Application of Fault and Fracture Density (FFD) Method for Geothermal Exploration in Non-Volcanic Geothermal System; a Case Study in Sulawesi-Indonesia

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ABSTRACT

In geothermal systems, faults, fractures, or contacts between intrusive and surrounding rocks may become conduits for thermal water. Fault and Fracture Density (FFD) is a simple method which is applied in geothermal exploration to locate highly fractured areas. These areas are assumed to be associated with thermal water reservoirs at the depth. The method has been applied in some low terrain volcanic geothermal systems in New Zealand such as Mokai, TeKopia and Rotokawa geothermal fields. Zones with high FFD values usually correlate well to thermal manifestations and associated subsurface reservoirs. In contrast, the FFD method gives a different result when it is applied to non-volcanic high terrain geothermal systems.

In this paper, the FFD is applied to three non-volcanic high terrain geothermal systems in Sulawesi. The results show that the high FFD zones have no correlation with the occurrence of surface manifestation, low resistivity anomalies, or demagnetized bodies, which are the main common indicators of the occurrence of geothermal reservoirs at depth. Instead, thermal manifestations appear at the transitions from high to low density FFD contours, which reflects the flank or the slope of the terrain. High FFD areas are mainly associated with the top of high elevation topography where the terrain is very rugged. The fractures here are the result of tectonic deformation and erosion.

The result of the study suggests that the occurrence of the thermal springs is dominantly controlled not only by the structure, but also by the regional hydrology, such as formation dips, faults, fractures, or contact. Thermal water from distant reservoirs may be transported by regional hydrological flow to the manifestation area. Consequently, the sources of the thermal water in geothermal reservoirs are not indicated by high FFD zones, but at the transition of moderate to low FFD zones. These zones appear to correlate well with horizontal derivative images from gravity data, which suggest a deep highly fractured zone that may be a permeable zone with geothermal potential.

1. INTRODUCTION

Fault and Fracture Density (FFD) is a simple method used to assess highly structure density areas formed by interconnection of faults and fractures. These fractures may be tectonic in nature, and this type of fracture develops due to rock deformation during tectonic activity, such as folding and faulting. On the other hand, these fractures may have formed around intrusive bodies, which develop during the intrusion of igneous rock into the surrounding rock. These structures are potentially permeable zones that can act as paths for thermal fluid to flow from the reservoir at depth to the shallower level. It has been proven in geothermal exploration and exploitation that these permeable zones are significant drilling targets to find productive wells (Soengkono, 1999a and 1999b). Thus delineation and detection of areas with high densities of faults and fractures is very important for geothermal exploration and exploitation.

The FFD method utilizes digital topography data and the shaded relief tool, which is available in some mapping or GIS software, such as Surfer and ArcGIS. For example, when using the shaded relief tool in Surfer software, one can delineate the lineaments which appear as the result of light rays from the pseudo sun at different angles. The density of these lineaments over the study area (e.g. in areas of geothermal anomaly) is shown by the density of this lineament in every section of the grid which divides the study area. The dimension of the grid is usually 1 km x 1 km. The density is defined as the total length of the lineaments within each grid block. Thus, the unit for the density is km^{-1}. The density value in each grid may be contoured to show the area of the same density value.

In some of geothermal fields in New Zealand, such as Te Kopia (Soengkono, 1999a and 1999b), Mokai (Soengkono, 2000), and Rotokawa (Suryantini, 1999), the FFD have proven to be a simple but powerful method for delineating permeable zones. Areas delineated by the high FFD contours (or anomaly areas) coincide well with areas of low resistivity and hydrothermally demagnetized rocks, which are indicators of geothermal reservoirs in volcanic rocks (Soengkono, 1999 a and 1999b, 2000; Suryantini, 1999).

The three geothermal fields mentioned above exhibit some geological similarities. Firstly, the geothermal fields are high temperature geothermal systems, where hydrothermal alteration is generally very intense and can mask the appearance of faults or fractures. Secondly, the fields are within low to moderate terrain, causing the hydrological flow to spread at short distances, and thus, the surface manifestation of thermal water such as springs, fumaroles, and hydrothermally altered rock are concentrated in nearby low terrain areas. Hence, the reservoir may be located close to the manifestation area.

In this study, the FFD is applied to three geothermal prospects in Sulawesi Island, Indonesia. Most of the prospects in this study are characterized by medium temperature. The structural controls dominate the distribution of the surface manifestations, which are mainly thermal water springs. Geologically, the young volcanic activities which indicate potential heat sources of high temperature geothermal systems occur only in the northern arm of this island. The geothermal systems that are located

elsewhere on the islands are associated with cooling plutons at depth. Most geothermal prospects in Sulawesi Island, including the study areas, were investigated during reconnaissance and inventory mapping by Directorate of Mineral Inventory or DIM (now is PDSG?). At a minimum, geological and structural mapping in the scale 1:100 000 is available for every prospect. Geochemical data consists of mercury, CO_2, and temperature distribution maps, in addition to cation and anion data from cold and thermal springs. Geophysical data include electrical resistivity mapping and sounding, geomagnetic surveyes, and gravity.

Some of the prospects have been drilled to determine the temperature gradient to a depth of 250 m. These data sets are the best resource for validating the results of FFD studies.

Three main geothermal systems were the focuses of this study: the Suwawa Prospect in the Gorontalo Province and the northern Sulawesi Province, and the Pulu and Marana Prospects on the western coast of the Central Sulawesi Province, as shown in Figure 1. The association between the FFD anomalies and the conceptual model of every prospect is discussed.
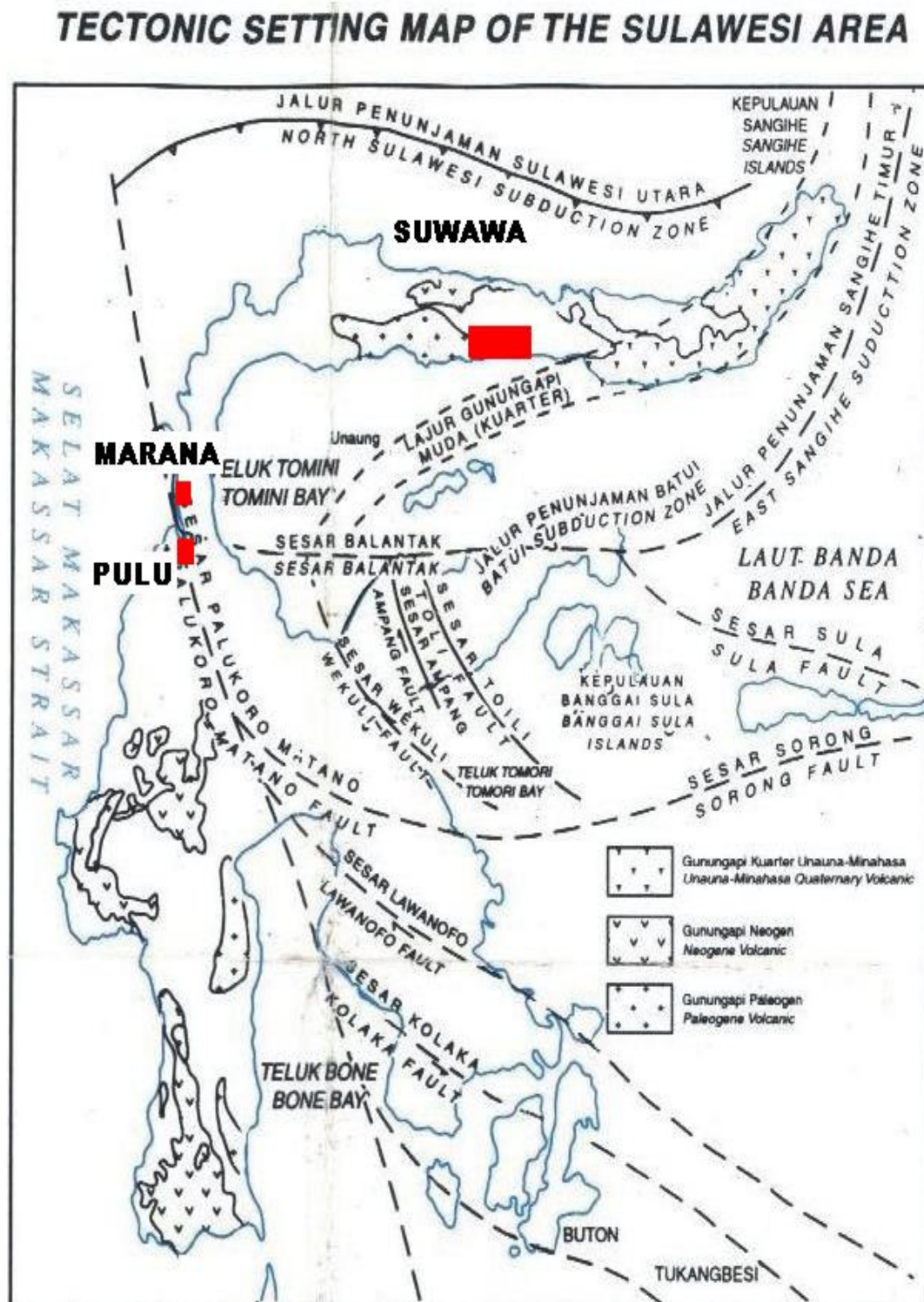

Figure 1: Tectonic and geology setting of Sulawesi Island, and the location of study area.

2. GEOLOGY AND TECTONIC SETTING OF SULAWESI ISLAND

Sulawesi Island (formerly known as The Celebes) is situated along the eastern margin of the stable cratonic area of Sundaland. Three plates collide with each other at this location, resulting in very complex tectonics in the region. Western Sulawesi is located on the eastern margin of Sundaland. The basement promontory protrudes southeast from Asia and is the site of collision with the Australian micro-continent. The major fault separating western and eastern Sulawesi is the Palu-Koro Fault, which is a left lateral fault. The northern arm houses an active magmatic arc resulting from the northward translation of the Australian crust. The eastern and southeastern arms are composed of ophiolitic and microcontinental fragments that accreted onto western Sulawesi during the Cenozoic. The geological and tectonic setting is described in Figure 1.

3. GEOTHERMAL SYSTEMS OF STUDY AREAS

3.1 Suwawa Prospect

The Suwawa Geothermal Prospect is located in the Gorontalo Province in the northern arm of Sulawesi Island. The following description of the prospect is summarized from several reports published by DIM (Bakrun, et al., 2004; Nanlohi, and Dikdik, 2006; Nanlohi, et al., 2004; Nanlohi, 2004; Rezky et al., 2005; Situmorang, et al., 2005; Sulaeman, and Asngari, 2005; Widodo et al., 2005). This area is geomorphologically divided into three units: (1) an alluvial plain along Bone River with dip slope of <10°, (2) moderately wavy volcanic hills in the southern area, with a dip slope of 20°-30°, and (3) sharp, highly wavy plutonic hills with dip slopes of >40°. With respect to geology, the study area is mostly covered by lava and intrusion rocks (i.e. granite and diorite). Pyroclastic flow and alluvial deposits cover about 15% of the western and central parts of the area. Faults are dominant in this area and mainly trend NW-SE and WNW-ESE. At least eight (8) major faults occur in this area. Geothermal manifestations such as hot springs are strongly controlled by these faults. There are two major hot springs that indicate the occurrence of geothermal systems in this area: (1) Libungo springs, which consist of three springs, and (2) Lombongo springs, which consist of two springs. Libungo-1 occurs near the contact of Young Pinogoue Lava, whereas both of Lombongo springs are located in the vicinity of a fault zone. The Na-K geothermometer from Libungo Springs, which contains water with magmatic chloride character, indicates that the associated reservoir temperature is lower than 200°C. The temperature gradient well near Libungo-1 (i.e. SWW-1) gives slightly higher results, with a geothermal gradient of 14°C/100 m (Nanlohi and Dikdik, 2006). The ground surface alteration is less intense.

The true resistivity map indicates a closing area of a low (<30 ohm-m) resistivity anomaly around Libungo Springs. The magnetic data shows no significant correlation with resistivity map, and the low value of the total residual magnetic anomaly is widespread in this area. The gravity map indicates a depression in the western part of the area, which is probably associated with the low terrain area consisting of lake deposits and pyroclastic fall deposits. This depression is possibly bordered by two major faults trending NW-SE and WNW-ESE. Adjacent to this depression are high positive gravity anomalies located in the north and south, which coincide with granite-diorite intrusions and Young Pinogue lava, respectively. The horizontal derivatives map, which usually indicates enhancement of faults and contact (for example between intrusive rocks and sediment), indicates that the Libungo Springs are located adjacent to the fault and within the Young Pinogue Lava.

This suggests that the springs might flow through faults or through the vesicles within the lava. The high terrains south of Libungo Springs tend to control the regional hidrology of the area. Thus, the recharge of the springs possibly originates in the south and flows to the north. The meteoric water could mix with the thermal water during the flow, resulting in the water at the Libongo Springs. The reservoir of the thermal water is probably in the south within the Young Pinogue lava. A prospect map is shown in Figure 2a.

3.2 Marana Prospect

The Marana Geothermal Prospect is in the Central Sulawesi Province on the western coast of central Sulawesi. Regionally, this area is adjacent to the Palu Koro Fault Zone. The geomorphological unit is divided into three areas: (1) flat terrain along the coast, (2) steep sloping hills in the east that consist of metamorphic rock and granite plutons, and (3) low-moderately wavy hills of sediment and alluvial deposits in the central part of the prospect. The two major faults in this area are the Marana Fault and the Masaingi Fault. These faults are almost parallel to each other and trend NE-SW from the central part to the east, but they have an almost W-E direction from the central part to the western coast. Two spring complexes indicate the occurrence of the geothermal prospects: Marana Springs and Masaingi Springs, while ground surface alteration is less intense. They are located adjacent to the Marana Fault and the Masaingi Fault, respectively, suggesting that the dominant controlling factor of the manifestation is structural geology.

Both Masaingi and Marana Springs contain immature water, but Masaingi is chloride water at 90°C and pH 8.1. The spring flow is about 2 l/s, but the geothermal gradient well (MM-1) drilled near the springs gave a very high flow rate of about 317 l/s (Nanlohy, F, 2004). The Na-K and Na-K-Mg geothermometers suggested that the reservoir temperature is less than 220-230°C. Due to very high flow rates, the temperature gradient data could not be obtained from well MM-1 (Bakrun . et al., 2004)

The true resistivity map shows two areas of low resistivity (<50 ohmm) to the NW and SE of the prospect. However, this low resistivity reflects the property of the sediment rather than clay altered rock. On the other hand, the true resistivity value near Masaingi Springs is about 50-100 ohm-m and has a NE-SW trend, which coincides well with Masaingi Fault. It suggests that the occurrence of the geothermal system in this prospect is controlled by the Masaingi Fault, as is revealed by Masaingi springs and the resistivity trend around this spring. The residual total magnetic anomaly map indicates a closing area with low values (±0 nT) just north of the Masaingi Springs. Unfortunately, the demagnetized body has not yet been defined. The bouguer and residual gravity anomaly shows a high positive anomaly to the NE of Masaingi Springs with a similar direction to that of the Masaingi Fault. Using horizontal derivatives to enhance the edge of the body of this positive anomaly makes it possible to delineate the source of the anomaly body at depth. The results of horizontal derivatives to the gravity data suggest that there is probably an intrusive rock at depth that could be the heat source of the system. Masaingi Springs is located at the southern flank of this anomaly, which is also the flank of the high topography. It suggests that the regional flow of meteoric water may come from the NE or N to Masaingi

River and to the location of thermal springs. The Masaingi thermal springs is thus suspected to be the upflow of the system, as is also suggested by geochemical data. Further suggestion is that the Marana springs may be the outflow of the system. The reservoir of the thermal water is probablya fracture system within the Masaingi Fault Zone. A map of the prospect is shown in Figure 2b.

3.3 Pulu Prospect

The Pulu geothermal prospect is located less than 100 km south of Marana Prospect. This area is probably part of the segment of Palu Koro Fault Zone, which formes a graben called the Pulu Graben. The springs are the indicator of the geothermal systems located in the fault zone. Morphologically, areas to the west and east of the Pulu Prospect are dominated by high terrain of granitic rocks and schist, respectively. In the middle is a flat alluvial plain. According to Cl-Li-B content, there are three groups of springs which reflect the three different reservoirs: (1) Pulu-Limba-Walatana springs, which are located in the Pulu-Rogo Fault Zone to the west of the study area; (2) Mapane-Kabuliburo-Simoro spring, which is in the southern part of the study area and is associated with the eastern fault bordering the graben (the Palu-Padere Fault); and (3) Sibalaya spring, which is located to the north east of the study area. The hottest springs are Mapane and Kabuliburo (94°C), while temperatures at Pulu-1 and Pulu-2 are 76°C and 79°C, respectively. The other springs have temperatures below 50°C. Unfortunately, geophysical surveys were conducted only the area near Pulu springs and not in the Mapane-Kabuliboro springs. Therefore, most discussion is limited to the Pulu Springs area. The Pulu Springs contain bicarbonate water with small amounts of chloride and sulfate. These springs appear from the contact between granite and collovium in the vicinity of the Pulu-Rogo Fault Zone. The water chemistry indicates mixing of thermal water with surrounding rock and thus shows no indication of volcano-magmatic association. SiO_2, K-Na and K-Na-Mg geothermometers suggest reservoir temperatures between 140 - 160°C. (Suhanto and Bakrun, 2004)

The resistivity line survey did not include the area near Pulu Springs due to the steep terrain. Therefore, information derived from resistivity data is very limited, and the interpretation of the low resistivity anomaly area beyond Pulu Springs to the north, west, and south is speculative. The low resistivity value indicated on the true resisitivity map near this spring is <15 ohm-m (Suhanto, 2004). On the other hand, the gravity and geomagnetic line survey was able to pass through the area containing the springs. The hypothesis derived from these data in the location of the springs to the east is more certain. The gravity data confirm the occurrence of the graben and Pulu Springs in the western fault zone bordering the graben. Use of the horizontal derivative filter for gravity data makes it possible to see the extent of this fault zone, which potentially houses a permeable geothermal reservoir. The total anomaly magnetic map shows a very low value near these springs. However, this may suggest the occurrence of sediment material in this area, as is the case in the sedimentary unit in the central part of the study area. The reservoir boundary of the Pulu Springs Prospect is then delineated near the permeable zone shown by the high value of the horizontal derivative from gravity data. The Pulu Prospect is presented in Figure 3a.fd

4. FAULT AND FRACTURE DENSITY AND THE ASSOCIATION WITH GEOTHERMAL PROSPECT AREA.

The FFD maps of the geothermal prospects discussed above are shown in Figure 3. They are made by the people who have geological backgrounds but no knowledge about the area. This was performed in order to reduce bias in delineating the lineaments. The shade relief map was constructed from digital topography data published by Bakosurtanal (Indonesian agency for survey and mapping). Soengkono (1999) applied a 3 km/km^2 FFD contour to define the anomaly area. In this study, it was attempted to use the same contour cutoff as the previous author.

In the Suwawa Prospect (Figure 3a.), the high FFD anomaly value (> 3000 m/km^2) is located to the south and north-northeast of the expected reservoir area. These areas are associated with the Lava and Granite-Diorite units in the geology map, respectively. It seems as if the morphology and topography of the terrain resulted from erosion and that a deformation process controls the high intensity of fractures in this area, as is reflected by the high FFD contour. On the contrary, most of the springs found in the Suwawa Prospect occurred at the transition between high and low FFD anomaly areas. This transition also reflects the dip slope of the topography or morphology from high to low terrain. This slope can be a fault zone, the contact between hard and soft material/rocks, or the sediment rocks where the bedding dips toward the low terrain. In the Suwawa Prospect, this slope is mostly contact between Lava or Granite-Diorite rock with pyroclastic and lake deposits and occasionally parts of fault zones. Thermal fluid is likely to ascend to the surface in this weak and permeable zone. On the other hand, the highly fractured area marked by the high FFD contour (> 3000 m/km^2), which is located mostly at the high topography (high elevation), is probably a favorable area for meteoric water recharge.

The FFD map of the Marana Prospect is presented in Figure 3b. If the FFD contour of > 3000 m/km^2 were taken as the cutoff to determine the geothermal anomaly area, the area would be overestimated. Therefore, the highly FFD anomaly area is defined by the contour > 5000 m/km^2. The anomaly of high FFD in the east is associated with granite and schist rocks where the elevation is high and the morphology is steep and sharp. The other anomaly in the north is on the sedimentary unit, but the elevation is also high, suggesting a hard rock beneath the sediment covering, which is perhaps an intrusive body or metamorphic rock. An interesting anomaly is located just north of the Masaingi Spring. Here, the high FFD anomaly area more or less coincides with the boundary of the geothermal reservoir. However, the geothermal reservoir boundary in this prospect is mostly delineated by the reservoir's location in the Masaingi fault zone rather than delineating the anomaly from low resistivity, demagnetized bodies, or surface manifestation. The Masaingi Springs and Marana Springs are essentially located at the transition of high FF to low FFD contour which also mark the flank of high topography.

The Pulu Prospect is located in a graben. The prospect is bordered by on the west and east by high topography granite and metamorphic rock, respectively. This morphology strongly affects the results of FFD analysis. As can be seen in Figure 3c, the high FFD anomaly contour (>3000 m/km^2) occurs to the west and east of the study area and coincides with this high topography. The occurrence of the Pulu Springs and other springs coincides with the transition of high to low FFD anomalies, or at the flank of

this high topography high. This flank or slope is actually the scarp of the fault zone bounding the graben. The high FFD anomaly area is on the top of the high topography area, which is probably associated with fractures in the rock resulting from rock deformation and erosion. This zone may become the recharge area. Thermal flow from the subsurface may ascend through the fault zone to the surface and reveal itself as thermal springs.
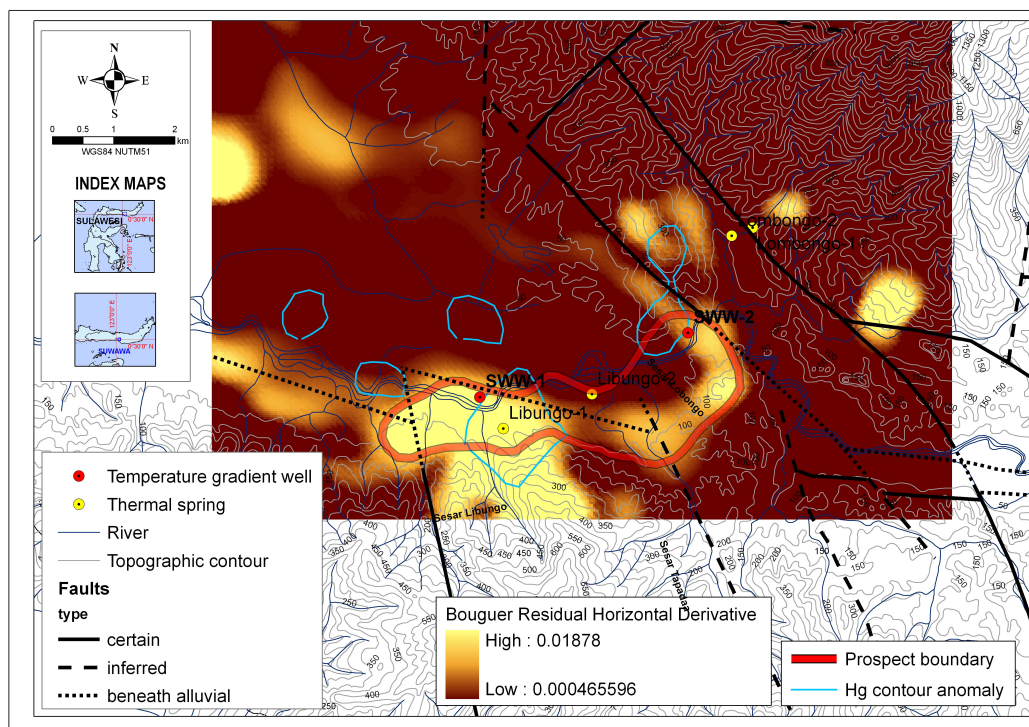
5. DISCUSSION.

In high temperature, low to moderate terrain, the application of FFD to geothermal systems is optimal. This is because surface manifestations that are mainly caused by the interaction of thermal fluid with the surrounding rock through faults and fractures are very intense and concentrated in a low terrain area above a geothermal reservoir.

Faults and fractures may be masked by the alteration or deposition of minerals carried by thermal water. The appearance of the surface manifestation such as ground alteration, mineral deposition (e.g. silica sinter), and the occurrence of thermal springs and fumaroles thus reflects the faults and fractures that host fluid flow. The morphology produced by this surface manifestation may be undulating topography comprised of silica deposition along the fracture or lineaments of springs along the fractures and faults. These are some morphology forming lineaments in shaded relief map. Other lineaments may be the offset of stream direction or morphology. These lineaments, in turn, control the results of high or low FFD anomalies.

On the contrary, in low-moderate temperature high terrain geothermal systems, the manifestations are mostly thermal springs with less intense ground alteration or mineral deposition from thermal water. The thermal water perhaps originates from a reservoir far from the occurrence of the thermal spring itself. Thus, the area of the high FFD anomaly does not correlate with the geothermal reservoir at depth. Instead, it reflects the fractures formed by deformation or erosion of the hard rock forming high terrain.

The regional hydrology may be strongly involved in the distribution of the thermal water. In the step terrain of crystalline rock, some of the meteoric water may run off (Singhal and Gupta, 1999). But some of the meteoric water from the rain might infiltrate through the fractures and flow regionally through weathered rock down the slope to the area of low or flat terrain. During this regional flow, the ascending thermal water could mix with the meteoric water to produce thermal springs located far from its thermal water reservoir. This is called outflow. However, this mixed thermal water may be trapped in a secondary reservoir beneath the thermal springs. Because of this process, the chemical composition of thermal springs is usually immature water with less chloride content and low indications of magmatic water. Mixing causes the initial temperature of the thermal water to decrease, and the pH to increase from neutral to slightly high values. Thus, the rock or ground alteration caused by water and rock interaction is less intense. This interferes with resistivity surveys, and low resistivity zones are sometimes given high values (>10 ohm-m), which is similar to cases with low resisitivity caused by sediment. Because of low-moderate temperature, the demagnetized body which occurs at temperatures above 500°C could not be happened. Thus, the geomagnetic survey data show scattered relatively low magnetic anomalies that still have high values. On the contrary, because the subsurface thermal water flow is controlled by subsurface fractures or faults which are sometimes covered by alluvial or other surficial deposits, gravity data with a horizontal derivative filter can usually indicate the occurrence of this subsurface structure. On the other hand, the FFD method only detects the surface structure, where in this case, the anomaly is associated with fractures caused by tectonic deformation.

Although it is not discussed in this paper, the application of FFD in three other low-moderate temperature geothermal systems in Sulawesi yielded similar results to those discussed above.
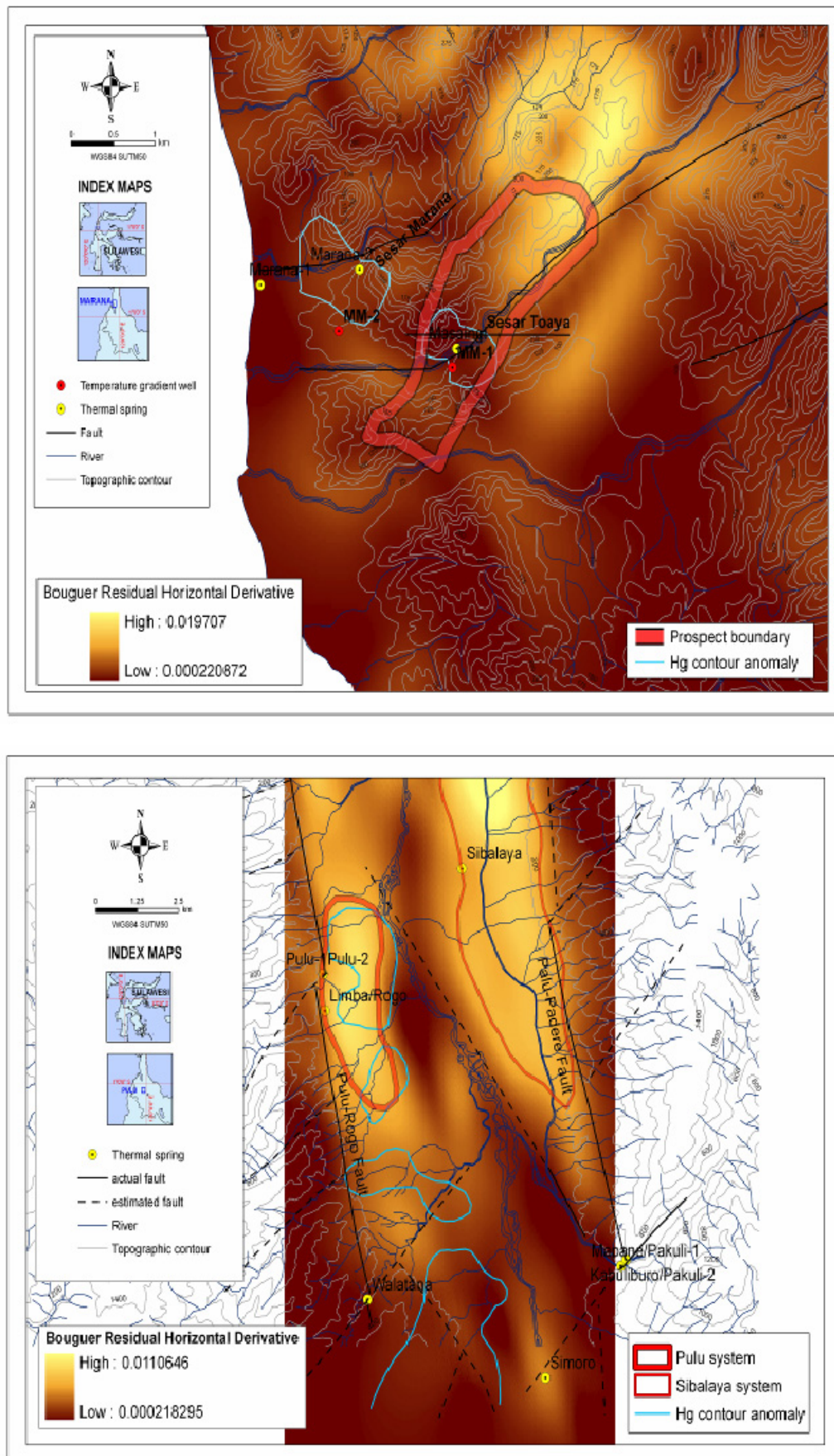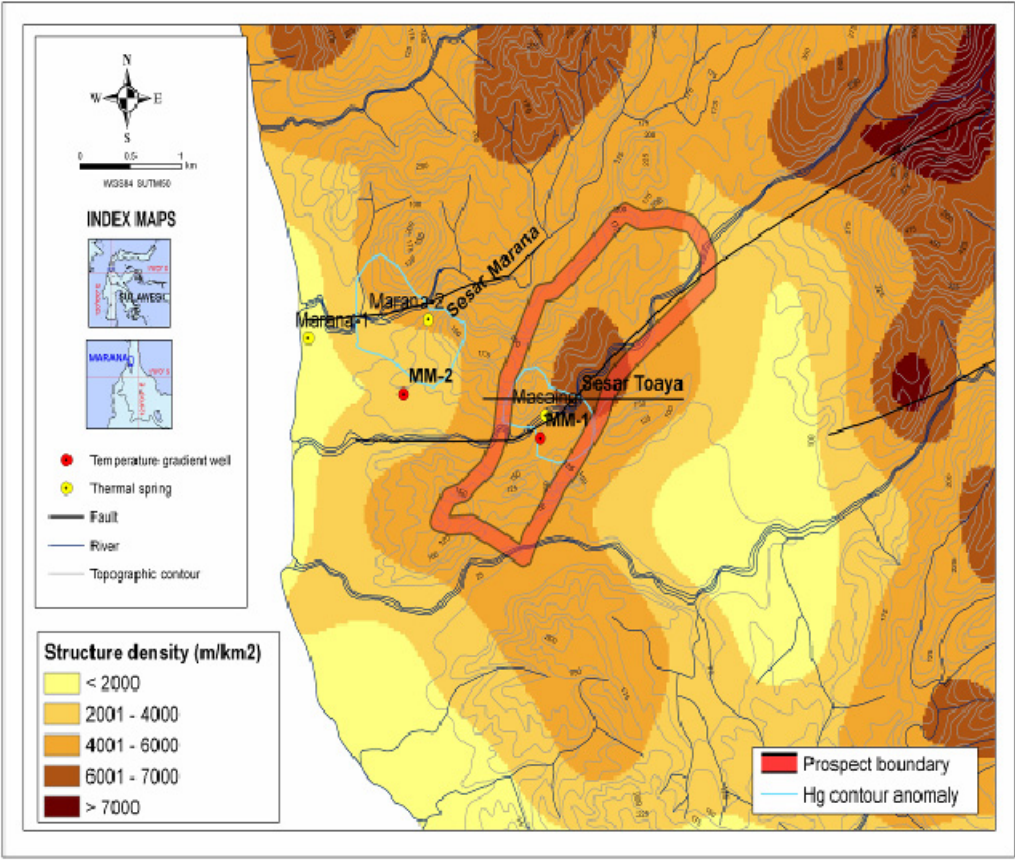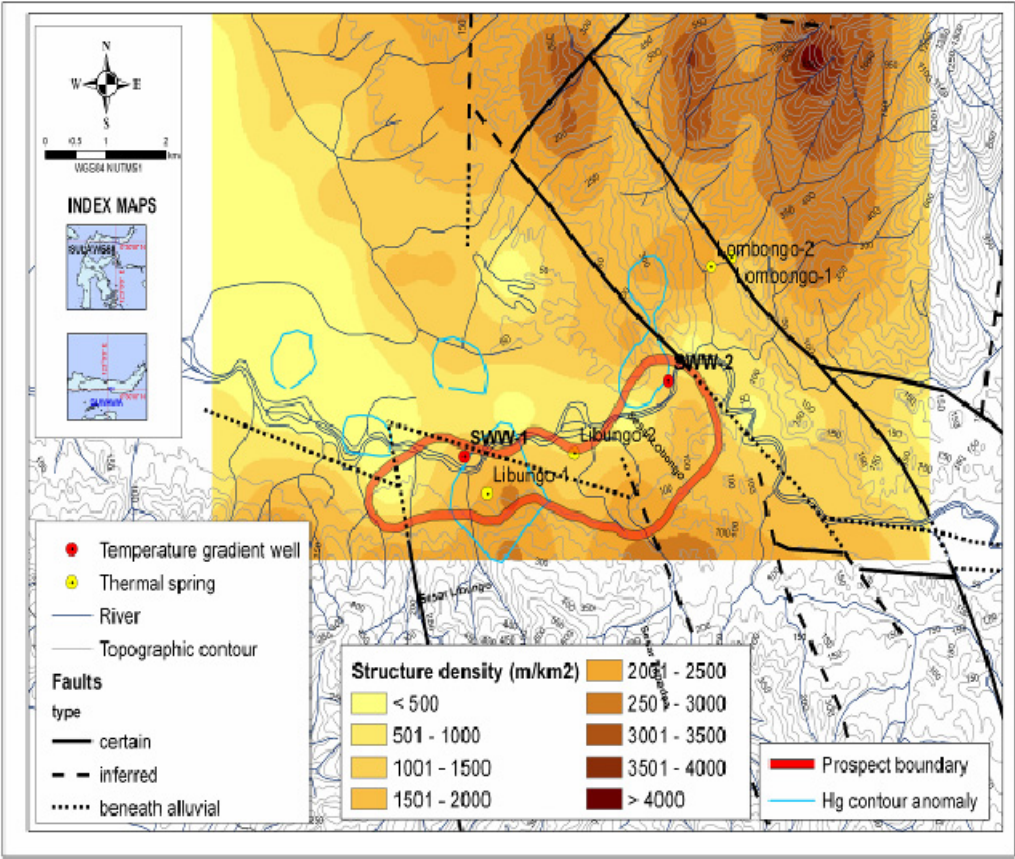
Figure 2: Prospect map of (a / top) Suwawa , (b / middle) Marana, and (c / bottom) Pulu
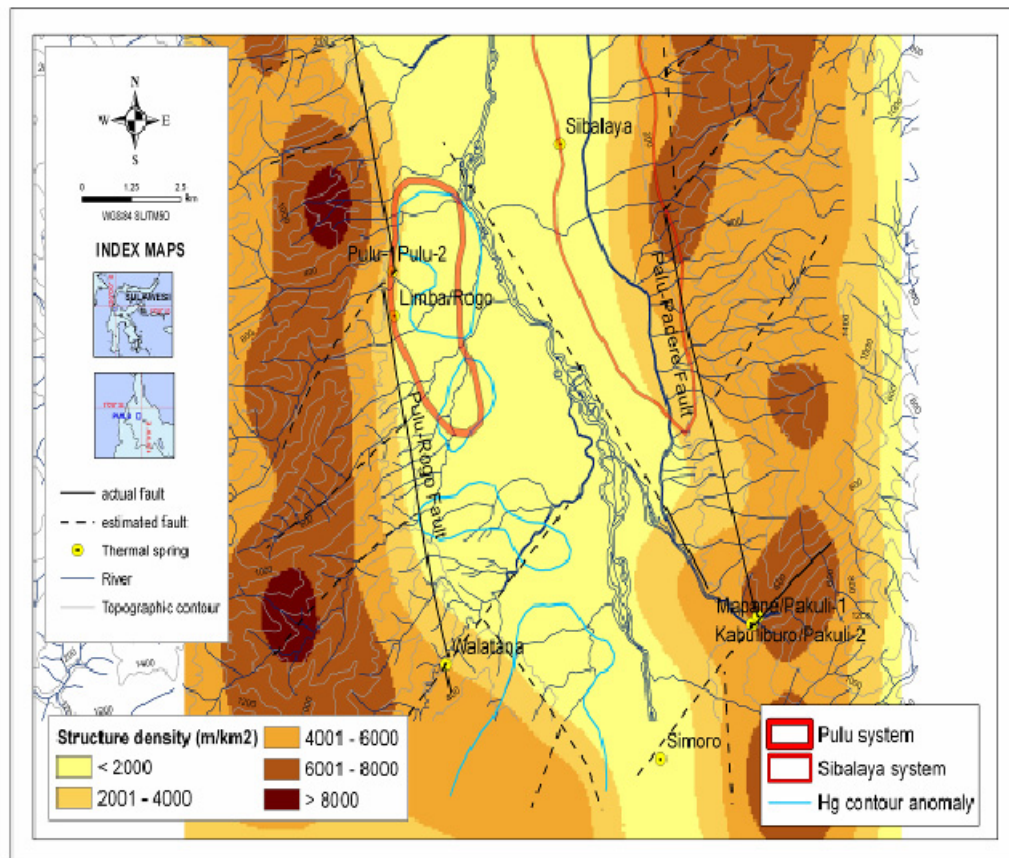
Figure 3: FFD map of (a / top) Suwawa , (b / middle) Marana, and (c / bottom) Pulu

6. CONCLUSIONS.

This study demonstrates that the application of FFD in low - moderate temperature geothermal systems must be used with careful consideration of the regional hydrology of the area. High value FFD contours are usually located on top of high terrain, which may be associated with fractures caused by tectonic deformation and could become recharge areas. Thermal springs and other surface manifestations often occur at transitions between high and low FFD contours that reflect the slope or the flank of the terrain. The FFD is not associated with low resistivity values or demagnetized body. The horizontal derivative of gravity data may be a good indicator of subsurface structures controlling the occurrence of thermal springs.

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