Delineation of the permeable zone using microearthquake data in the geothermal field R

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Abstract. Reservoirs are an important component in geothermal systems. Hot fluids accumulate in reservoirs, which consist of thick layers of permeable rock. Micro-earthquake methods can be used to identify the permeable zone in a geothermal system. In particular, observations of micro-earthquake hypocenters provide a promising technique to detect such permeable zones. Determinations of the hypocenters are performed using the single-event determination method. Micro-earthquake hypocenter relocations are performed to obtain more accurate locations and to reduce errors that occur because of inaccurate velocity models. The relocation method that is used in this study is double-difference relocation, which is the most efficient and fastest method available and is capable of generating small errors with no necessity of station corrections. In this study, we use data recordings by 18 stations of the micro-earthquake activity in the geothermal Field R from June to October 2012. The processing data start from raw time series data. The distributions of the relocated hypocenters were then matched to the supporting magnetotelluric and geologic data. The result of this study shows that there is a significant amount of seismic activity on the southern part of Mount R. The distribution of micro-earthquakes forms a cluster and a northwest–southeast structure pattern. The distribution of the hypocenters can be interpreted as the permeable zone beneath the surface, with the northwest–southeast fault pattern as the hydrogeology controller of the geothermal system in the geothermal Field R.

Keywords: Microearthquake data, double-difference relocation, permeable zone, geothermal

1. Introduction

Energy plays an important role in economic growth, life development, and human welfare. Increases in industry and population with time lead to increasing energy demands. The electricity demand in 2025 is expected to reach 457 TWh, with an average growth of 8.6% per annum for the period of 2016–2025 [1]. Indonesia is considered to have one of the world’s largest geothermal potentials of approximately 28,000 MW [2]. Geothermal energy could provide a solution to meet the electricity demands in the coming years.

To achieve the national electrical energy demand, it is necessary to study the geothermal system in a potential field to investigate the possible distribution of geothermal resources. Micro-earthquake data have commonly been considered as a tool to assess the permeability structures in geothermal reservoirs, monitor the migration pattern of injection fluids, and determine reservoir boundaries. Micro-earthquakes
are caused by local movements in the subsurface, such as fractures, fluid injection processes, drilling activity, and fluid migration, and are associated with changes in the pressure, volume, and content of the rock pores.

The “R” geothermal field is situated in the Lampung province, approximately 60 km southeast of the city of Bandar Lampung. From June to October 2012, the natural seismicity of the region was measured using 18 surface stations. The instruments were installed at depths of 2–8 m. Data were continuously recorded at a rate of 200 samples/s. The initial locations of the microearthquake events were determined using Geiger adaptive damping method, and relocations of the events were determined using double-difference relocation.

2. Geologic setting

The island of Sumatra was formed by the collision of the Sundaland continental crust with the Indian–Australian oceanic crust. The collisions in the southern part of Lampung produced magmatic activity at some locations, one of which was Mount R. Mount R is thought to be a post-caldera volcano built up inside the caldera margin in the Quaternary period. It is made up of basaltic to andesite lava, pyroclastic breccia, and tuff.

Detail mapping and LiDAR topographic interpretations around Mount R have indicated a primarily northwest–southeast structural pattern. This trend is parallel to the Sumatra Fault Zone. The existence of a north–south structural trend can also be seen in the structural map shown in figure 1. This may be related to the basement structure pattern commonly found in the Java Sea [3]. Minor east–west and northeast–southwest structural patterns can also be observed in figure 1.

The existence of geothermal systems is represented by various thermal manifestations that flow on the north and south sides of Mount R and are shown in figure 1 as colored dots [4]. The manifestations on the southern flanks consist of fumaroles, steam vents, warm ground, kaipohan, and hot springs with temperatures ranging from 34 °C to 110 °C. The northern manifestations consist of warm springs and hot springs with temperatures ranging from 33 °C to 57 °C.

![Figure 1](image-url)

Figure 1. Structural map of Mount R superimposed over the LiDAR surface topography. The colored dots indicate the surface thermal manifestation of the geothermal system [4].
3. Methodology and data

The study process can be schematically expressed in the flow of diagram shown in figure 2. During the five months of recording, more than 100 earthquake events were detected. The P- and S-wave arrival times were picked manually using the Seisgram2k software. The micro-earthquake events were recorded using instruments with three components providing data in the vertical (Z), north–south (N–S), and east–west (E–W) directions. The P-wave arrival times can be easily estimated by observing the data in the vertical component (Z). Accurately determining the S-wave arrival times requires a transformation to the frequency domain. In addition, we applied criteria to select proper earthquakes and obtain only local earthquakes. The events must have a difference in arrival time between the P- and S-waves of less than 3 s, and the events must be recorded by at least four stations. Filtering techniques (i.e., band-pass and low-cut filters) were also implemented to suppress noise and to improve the picking quality of unclear P- and S-wave arrival times.

For the velocity model, we used a velocity reference based on the field data. The velocity structure that we used in this study is illustrated in table 1. We used a Vp/Vs ratio of 1.65.

Table 1. One-dimensional velocity model applied to determine the hypocenters.

| Layer number | Layer thickness (km) | P-wave velocity (km/s) |
|--------------|----------------------|------------------------|
| 1            | 0                    | 2.5                    |
| 2            | 0.53                 | 2.9                    |
| 3            | 1.44                 | 4.56                   |
| 4            | 7.00                 | 5.80                   |
| 5            | 15.00                | 6.40                   |
| 6            | 16.00                | 8.00                   |
4. Results and discussion
In total, 145 events were recorded during the period from June 2012 to October 2012. The initial locations of the micro-earthquake events were determined using the single-event determination method with the Geiger adaptive damping method. The hypocenter locations were then revised and updated via double-difference relocation. In the relocation process, only 130 events were relocated properly.

Figures 3 and 4 show a comparison of the distributions of the epicenters and hypocenters of the initial and relocated locations, respectively. The magnitudes of the micro-earthquake events ranged from 1.01 to 3.00. The earthquake magnitudes were determined via the Tsumura magnitude calculation [5].

A comparison of the epicenter maps of the initial and relocated locations (shown in figure 3) indicates that (i) the initial locations of the earthquakes spread all over the field area and (ii) there were earthquake events that were located far from the recording stations. However, the micro-earthquake events are mostly distributed in the southern part of the study area. From figure 3 and figure 4, we can see that

Figure 3. Comparison of the epicenter maps showing the results of the (a) initial, and (b) relocated epicenter locations.

Figure 4. Comparison of the hypocenter maps showing the results of the (a) initial, and (b) relocated hypocenter locations.
the relocated earthquake hypocenter distribution is increasingly localized and is within the range of the recording stations. The earthquake hypocenters are increasingly clustered in a certain range and zone. There are hypocenters that appear to form a straight-line pattern in the northeast–southwest and northwest–southeast directions. These are thought to be the faults that control the hydrogeology of the geothermal system in the study area. We can also see that there are clustering events within a depth of 448–6000 m relative to the mean sea level. These events are thought to occur in the permeable zone, and this analysis is supported by an S-wave splitting analysis.

From the S-wave observations made in the data processing stage, we identified 52 events indicating a delay time between the arrival of the S-wave on the vertical and horizontal axes. The distribution of earthquake hypocenters experiencing shear wave splitting is shown in the circled areas in figure 5. Figure 5 indicates that the earthquakes with S-wave splitting form patterns and are at distances of 7,500–12,500 m with depths of up to 6,000 m below mean sea level. The zones marked with circles are interpreted as fracture zones present in the “R” geothermal field.

The earthquake epicenters are spread between the three fumaroles present in the “R” geothermal field. In figure 6, the epicenter distribution following the geologic structure orientation is increasingly apparent, as shown by the yellow circle. There is an epicenter distribution with a northwest–southeast orientation that fits the existing fault structure. In addition, there is an epicenter orientation that follows the geologic structures in the southwest–northeast and north–south directions.

**Figure 5.** Hypocenter distribution with shear wave splitting data in the circled areas.

**Figure 6.** Epicenter distribution overlaid with geological data.
However, the spread of epicenters with a southwest–northeast orientation is not exactly in the fault zone indicated on the geologic map but is shifted slightly toward the north. This could be because the fault has a nonvertical dip that causes the epicenter locations to be shifted relative to the surface fault area. Both the epicenter orientations, north–south and northeast–southwest, agree with existing geologic structures that can be interpreted as fractures acting to control the discharging and recharging fluids in the geothermal system of Mount R. Figure 6 also indicates an epicenter distribution that follows the orientation of small fracture structures that exist on the south side of geothermal field R, i.e., a distribution with a north–south orientation.

Figure 7 shows the correlation of the hypocenter distribution with magnetotelluric (MT) data. It can be seen that most of the earthquake hypocenters are located under low-resistivity layers. This layer is the clay cap present in the R geothermal system. Therefore, the hypocenters likely originated from the permeable reservoir layer. Figure 7 and figure 8 show that the hypocenters form a straight-line pattern toward the surface. These hypocenters are thought to occur as a result of the fracture represented by a dotted black line, which serves as a pathway for the hot fluid to reach the surface and produce a manifestation on the surface. However, in figure 7, the fault is not located exactly under the manifestation. This result is, however, biased because the fluid moves up to the surface through the existing fault and then swiftly descends into the foothills in the north, where it produces hot springs. The hypocenter distribution in figure 7 indicates the high-resistivity layer. This layer is thought to be the permeable layer in geothermal field R.

![Figure 7. Hypocenter distribution with respect to MT data.](image1)

![Figure 8. Delineation of geothermal field R within the dashed-line area.](image2)
From the merging of the hypocenter distribution with the geologic and MT data in figure 6 and figure 7, it was found that the three datasets mutually support each other. The hypocenter distribution resides in areas with high-resistivity values, and there is a hypocenter distribution that follows the fracture orientation of a geologic structure. From the obtained results, we can delineate the permeable zone in geothermal field R, as shown in figure 8.

5. Conclusion
The distribution of the hypocenter locations obtained using the single-event determination method is still diffuse and not exactly in the form of the permeable zone pattern and fracture structure. The double-difference method can better relocate the hypocenters and the positions of the hypocenter distributions, more accurately depicting the permeable zone pattern and fracture structure as well as resulting in smaller residual errors. Shear wave splitting observations can be used here to indicate the fracture zone of the geothermal reservoir. The epicenter and hypocenter distributions can be used to identify the structures confirmed by the geologic and MT data. The delineation result of the fault zone indicates that the permeable zone has an area of approximately 15 km$^2$ with a depth of 6500 m relative to the mean sea level.

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References
[1] ESDM 2016 *Pengesahan Rencana Usaha Penyediaan Tenaga Listrik PT Perusahaan Listrik Negara (Persero) Tahun 2016 s.d. 2025* (Jakarta: ESDM)
[2] EBTKE 2012 *Profil Potensi Panas Bumi Indonesia* (Jakarta: Kementerian ESDM)
[3] Martodjojo S 2003 *Evolusi Cekungan Bogor* (Bandung: Penerbit ITB) p. 238.
[4] Darmawan I G B, Setijadji L D, and Wintolo D 2015 Geology and geothermal system in Rajabasa Volcano South Lampung Regency, Indonesia (Approach to field observations, water geochemistry and magnetic methods) *Proceedings World Geothermal Congress 2015* Melbourne, Australia, 19-25 April 2015.
[5] Tsumura K 1967 *Bull. Earthq. Res. Inst.* 45 7-18