the low magnetic anomaly area might indicate a heated region as

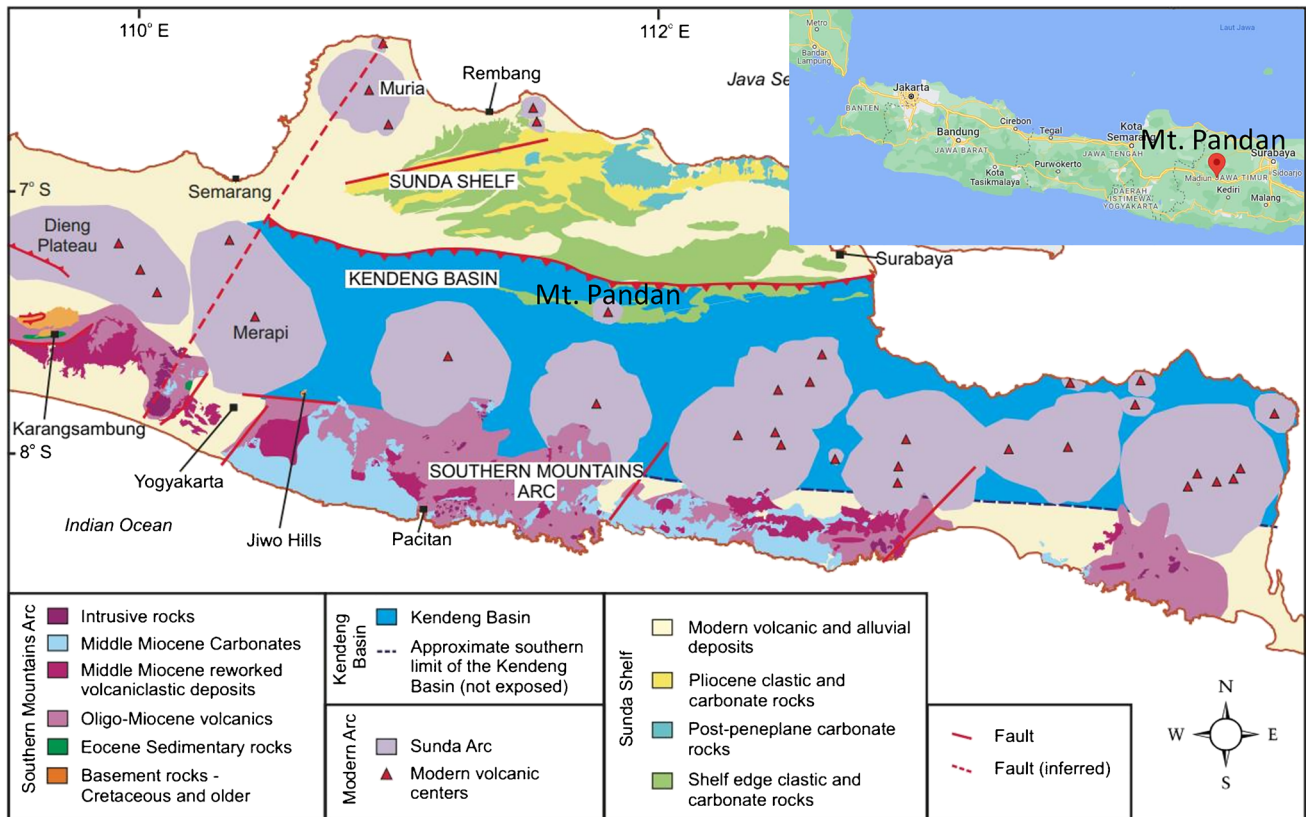


Fig. 1 Simplification of the Geological Map of East Java modified from Smyth et al. (2008)

a potential geothermal area. However, this interpretation is a preliminary indication qualitatively. Further research is required to confirm this interpretation. If the anomalies are related to the existence of a geothermal system, the area may be the location of a heat source.

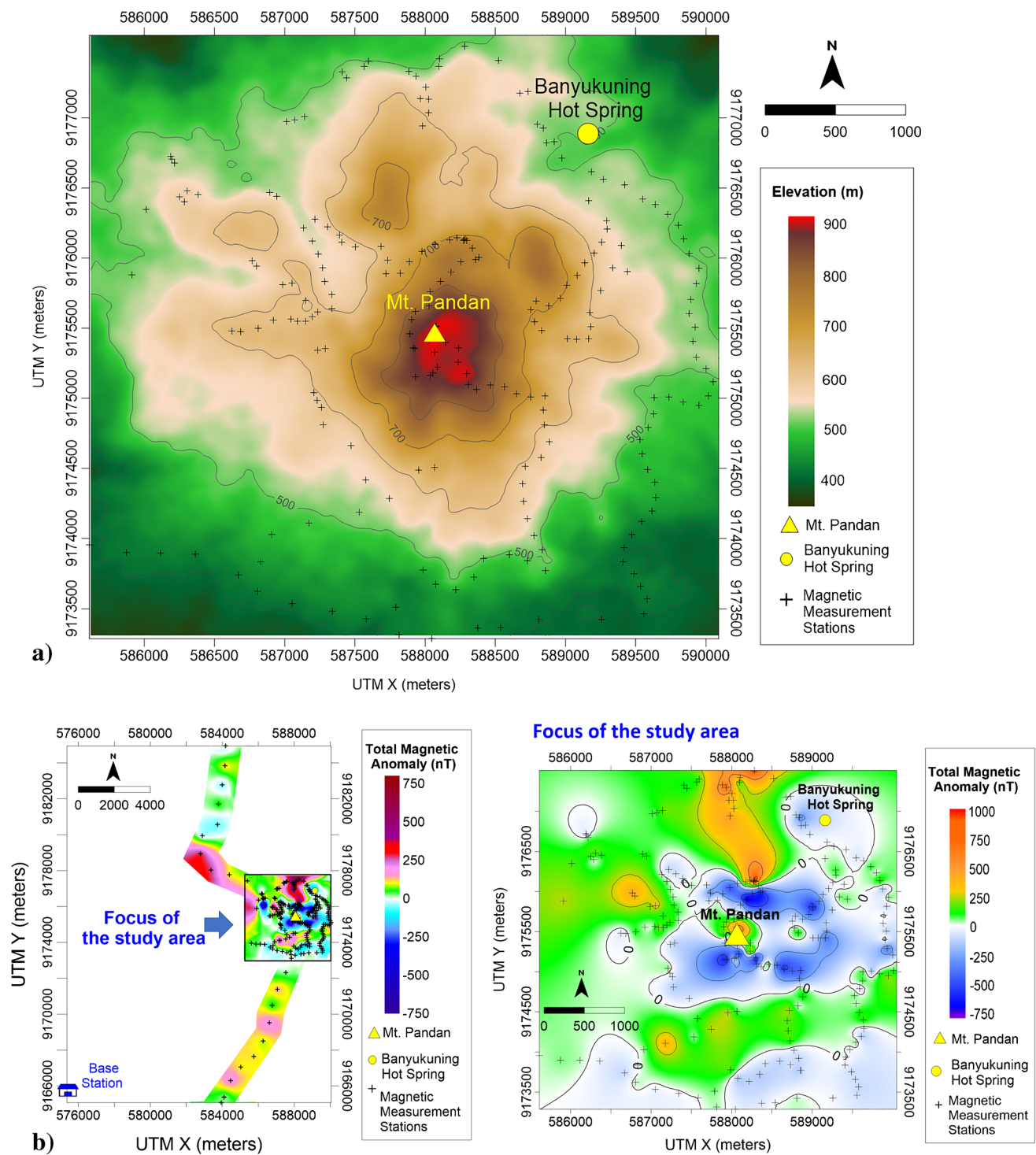
The magnetic residual anomaly map in Fig. 4 shows high magnetic anomalies around the summit of Mount Pandan and extending to the north and negative anomalies around it. Based on the correlation with the geological features of the research area, areas with high residual anomaly values indicate rocks with high magnetic properties that are located at shallow depths. If we consider the location, i.e., a volcanic area, the high anomaly is likely caused by the intrusion of an igneous rock body. This rock is interpreted as an andesitic igneous rock that breaks through the rocks above it to a relatively shallow depth.

The low residual anomaly surrounding the summit area of Mount Pandan reveals a trend that extends south-north. This low anomaly trend can be interpreted as an area with low magnetic properties at shallow depths. If it is related to the existence of a hot spring, namely, Banyukuning, this low anomaly area can be interpreted as a path of movement of geothermal fluids.

If the anomaly is related to regional anomaly data, note that a negative regional anomaly appears on the southern side, so the geothermal fluid may originate from a heat source in the southern part of the study area. In this region on the south side stands Mount Wilis, a larger volcano. Therefore, the heat source in the Mount Pandan area may derive from the same heat source as Mount Wilis, and this heat may flow through the fault structure or existing rock fractures.

For the purpose of fault interpretation, we calculate the improved normalized horizontal (INH) tilt angle from the magnetic anomaly that has been reduced to the pole. The mathematical calculation of the INH refers to the equation from (Nishijima and Naritomi 2017). We combine information from the INH map and residual map to estimate the possible fault structure.

In the modeling stage, we use a forward modeling technique to model the subsurface conditions based on magnetic residual anomaly data that have been reduced to the pole. We model the induced magnetic field and assume that the magnetization is purely induced. This assumption is often used to simplify the interpretation of magnetic data, according to Baniamerian et al. (2020).



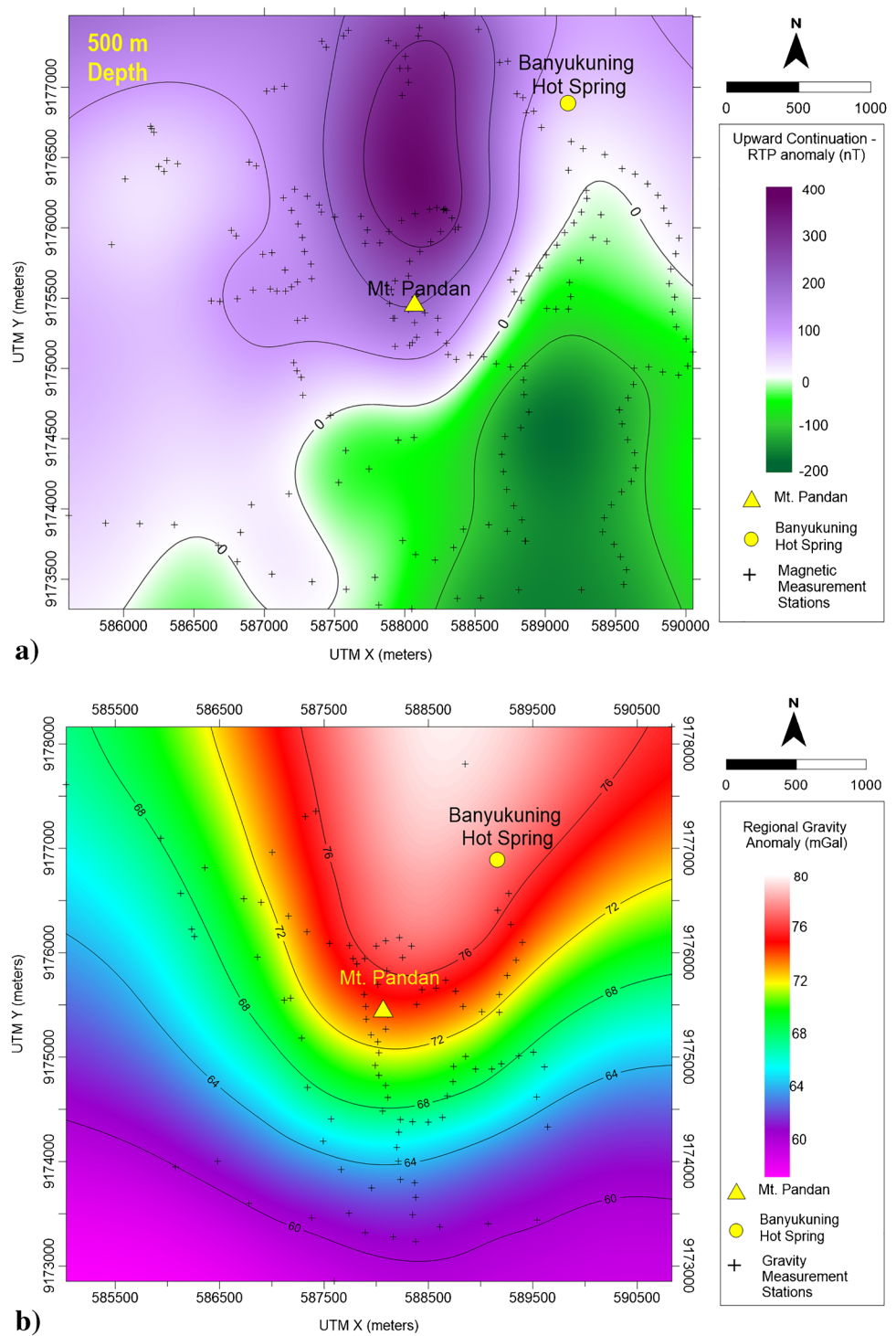
**Fig. 2** a Topographic map of the Mt. Pandan area; b total magnetic anomaly map of the Mt. Pandan area

### Results and discussion

The interpretation of the fault structure was carried out by analyzing the RTP map for residual anomalies and the INH

tilt angle map. INH map could identify the fault structures better than residual anomaly map for some locations. Figure 5 shows the trend of the fault structure in the NW–SE-, SW–NE-, and W–E-direction. The fault structure that is

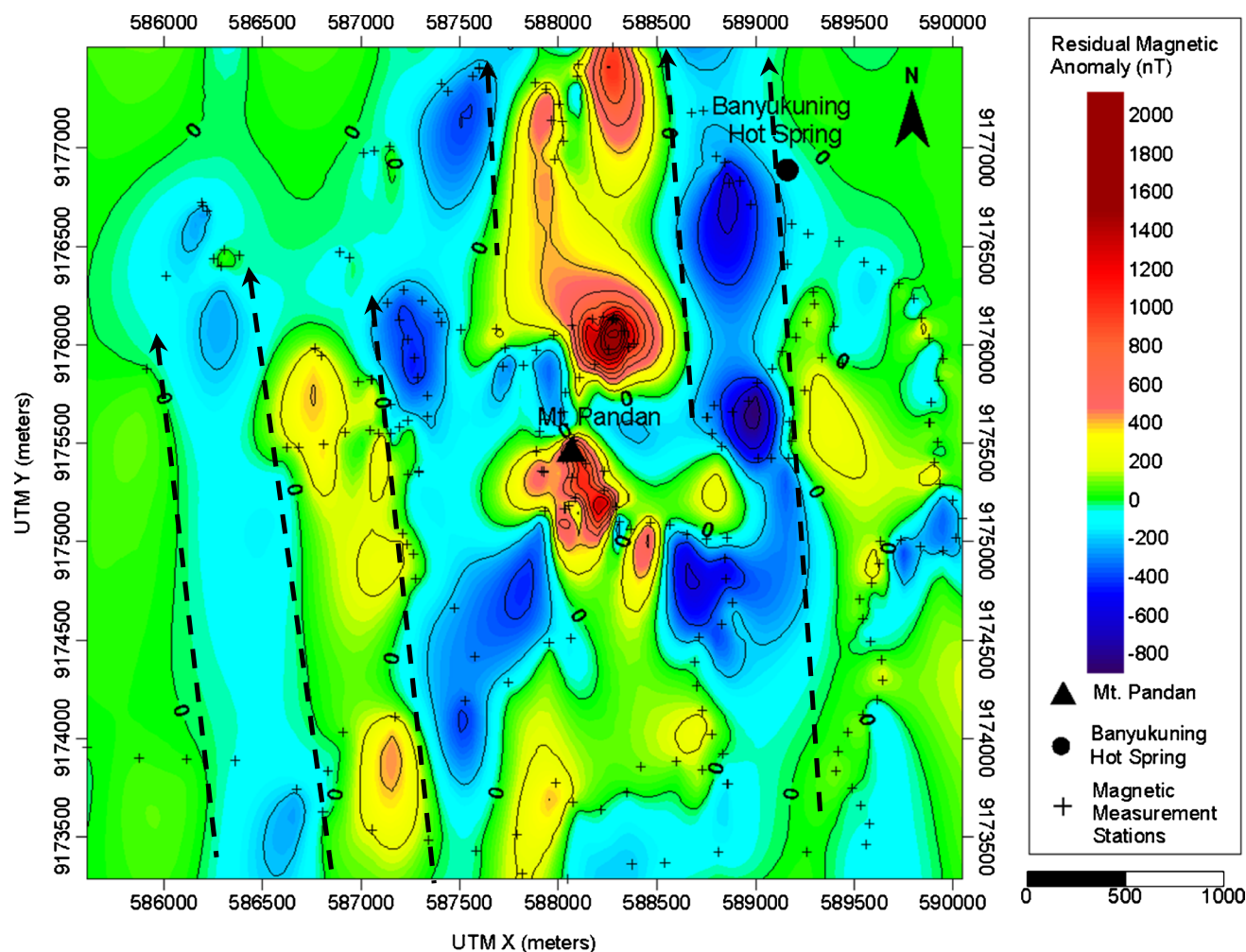
**Fig. 3** **a** Upward continuation of the RTP magnetic anomaly map of the Mt. Pandan area; **b** regional gravity anomaly map of the Mt. Pandan area from Aji et al. (2018)



located around the Banyukuning hot spring has a NW–SE orientation that is identified as the path of movement of geothermal fluids, and the spring appears as a manifestation on the surface.

Two modeling profiles are constructed: SW–NE and NW–SE profiles, shown in Fig. 6. Some complementary data are used to support the modeling process, such as the

Bojonegoro map sheet produced by Pringgoprawiro and Sukido (1992) for estimating the rock formations and seismic sections available from Prasetyadi (unpublished dissertation, 2007) in Thoha et al. (2014); the susceptibility data refer to research from Clark and Emerson (1991) and Saepuloh et al. (2017). Modeling is carried out by assuming an andesitic igneous rock that breaks through the sedimentary



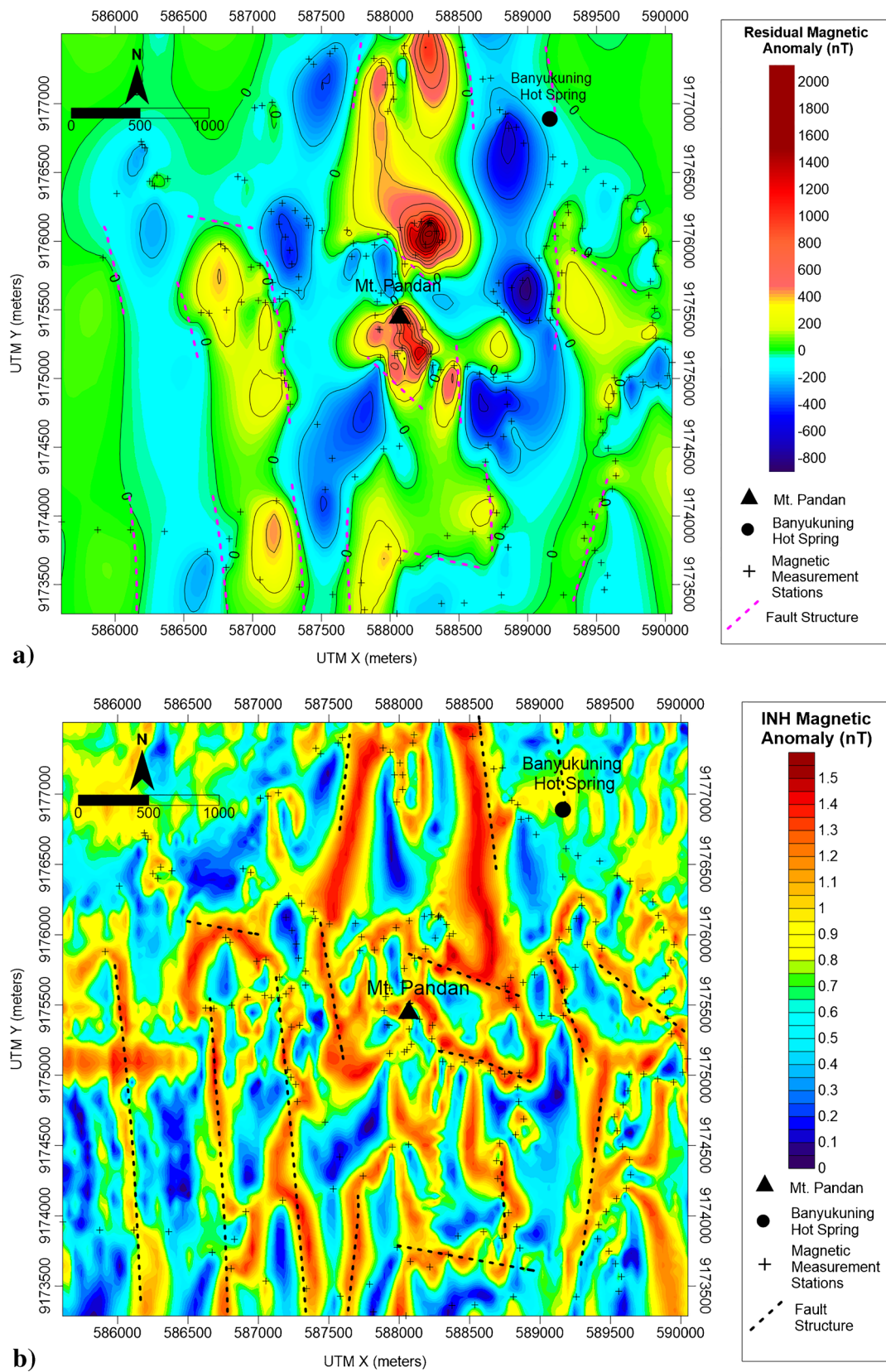
**Fig. 4** Residual anomaly map and possible heat transfer from south to north

deposits based on geochemical information and geological information.

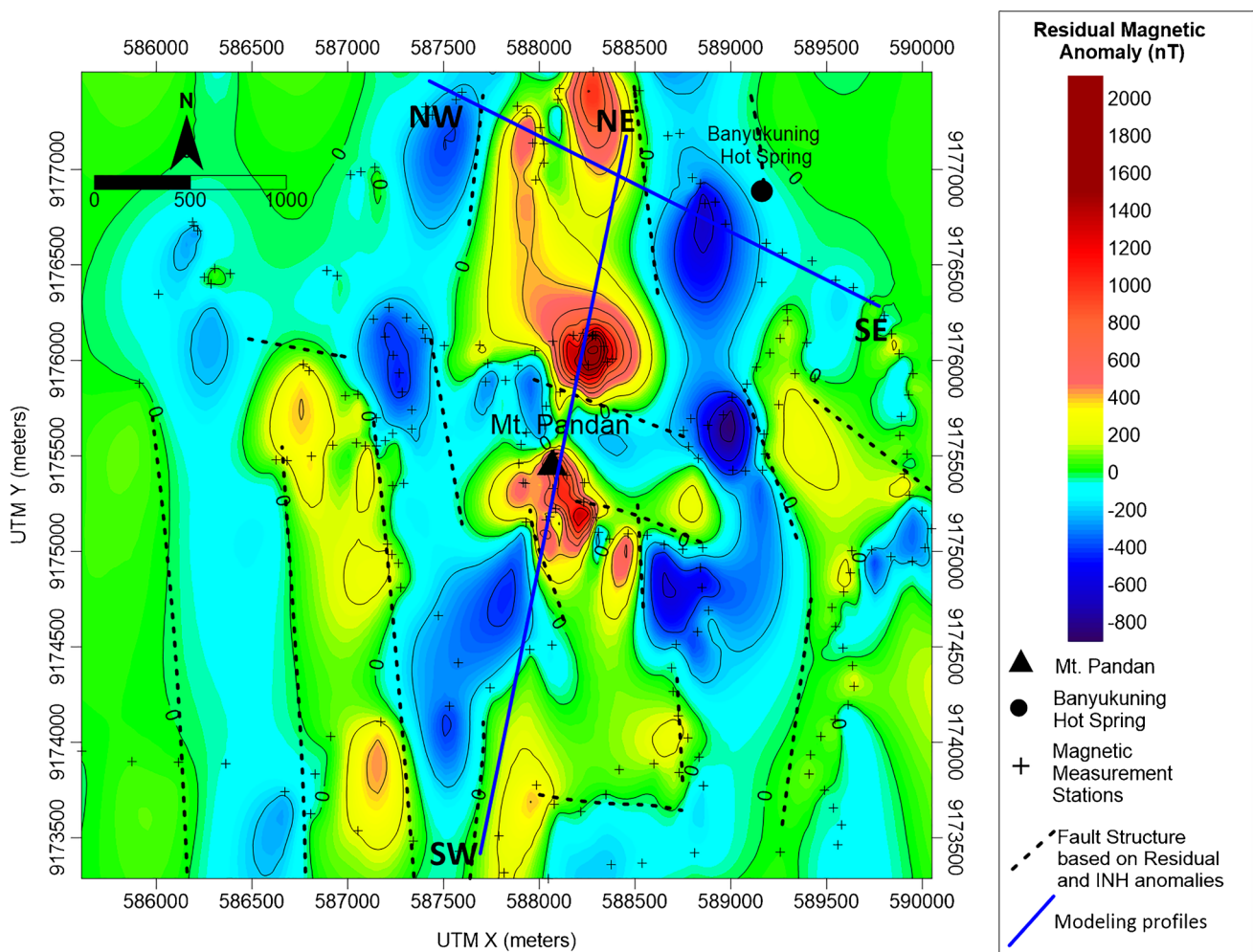
Modeling results can be seen in Figs. 7 and 8. According to Smyth et al. (2008), the thickness of the sedimentary rocks in the Kendeng zone, based on information from gravity data, reaches 10 km. Based on information from seismic cross-sectional data and geological maps of the study area, several rock formations are identified as follows from oldest to youngest: the Kerek Formation, Kalibeng Formation, Klitik Formation, Pucangan Formation, and Pandan Breccia. Location with high RTP anomaly is modeled as a location where intrusion of the andesitic igneous rock reaches close to the surface. This intrusion does not appear on the surface because it is covered by volcanic breccia. In the southern part of the summit of Mount Pandan, a negative anomaly is found to be the result of the very low magnetic properties of the rock in the area. According to Ritis et al. (2007), the negative anomaly value in the RTP data can arise because in the

RTP transformation process, the anomaly is attenuated. In this case, the area with a negative anomaly value is interpreted as an area with thick sedimentary deposits that have lower magnetic properties than the surroundings. The presence of a fault structure serving as a pathway for heat movement explains why the rocks in the zone have low magnetic properties. The other low anomaly area is located at the location of Banyukuning hot spring manifestation. The fault structure in the area is identified as a pathway for heat movement that results in the appearance of hot springs on the surface.

By integrating the model obtained from the forward modeling of magnetic anomaly data and other supporting data, the heat source is interpreted to underlie the southern side of Mount Pandan. This heat source probably originated from the same source as Mount Wilis. The magma as the heat source probably flows through the fault structure or fractures and is stored in the area around Mount Pandan with a very low magnetic anomaly response.



**Fig. 5** **a** Fault structure interpretation from residual magnetic anomalies; **b** fault structure interpretation from the INH map



**Fig. 6** The locations of the modeling profiles on the residual magnetic anomaly map

Based on research from Hochstein and Sudarman (2008), there is also some evidence of hydrothermal activity around Mount Wilis. At a distance of 10 km to the west of Mount Wilis is Lake Ngebel, which was probably formed due to a hydrothermal eruption. In addition, at a distance of 1 km on the southern side of Lake Ngebel, several manifestations of fumaroles and hot springs, namely, Tirtohusodo hot spring, which has a neutral pH with the chloride-bicarbonate water type, are also found. According to Hochstein and Sudarman (2008), the manifestation area on the west flank of Mount Wilis is an outflow of the geothermal system in the Mount Wilis area.

Information from the tomographic study from Martha et al. (2017) can be seen in Fig. 8a showing that the southern part of East Java has a high shear wave velocity and that the northern part has a low shear wave velocity. The high shear wave velocity is related to the presence of igneous rocks from the southern mountain zone, which is the location of past volcanism on the island of Java,

while the low shear wave velocity is related to the presence of basins where sediment thickening occurs. On the map of shear wave velocity in East Java at several depths that can be seen in Fig. 9a, the area between Mount Pandan and Mount Wilis has low shear wave velocity from the surface to a depth of 2 km from mean sea level, which is related to the presence of sedimentary rock. At a depth of approximately 2.3 km from mean sea level, the shear wave velocity increases. This has been interpreted as evidence of consolidated igneous rock or magmatic intrusive bodies (e.g., Young et al. 2013; Crowder et al. 2019; Yudistira et al. 2021). At a depth of 8.5 km from mean sea level, the shear wave velocity decreases, which is probably related to the presence of a magma chamber that supplies magma to Mount Wilis and Mount Pandan; information from Santoso et al. (2017) reports that in the Mount Pandan area, an earthquake occurred, which is interpreted in terms of tectonic activity or magma movement or both.



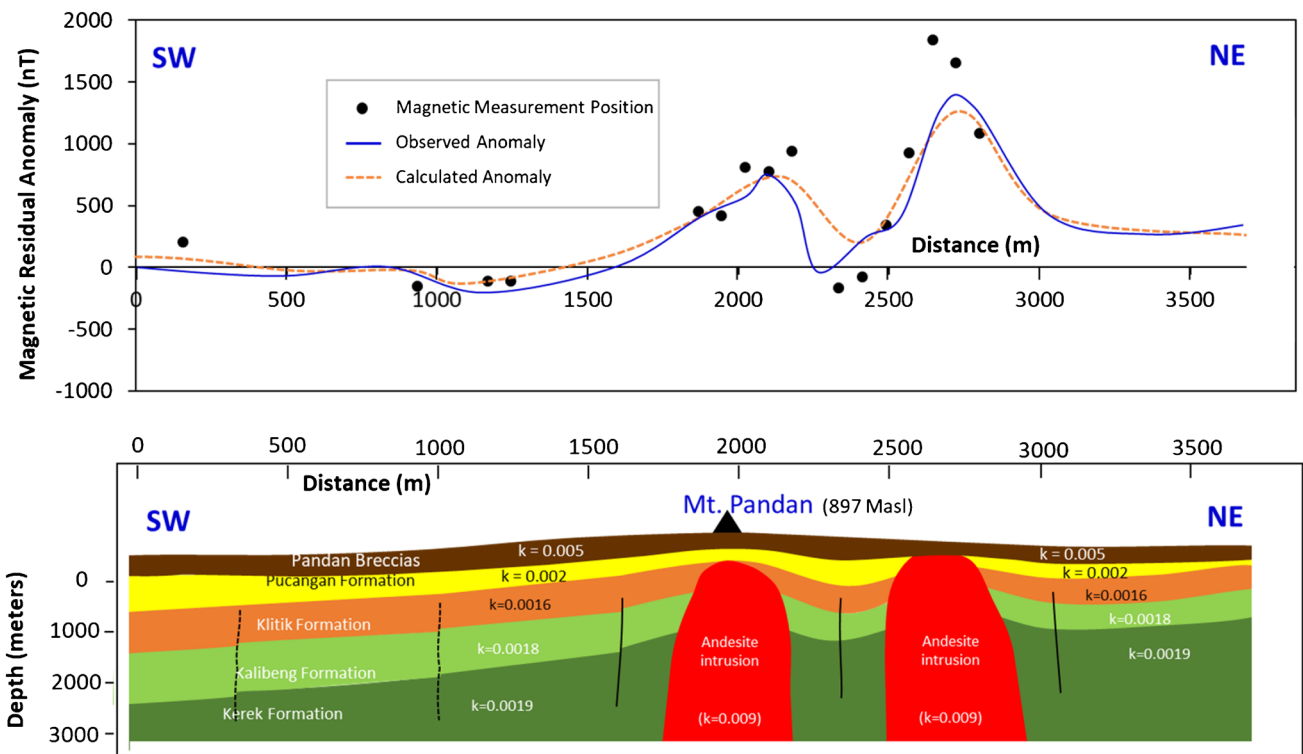
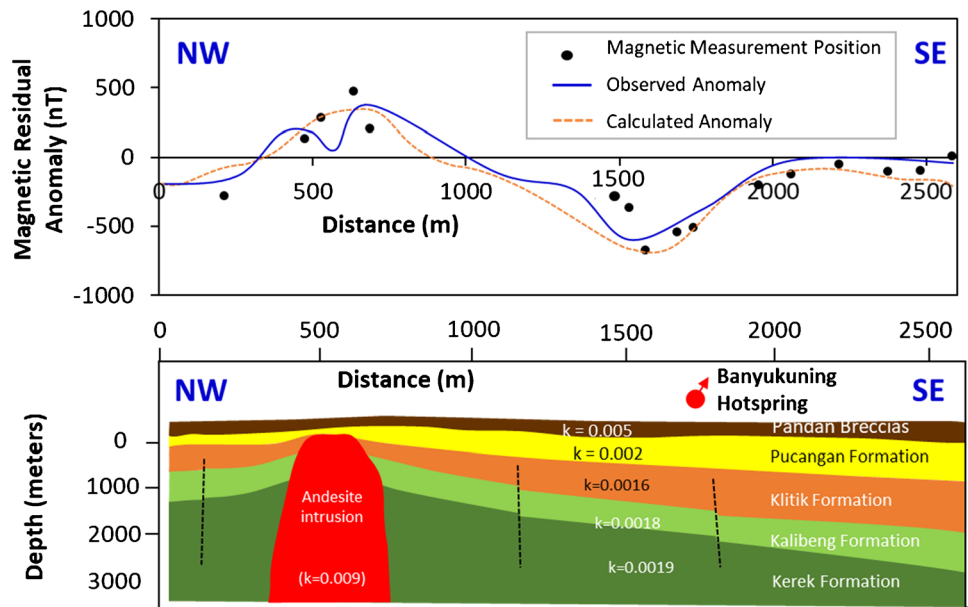


Fig. 7 Subsurface model from the forward modeling process of the southwest-northeast profile

Fig. 8 Subsurface model from the forward modeling process of the northwest-southeast profile



Furthermore, information from gravity data for the East Java area in Waltham et al. (2008) shows that the area between Mount Pandan and Mount Wilis is a transitional area from high anomalies on the southern side to low anomalies on the northern side. In this area, the gravity anomaly is higher than those on the western and eastern

sides, which are very negative. This is possibly due to the presence of magmatic intrusions and a magma chamber. Therefore, it is possible that magma flows from one place between Mount Pandan and Mount Wilis toward both volcanoes. Detailed gravity and geomagnetic studies in the area between Mount Pandan and Mount Wilis provide an

**Fig. 9** **a** Shear wave velocity map of East Java modified from (Martha et al. 2017); **b** Bouguer anomaly map of East Java modified from (Waltham et al. 2008)

opportunity to learn more about the relationship between the two mountains and the geothermal system.

Moreover, the layer that has the potential to become a reservoir is interpreted to originate from the Kalibeng Formation, which is composed of tuffaceous sandstones with a cap layer in the form of claystone from the Klitik Formation. Based on the analysis of the geochemical data, the reservoir temperature can be estimated in the range of 153 to 222 °C. By integrating this information, the authors attempt to develop a schematic model of the geothermal system in the Mount Pandan area, as shown in Fig. 10.

## Conclusion

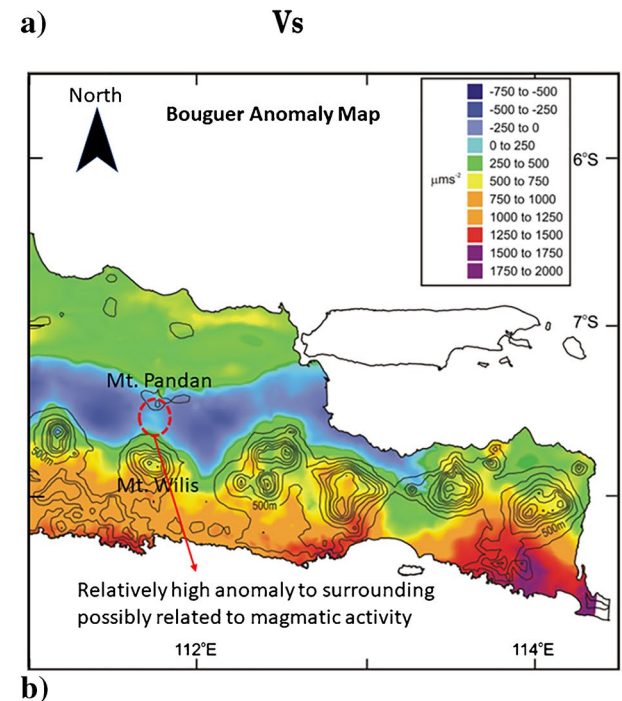
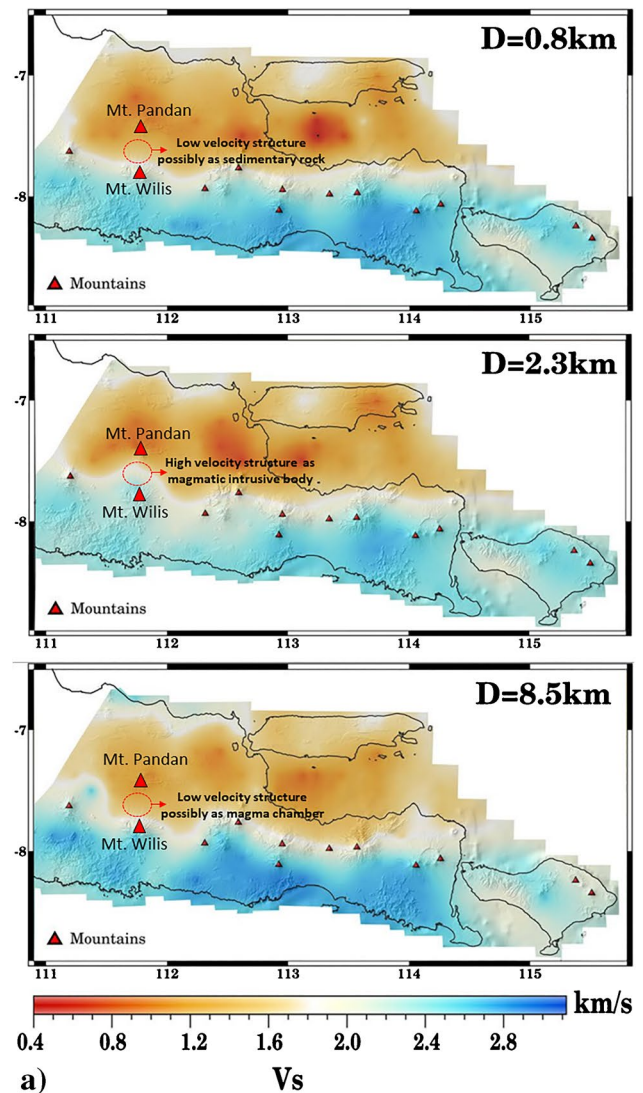
There is a possible heat source in the south of Mount Pandan, which appears as a low magnetic anomaly area with heat movement following the low magnetic anomaly residual trend from south to north. This movement trend is supported by the structural interpretation, which shows the results of several potential structures with S–N, SW–NE, and W–E trends.

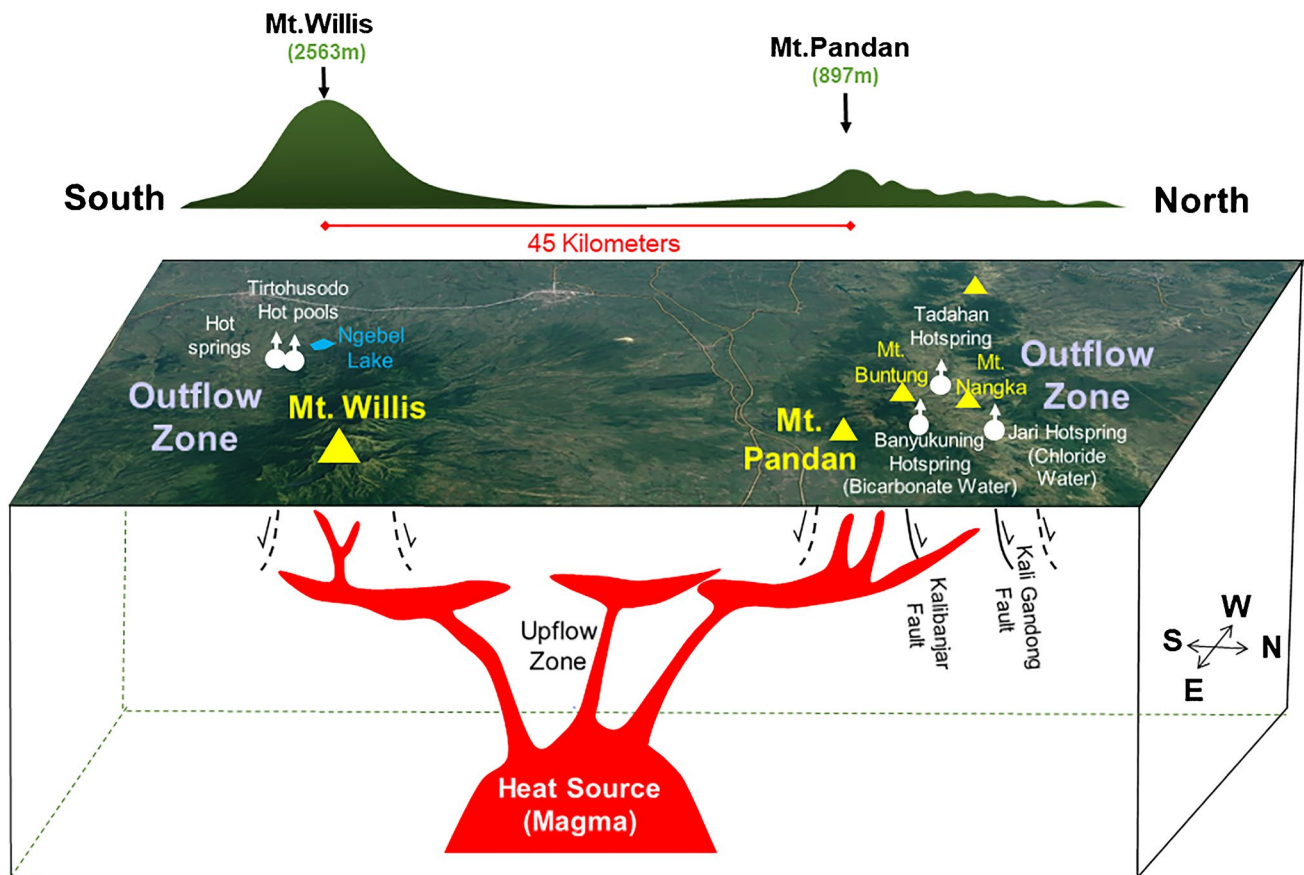
Based on forward modeling of residual magnetic anomalies, the subsurface conditions in the Mount Pandan area are modeled consisting of 4 layers in order from the top: volcanic breccias, claystone layers, sandstone layers, and andesite bodies; these andesites intrude the layers above and in several locations, especially around the summit of Mount Pandan, reach close to the surface, which is characterized in this area by a high magnetic anomaly value. The heat source is located on the southern side of Mount Pandan and probably represents the same heat source as that for Mount Wilis. In addition, the reservoir rocks are interpreted to be tuffaceous sandstones from the Kalibeng Formation with clay caps originating from the Klitik Formation.

Thus, the area of Mount Pandan and Mount Wilis represents an outflow zone. Further research is recommended to better understand the relationship between the two mountains, so the authors propose conducting research in the regional area from Mount Wilis to Mount Pandan.

**Author contribution** All the authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Susanti Alawiyah, Waskito Aji, and Eko Januari Wahyudi. The manuscript was written by Susanti Alawiyah, and all the authors reviewed and approved the manuscript.

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**Fig. 10** Schematic model of the geothermal system in Mount Pandan

## Declarations

**Competing interests** The authors declare no competing interests.

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