

Review of Regional Geological Structures on the Appearance of Geothermal Manifestations in the “Neck” Region of Western Sulawesi Island

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Abstract: Palu-Koro fault is a major fault in western neck of Sulawesi Island. It is shown by Mw 7.5 struck the area in 2018. Its trace can be observed by the appearance of surface ruptures. We recorded their geographic coordinates and observed the geological conditions of the surface such as structures form, properties of rocks, and physical properties of local hot springs. Then we conducted a qualitative interpretation by integrating field observation data on several references related regional geological structure of the area. From the results of the review, we suspect that there is a very close relationship between the activities of the geological structure and the appearance of several hot springs in the neck region of western Sulawesi. This is evidenced by the presence of 7 points of manifestation with the same pattern as the direction of orientation of the main fault, which is relatively north-south. However, one of requirements of the manifestation appearance on the surface is the existence of the fractures as up flow channels of geothermal fluids. Heat source is interpreted to come from intrusive igneous rocks as hot rocks conducting heat to the aquifer which heats the hydrological system around the area. We conclude that geothermal manifestations in the western neck of Sulawesi Island are tectonic geothermal related to the geological structures and not to the volcanic activity.

1 Introduction

Geothermal energy extracted from subsurface is known as geothermal energy [1]. The energy is one of clean energy resources which is more important as hydrocarbon alternative [2]. Before developing and exploiting geothermal energy, exploration activities need to be carried out first to assess geothermal potential which exists in an area. Generally, the initial stages of geothermal exploration are carried out using geological, geophysical, and geochemical investigation methods around the potential area indicated by geothermal manifestation presence [1-6]. The investigation results are developed into a conceptual model of geothermal system that represents the characteristics of geothermal system in the area.

According to Soengkono [7], an important aspect of the geothermal exploration is by knowing the geological structures such as fault and joint zones. This is because geological

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structures, providing geothermal fluids to enter and exit the geothermal system, is the main control of the hydrogeological system [8]. So, there is a close relationship between fault existence and the geothermal manifestation appearance such as hot springs on the surface.

The relationship can be proved based on case studies of the existing active fault, Palu-Koro, which characterized by the presence of several hot spring spots around the fault line [9-10], and there is always a left-lateral shift, strike-slip movement, each year at a rate of 34-58 mm/year [11-13]. The existing fault is a major fault in Central Sulawesi Province of Indonesia, with profile length on land of 200-300 km, and if added to the length of the profile in ocean the overall length is about 500 km [10, 14-15]. The Palu-Koro Fault has 4 segments, *i.e.*, the Palu segment, the Saluki segment, the Moa segment, and the Meloi segment [13]. The segment which has fault lines that can be identified on land is starts from the Koro Valley to the Palu Valley. This fault is a sliding fault zone oriented northwest-southeast, the southeast end of this fault segment continues to the Matano fault segment to the east, and some researchers say there is a continuous section towards Bone Bay [9, 14, 16-17]. From Palu Valley to the north-northwest direction, this fault continues into Makassar Strait and meeting with the North Sulawesi Trench [15, 18-19].

On September 28, 2018 there was a 7.5 Mw earthquake in Donggala Regency, Central Sulawesi Province, which was triggered by the shift activity of Palu-Koro fault. Some natural disasters that struck Palu City and its surroundings followed after the earthquake, however there is wisdom related addition information about Palu-Koro fault line that could be scanned based on the appearance of the surface rupture path. This path crosses the territories of Sigi Regency, Palu City, and Palu Bay then continues to the north, to the western neck of Sulawesi Island, which is administratively included in Donggala Regency. It is described on a regional scale a month after the earthquake by Valkaniotis, *et al.* [20], which has been surveyed directly in the field by Abdullah and Abdullah [21]. What is quite amazing here is that if the surface rupture is an expression of the main Palu-Koro fault line, it is quite different compared with the fault line route which not yet clearly confirmed according to previous references back before the earthquake happened because the fault line route is different based on currently visible lane that crossing the western neck of Central Sulawesi. Based on these informations, we are compelled to conduct a review of the existence of major faults and its implications on the emerging of geothermal manifestations in the neck region of western Sulawesi. This is an approach to find out that the surface rupture is an representation of Palu-Koro fault, by proving that around the active fault line there are hot springs in the vicinity. The results of this study will, of course, be able to provide additional literature related the concept of the relationship between faults and geothermal.

2 Method

Our research area is in the western neck of Sulawesi Island area (see Fig. 1) which is administratively part of Palu City and Donggala Regency, Central Sulawesi Province. We conducted field survey at the area where geothermal manifestations appears. We recorded their geographic coordinates and observed the geological conditions of the surface such as structures form, properties of rocks, and physical properties of local hot springs. Then we conducted a qualitative interpretation by integrating field observation data on several references related regional geological structure of the area. So that we are looking forward to find out the relationship between the geological structure activity and the appearance of several hot springs in research area.

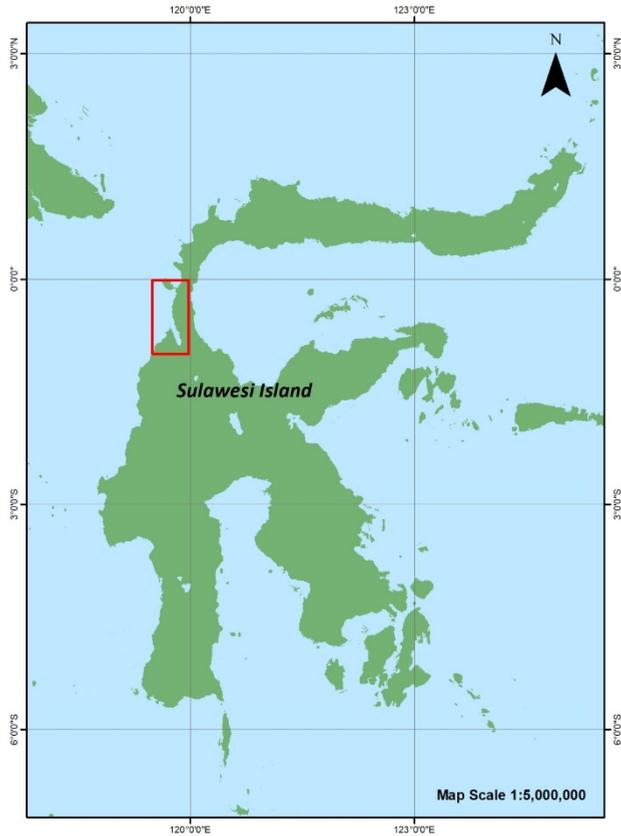


Fig. 1. Study area in western neck of Sulawesi Island marked by red rectangle.

3 Result and Discussion

3.1 Central Sulawesi Tectonic and Palu-Koro Fault

Sulawesi Island is located in the central part of the Indonesian archipelago. The tectonic order of this region is known as a triple junction area, which is the meeting place of three large plates, *i.e.*, the Indo-Australian plate, the Eurasian plate, and the Pacific plate, and is also influenced by two other small plates, *i.e.*, the Philippine plate and the Caroline plate [14-18, 23-29]. The implication of this condition is that the geological processes that work in this area are very complex, *e.g.*, the unique shape of Sulawesi Island such as the letter "K" and many large-scale geological structures can be found in the form of faults, trenches, troughs, and thrusts, which are around Sulawesi Island, Nusa Tenggara and Molucca sea [19].

The implications of geodynamic process specifically make Sulawesi Island as if it was torn up by various faults, *i.e.*, Palu-Koro fault, Poso fault, Matano fault, Lawanopo fault, Walanae fault, Gorontalo fault, Batui fault, and Tolo fault. The other faults that are also in the middle of Sulawesi Island (Central Sulawesi Province) are the Sausu fault, the Parigi fault, the Tokararu/Tambarana fault, the Malei fault, the Palolo graben system, the Budong-budong fault, the Salulore fault, the Bungadidi fault, the Loa fault, the Tambarana fault, the Malei fault, the Palolo graben system, the Budong-budong fault, the Salulore fault, the Bungadidi fault, the Loa fault, Wekuli, and Towuti fault [13]. In the northern part of Sulawesi

Island there is a north Sulawesi trench formed by subduction of oceanic crust from Sulawesi sea, in the southeastern part of Sulawesi there is the Tolo fault which is a place of subduction between the southeast arm of the island and the northern part of the Banda sea, where the two main structures are connected by the Palu-Koro fault and the Matano fault. As for the western part of Sulawesi there is the Makassar Strait which separates the western part of Sulawesi from the Sunda arc which is part of the Eurasian plate which is predicted formed by splitting process of the oceanic floor during Miocene [30]. Regional tectonic processes on the mainland of Sulawesi have taken place repeatedly, so the effect has been to overhaul all rocks, various types of rocks mixed so that the stratigraphic position becomes very complicated, and raises the intrusion domes of granite rocks and the formation of new fracture structures, shear faults and normal faults.

Palu-Koro fault, of the evaluated faults in the triple junction region, is the most highlight to be investigated because of its long dimensions, an active fault which is proved by its strike-slip shift, left lateral, each year, have several hot springs around the track [9-10], and are considered to represent the greatest seismic risk among others [14]. One of the earthquake events that was triggered by the Palu-Koro fault is the 7.5 Mw earthquake, occurred on September 28, 2018, its point center around Sirenja District, Donggala Regency or about 70 km to the north of Palu City. The incident has become a disaster for the Palu City and its surroundings. At that time, more than one type of natural hazard ravaged the area, with processes or sources of the events that did not normally occur such as land movements - the effects of liquefaction and tsunamis that were randomly generated by landslides at sea. However, all the events at that time all originated when there were shifting movements from the Palu-Koro fault resulted earthquakes and their derivative phenomena. The maximum shift at that time was 6 ± 0.5 m in the vicinity of Palu City, and on average between 1.9 m and 4.7 m in the northern and southern regions of Palu City [31]. After the incident, many researchers studied or mapped surface rupture path of Palu-Koro fault which was investigated using various sources of the data and methods, both by field surveys and utilizing digital or satellite data [21, 31-37]. The results show that rupture of Palu-Koro fault length > 150 km starting from the Palu Valley (south) to the western neck of Sulawesi Island (north).

3.2 Regional Geology

Before the occurrence of the 7.5 Mw earthquake in 2018, the major fault lines in the area were either unknown or depicted differently from the traces that appear today. The main fault, Palu-Koro, is previously depicted continuously from Palu City to Banawa, Donggala Regency, then continued to Makassar Strait and ended at the western part of the north Sulawesi trench. Nowadays the fault line can be figured out through its surface rupture traces which are interpreted to veer in Palu Bay (from west to east) to the mainland of western neck of Sulawesi [21]. It is not something new for us. We realize its existence which is clearly proved by appearances of hot spring chain around the area, but the existence has just been revealed on the surface after the earthquake. It is impossible to have geothermal potential that has relatively perpendicular pattern oriented north-south if there were no influential geological structures. We presumed that there is sub order fault line of the main fault line controlled the appearance of the hot springs (see Fig. 2).

Based on field study in the western neck of Sulawesi Island, there are 7 locations of geothermal manifestations in the form of hot springs (see Fig. 2). The administrative regions for the hot springs are located in Donggala Regency, precisely in Mapane Wani Village, Masaingi Village, Marana Village, Tamarenja Village, Lompio Village, Ombo Village, and Mapane Tambu Village. The geographical coordinates and temperature of hot springs are shown in Table 1.

Table 1. The Location of Potential Geothermal and Hot Spring Temperature

| No | Location | East (X)* | South (Y)* | Hot Spring Temperature (°C) |
|----|----------------------|-----------|------------|-----------------------------|
| 1 | Mapane Wani Village | 821879.14 | 9926615.89 | 45-50 |
| 2 | Masaingi Village | 813010.26 | 9935302.93 | 50-55 |
| 3 | Marana Village | 810661.52 | 9935945.33 | 50-54 |
| 4 | Tamarenja Village | 811331.45 | 9952419.01 | 50-65 |
| 5 | Omo Village | 811073.86 | 9968253.69 | 45-50 |
| 6 | Lompio Village | 814882.00 | 9977160.86 | 55-75 |
| 7 | Mapane Tambu Village | 820735.02 | 9996562.53 | 55-65 |

*) 50S UTM Zone

There are five rock units in Palu and its surroundings which have been mapped regionally by Soekamto [10], *i.e.*, Alluvium and Coastal Deposits (Qap), Selebes Molasses of Sarasin and Sarasin (1901) (QTms), Tinombo Formation of Ahlburg (1913) (Tt), Metamorphic Complex (km), and Granite and Granodiorite (gr). The description is:

- **Granite and Granodiorite (gr).** The oldest unit is small intrusions of andesite and basalt in Donggala peninsula. These intrusions might be volcanic rock channels which part of the tinombo formation. Small intrusions which generally consist of diorite, diorite, and granodiorite break through tinombo formations, that is, before molassic deposits. All of them is unmapped. Granite and granodiorite are characterized by potassium phenocris feldspar up to 8 cm long. This intrusion rock is formed during middle to upper Miocene.
- **Metamorphic Complex (km).** The oldest metamorphic rock complex in the mapped area exposes only in the eastern bund which is the point center. The lithology consists of amphibolite schist, schist, genes, and marble. There are many schists on the western part of the area, while genes and marble are many exposed on its east side. The body of intrusive igneous rocks is unmapped. Generally, it is less than 50 meters wide, breaks through the metamorphic complex with futures from diorite to granodiorite. The age of the metamorphism is unknown, but it might be the Pre-Tertiary. Some schist is occurred during the Palaeozoic.
- **Tinombo Formation of Ahlburg (1913) (Tt).** This formation is widely exposed, both in eastern and western embankment. These rocks overlap the metamorphic rock complex (km), non-conformity layer. There is detritus derived from mematorf rocks. The deposits are mainly from shales, sandstones, conglomerates, limestone, radiolarian flints, and volcanic rocks (lava basalt, andesite, breccia) deposited in the marine environment, and intermittent with sedimentary rocks (wake sandstones, sandstones, limestone, flintstone) and metamorphic rocks. Near the intrusion there is slate stone and gravel, and closer to the contact are forming flite and quartzite. The western part of the western embankment contains more chert sandstones which originate from other area. Detritus of volcanic rocks are usually found in the sandstone. Limestone is observed only as thin layers in sedimentary lithology.
- **Celebes Molasse of Sarasin and Sarasin (1901) (QTms).** This formation is found at lower elevations on both sides of the embankment, overlapping incongruously the Tinombo Formation of Ahlburg (1913) (Tt) and the Metamorphic Rock Complex (km), containing sediment material originating from older formations, and consisting of conglomerates, sandstone, mudstone, coral limestone, and marl, all of which only harden weakly. Near the metamorphic rock complex in the western part of the eastern embankment the deposit mainly consists of rough boulder and is apparently deposited

near a fault. The rocks toward the sea turn instead into finer-grained clastic rocks. This layer formed during the Middle Miocene.

- **Alluvium and Coastal Deposits (Qap).** Consisting of gravel, sand, mud and coral limestone, formed in rivers, deltas and shallow marine environment, is the youngest sediment in the study area. The deposit might entirely be occurred during The Holocene.

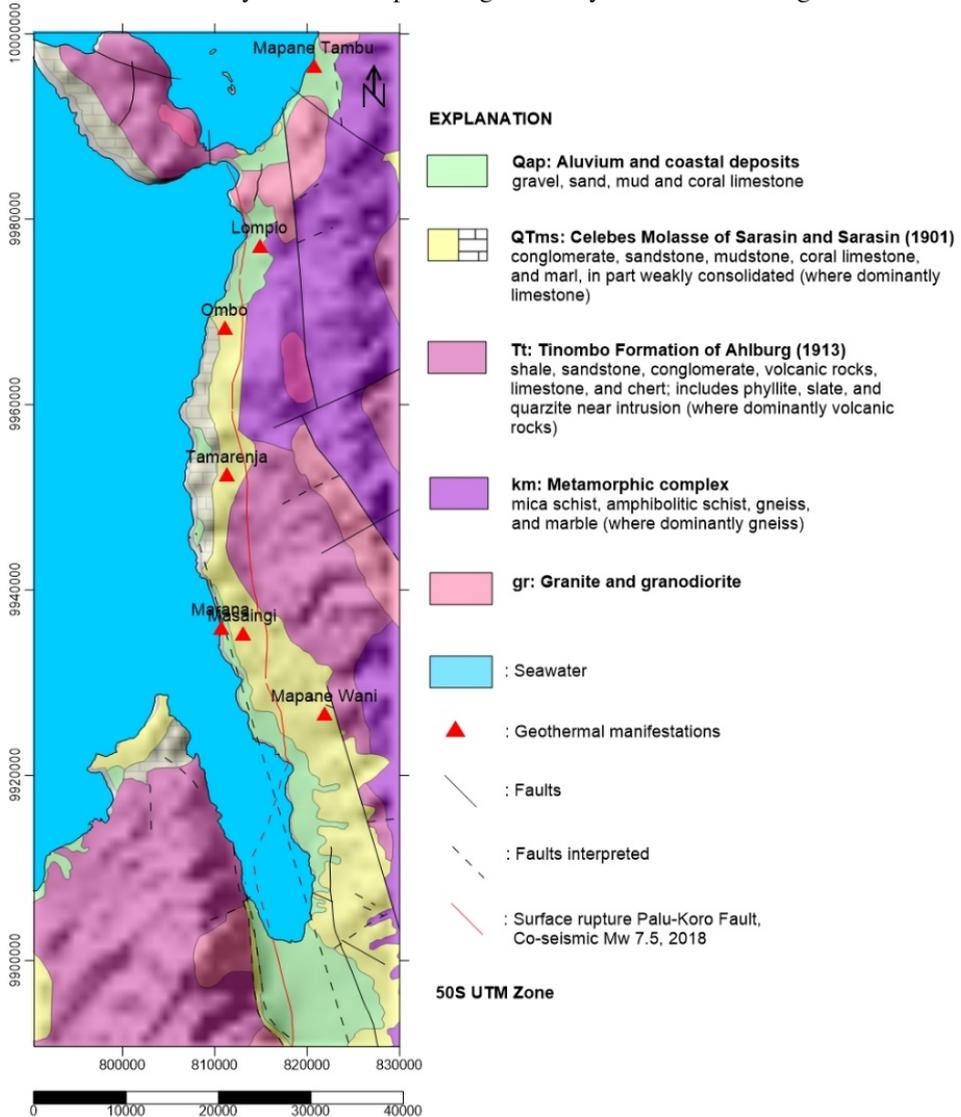


Fig. 2. Regional geological map of the western neck of Sulawesi Island and geothermal manifestation spots

Geothermal manifestations, hot springs, in the western neck of Sulawesi Island appear in the Selebes Molasse of Sarasin and Sarasin (1901) (QTms) and alluvium and coastal deposits (Qap). Alluvium and Coastal Deposits (Qap) consisting of gravel, sand, mud and coral limestone, formed in the environment of rivers, deltas and shallow marine environment, are the youngest sediments in this area. These deposits were formed in the Holocene. Selebes Molasse of Sarasin and Sarasin (1901) (QTms) are found at lower altitudes on both sides of the embankment, overlapping inconsistently on the Tinombo Formation of Ahlburg (1913)

(Tt) and the Metamorphic Rock Complex (km), containing detritus from older formations which consists of conglomerates, sandstones, mudstone, coral limestone, and marl, all of which only harden weakly. Near the Metamorphic Complex in the western part of the eastern embankment the deposits mainly consists of angular boulders which deposit near the fault. The deposits toward the sea turn to become finer-rounded clastic rocks. This layer is formed during the middle Miocene.

3.3 Characteristics of Geothermal Manifestations

The existence of Palu Koro Fault can be observed based on its landscape presented by the Shuttle Radar Topography Mission (SRTM) image and topographic map in the form of morphological lineament which is formed by curve between hill and valley and curve of transitional zone between hills and plains. The Palu-Koro fault is classified as an active fault [13-15, 18], and it is supported by the data of earthquake events recorded throughout the study area which is passed by the Palu-Koro fault line. The landscape along the Palu-Koro fault line in Palu region and the western neck of Sulawesi Island is fault walls bounded by active faults and many faults and lineaments which are less important and more or less perpendicular to this direction, as seen throughout the area thus has implications for the appearance of hot springs on the surface as geothermal manifestations [40]. The relationship between geothermal potential that can be identified on the surface and the existence of geological structures, *i.e.*, fault, joints, and fracture is closely related. The geological structures control the mediums that carries heat from geothermal reservoirs to the surface [6-8, 38-46].

The structures that develop in the western neck of Sulawesi Island is dominated by faults that are trending relatively north-south which are shown by the surface rupture co-seismic Mw 7.5, 2018. It is strongly suspected that the control of geological structures such as faults and joints have contribution to the emergence of hot springs. It can be identified from the patterns of lineaments and faults that pass through hot spring spots. Besides, the structures of igneous rock such as bat Olite and dike around the Palu-Koro fault area represent the presence of intrusive igneous rock [10, 30]. This is what we interpreted to carry heat and to transfer it to the layer above it with conduction process. Based on hydrogeological perspective, the intrusive igneous rocks bring heat to the aquifer which contains hydrothermal that can change the surrounding rock become alteration rock which produces clay mineral through chemical weathering. In the study area, the alteration process is likely to occur in sedimentary rock layers, namely Alluvium and Coastal Deposits (Qap) and Selebes Molasses of Sarasin and Sarasin (1901) (QTms).

3.3.1 Characteristics of Geothermal Manifestation in Mapane Wani, Masaingi, and Marana

Geothermal potential areas of Mapane Wani, Masaingi, and Marana are in one survey location because their hot springs came out adjacent to each other. Geothermal manifestations in the location are hot water seepage, puddle, and pool which are formed by hot springs that come out from fractures channel. The manifestations have sulfuric odor and clear color of the water (see Fig. 3, Fig. 4 and Fig. 5). The measured temperatures are range from 45-55 °C under normal atmospheric conditions. Geothermal manifestations in this location come out from sedimentary rock fracture, and their heat source presumably come from the body of intrusive igneous rocks that carry heat from stratum below. Local fault which is perpendicular to the main fault controls geothermal potential in this location.



Fig. 3. The appearance of geothermal manifestations, hot springs, in Mapane Wani Village

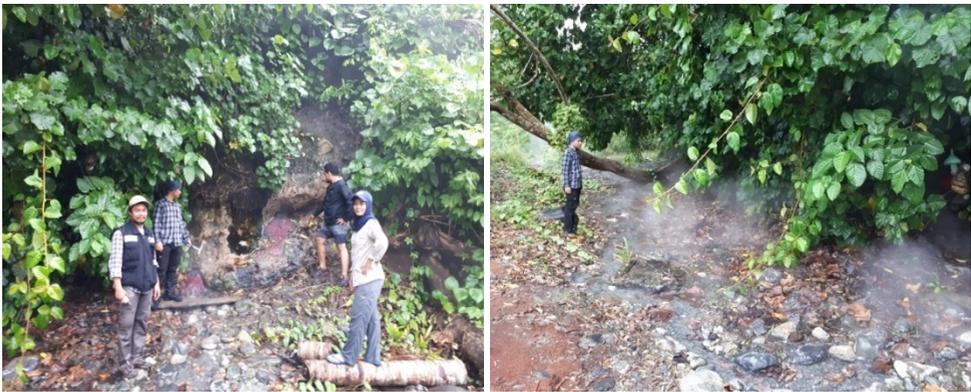


Fig. 4. The appearance of geothermal manifestations, hot springs, in Masaingi Village



Fig. 5. The appearance of geothermal manifestations, hot springs, in Marana Village

3.3.2 Characteristics of Geothermal Manifestation in Tamarenja

Geologically, geothermal manifestation characteristics of Tamarenja and Masaingi are similar. The intrusive igneous rock that presence in the local area is the heat source that is controlled by main fault trending almost north-south and small faults oriented perpendicular which become channels of hot springs. Geothermal manifestation characteristics in Tamarenja Village are hot springs coming out from rock fractures, such as seepage of water that flows to form small rivers. The hot spring has strong sulfuric odor and clear water color (see Fig. 6). The temperature of hot spring measured in this area is quite high ranging from 50-65 °C in normal atmospheric conditions.



Fig. 6. The appearances of geothermal manifestation, hot springs, in the Tamarenja Village

3.3.3 Characteristics of Geothermal Manifestation in Ombo and Lompio

Ombo hot spring appears on the Ombo river bank near the coast. Geothermal manifestations in this area are appearance of warm soil or sand on alluvium in tidal area and the warm water with bubbles formed by volatile components of hot springs (see Fig. 7-and Fig. 8). The warm water has sulfuric odor, clear water color, and temperature range of 45-50 °C. Whereas Lompio hot spring appears like stagnant springs forming a small river. It has odorless, clear water color, temperature around 55-75 °C, and heavy puffs of smoke that can be seen from afar. Hot spring in both areas are controlled by fractures and intrusive igneous rocks as hot rocks.



Fig. 7. The appearances of geothermal manifestations, hot springs and warm soil, Ombo Village



Fig. 8. The appearances of geothermal manifestations, hot springs, in the Lompio Village

3.3.4 Characteristics of Geothermal Manifestation in Mapane Tambu

Geothermal field of Mapane Tambu is the northernmost part in this study area. Geothermal manifestation that appear on the surface is warm pool in the form of a circle which has diameter of ± 7 m. The pool has bubbles, sulfuric odor, temperature around 55 - 65 °C, and clear water (see Fig. 9). The emergence of Tambu hot springs which form the pool is predictably caused by earthquake so the impact of the shaking made the ground sink which now looks like a sinkhole, and heat origin of the hot springs controlled by local geological structure. Tambu fault trending north-south and other shallow faults trending east-west facilitates up flow of geothermal fluid from its reservoir to the surface.



Fig. 9. The appearance of geothermal manifestation, hot pool, in the Mapane Tambu Village

4 Conclusion

There are 7 spots of geothermal manifestations in the western neck of Sulawesi Island, and the lineament pattern is the same as the orientation of the main fault, Palu-Koro. Now The fault can easily be recognized through surface rupture as evidence of the Mw 7.5 earthquake in 2018 at the region. Before the earthquake, the traces of the faults were previously unclear in the region, but it is suspected that the faults exist since a long time ago but proved only recently. We interpret that it controls geothermal manifestation appearances that exist even before the fault traces exposed because one of the conditions for the emergence of geothermal manifestation on the surface is that there must be channels either caused by joints or faults as

the up-flow channels of geothermal fluid. It is possible that the continuation of the fracture order from the main fault took control of the appearances of geothermal manifestations at each location. In addition, the origin of heat source is hot rock, intrusive igneous rocks which carry heat by conduction to an aquifer, geothermal reservoir, so that it can heat groundwater. Furthermore, the presence of sedimentary rocks namely alluvium and coastal deposits and the Selebes Molasses Formation of Sarasin and Sarasin (1901) which are in the top layer continuously influenced hydrothermal which alternates rocks around the area, because in some places there are clay minerals which presumed as a cap rock. Therefore, geothermal in the area is tectonic geothermal associated with geological structures and is not related to volcanic activity.

In this study, we interpret only the relationship between geological structure of main fault, Palu-Koro, and it contributes to the geothermal manifestation's appearances in the western neck region of Sulawesi Island. Nevertheless, the scope is in regional scale, so the research did not reach detailed exploration which could provide a larger dimension of geothermal prospect area or represent geothermal energy potential in every geothermal manifestation spots.

Acknowledgements

We would like to thank the Faculty of Engineering, Tadulako University for providing funding assistance for this research, as well as for giving us an opportunity to present the results at the International Conference : International Conference Urban Disaster Resilience (ICUDR), 2019.

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