Resistivity model of hallow subsurface to find the path of geothermal manifestation in Bora Village of Sigi Regency of Central Sulawesi

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Abstract. Bora geothermal is one of the manifestations that appear at the meeting of two fault zones namely Palu-Koro Fault and Palolo Fault. This geothermal is classified as non-volcanic. Existing tectonic activity, presumably leading to the formation of a depressive zone that triggers a rock intrusion process that conducts heat conductively. To find out the sub-surface structure, we apply the electrical resistivity tomography (ERT) method. The data collection technique we use is 2-D imaging with Wenner configuration, where the number of electrodes is 21 pieces at 6 m intervals. Shallow depths Penetration targeted about 20 m below ground surface (m.bgs. The resistivity values obtained are in the range < 0.15 Ohm.m to > 56.6 Ohm.m which indicates the subsurface layer is strongly influenced by the fluid. However, the interesting thing here is that the hot water pool formed on the surface of about 6 m dimension is passed through the path of ERT measurement around the electrode number 11 and 12, illustrated in the resistivity section to ± 10 m.bgs depth and turning toward the electrode number 4 up to 7 as the lowest anomaly source at depth > 15 m.bgs. This configuration of low resistivity anomaly is what we interpret as a shallow ground pathway with local high temperatures as the source of the emergence of Bora geothermal manifestations.

1. Introduction
The administrative boundary of geothermal in Bora village is located in Sigi Regency Central Sulawesi Province, Indonesia. Bora geothermal is now used as a geotourism location because of its unique shape such as a wide hot spring pool. The regional framework of the Bora emergence geothermal manifestations is influenced by the main fault structure north-northwest direction of the north-east Palu-Koro Fault and hit by Palolo fault trending almost east- which is perpendicular to the Palu-Koro Fault [1]. These faults are supposed to facilitate the appearance of hot springs in Bora Village. However, the phenomenon of the relationship between the existence of geological structures such as faults, stout, or fractures is closely related to the appearance of geothermal symptoms on the surface [2-7]. Where the geological structure is a control or intermediary medium that brings heat from the geothermal reservoir to the surface.

Generally, geothermal research activities focus on describing geothermal systems such as the presence of heat sources, reservoirs, rock caps, and faults, then reconstructing conceptual models and estimating their potential using integrated geological, geophysical and geochemical investigations [8-13]. However in this study, we focused on studying geothermal in Bora Village just to clarify the manifestation conditions of hot springs in superficial subsurface structures. Obviously we would like to
find the hydrogeological perspectives of the existence of hot springs and geological structures controlling direction of hot spring subsurface which flows out to the ground as a manifestation. For that purpose, we apply the electrical resistivity tomography (ERT) method which is usually used to study superficial under surface structures based on the distribution of rock resistivity values. The selection of this method is based on a case study of ERT application that has been successfully used in searching for anomalous objects under the shallow surface such as tracking the presence of buried pipes [14,15], holes and caves [16-19], slip fields in landslides [20-22], sewage seepage [23-26], and archaeological sites [27]. Therefore, in this paper we are trying to develop the application of ERT method in order to describe the path of Bora hot springs as a case study which can be discussed as a comparison of several cases of successful application of other ERT methods.

2. Geology and Characteristics of Bora Geothermal Manifestations on The Surface

2.1. Regional Geology
Regionally, Bora geothermal located above the Pakuli (Qp) Formation unit consisting of a conglomerate, sandstone, and the carbonate claystone which occupy the largest area, in the western part of the inquiry area. Age of the formation is the Late Pleistocene - Early Holocene (figure 1 and figure 2).

![Geological map of Bora and surrounding areas (modified from [28])](image)

Figure 1. Geological map of Bora and surrounding areas (modified from [28])
The oldest rocks found in Bora and its surroundings are the Wana (TRw) and Gumbasa (TRjgg) complexes that occupy the middle to the south and slightly north of the investigation area. The Wana complex (TRw) is composed of miscellaneous rocks of mica type, amphibol schist, gneiss and quartzite, while the Gumbasa Complex (TRjgg) consists of gneissan granite, gneissan diorite, gneiss and schist. Both complexes are Trias - Jura [28].

2.2. Geology Structure
Bora geothermal morphology is located in the graben / Palu valley area, where the main structure in the investigation area is dominated almost north-south direction ie Palu-Koro fault and northeast-southwest of Palolo fault. Both of these faults meet near the geothermal regions of Bora. The implications of the existence of the main structure form other small faults such as normal faults, oblique fault and horizontal fault (figure 3). These faults are allegedly acting as a medium of rising hot water on the surface, due to the activity that caused the destruction zone around the area of investigation.

Figure 2. Rock outcrops encountered in the field. (a) Conglomerate outcrop, clay with sandstone inserts east of ± 100 m from Bora hot springs, (b) Outcrop of quartzite cemented conglomerate to the northeast ± 150 m from Bora hot springs

Figure 3. Map of the alignment morphology at Bora and surrounding areas
2.3. Bora Geothermal Manifestation

Bora geothermal manifestation of a fumarole that smells of sulfur shaped like a pool of hot springs. In terms of environment, geothermal Bora classified as non-volcanic geothermal with dimensions of hot water pool Bora about ± 6 × 6 m. On the surface, this hot water temperatures up to 70°C, looks turbid, and slightly releases a cloud of smoke and gas as shown in figure 4.

![Figure 4. The appearance of Bora geothermal manifestations](image)

3. Application of ERT Method

3.1. Setup Measurement

The concept of resistivity measurement is done by injecting the current, I into the ground through two current electrodes C1 and C2 as in figure 5, and measuring the resulting ΔV voltage difference at two potential electrodes (P1 and P2). From the value of current I and voltage ΔV, we get the apparent resistivity value (ρa) calculated by the equation [21]:

\[ \rho_a = \frac{\Delta V}{I} \]  

where the geometry factor for Wenner configuration is:

\[ K = 2\pi a \]  

![Figure 5. Electrodes array use Wenner configuration](image)

In ERT field survey arrangement we use 2-D imaging array with Wenner configuration, where number of electrode is 21 and 6 m interval. The ERT trajectory profile we place adjacent to the Bora hot springs pool as shown in figure 6. This is done so that we can get a representative of subsurface structure with its dimensions with the Bora hot spring pool.
3.2. Resistivity Modeling

The result of ERT measurement is the apparent resistivity value which is the electrical signal response that comes from all possibilities at the subsurface, in this case the earth is considered homogeneous. However, the principle is, field surveys are always conducted on non-homogeneous mediums where subsurface resistivity has a 3-D distribution [29], in other words the earth model is not just one layer but consists of distinct layers and different in subsurface. To obtain a resistivity model of subsurface rocks that is "true" from the ERT measurement, the apparent resistivity value is processed through the inverse modeling method.

The relationship between apparent resistivity and true resistivity is complex. To solve the problem, in this research process inversion modeling is using RES2DINV software. This technique is based on the smoothness-constrained least-squares method and produces a 2-D subsurface model of apparent resistivity [29]. The quality of the inversion then can be checked by looking at the error value (\(e_{rms}\)) using the equation [30]:

\[
e_{rms} = \sum_{i=1}^{N} \left[ \frac{\log(\rho_{at\text{meas}}) - \log(\rho_{at\text{cal}})}{N} \right]
\]  

(3)
Where $\rho_{a_i,\text{meas}}$ and $\rho_{a_i,\text{cal}}$ are measured resistivity values and are calculated on the $i^{th}$ data, and $N$ is the number of data points.

The result of ERT data modeling using RES2DINV software consists of 2 pseudosection of measured and calculated resistivity, and the result of the inversion model of resistivity cross section can be seen in figure 7.

**Figure 7.** Result of data resistivity inversion modeling

### 3.3. Interpretation

From the data model of Bora geothermal ERT data, the resistivity values obtained are in the range $< 0.15$ Ohm.m to $> 56.6$ Ohm.m which indicates the subsurface layer is strongly influenced by the fluid (figure 8). This means that the character of the rock beneath the surface is porous, as some outcrops that have been found, namely the conglomerate and clay in sandstone insert. The fluid from below the surface is shaped like a lens from a layer of aquitard lens that is part of a semi-free shallow aquifer layer, not depressed. Possibly, with a thrust from the bottom is like the intrusion of igneous rocks that bring heat to the local groundwater layer, so that the groundwater is find a way in the fault zone or fracture to appear at the surface as a hot springs.

The interesting thing about this ERT cross-section, that is the hot water pool formed on the surface of about 6 m dimension is passed through the path of ERT measurement around 10th and 11th electrodes number, illustrated by the resistivity section to $\pm 10$ m below ground surface (m.bgs) depth and turning toward at 4th to 7th electrodes as the lowest anomaly source at depth $> 15$ m.bgs. This configuration of low resistivity anomaly is what we interpret as a shallow high-temperature ground pathway as the source of the pathway for the emergence of Bora geothermal manifestations.
Figure 8. Interpretation of the pathway of Bora hot springs manifestation based on resistivity value.
4. Conclusions
The influence of the main structures such as the Palu-Koro fault and Palolo faults, has implications for the formation of gaps as a medium of hot water rising to the surface in the geothermal area of Bora. This is triggered by the intrusion of igneous rocks that bring heat to the local groundwater layer, so that the groundwater find a way in the crumbling zone or fractures to appear at the surface as hot springs. Characteristics of geothermal manifestation of Bora in the form of fumarole that smells of sulfur shaped like a pool of hot springs, appears murky, and slightly release a puff of smoke and gas. In this paper, the application of the ERT method in the geothermal of Bora has successfully interpreted the path of Bora hot springs in shallow subsurface structures. Where the shape is like crack or fracture zone in porous rocks that bend up into the surface form like a hot spring pool. This is particularly evident in the ERT cross-sectional image of the low resistivity values sourced from the depth > 15 m. bgs rise and bend toward the right around the pool of springs or at 11th and 12th electrodes number.

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