Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Prospects in Lahendong Geothermal Field of the Tomohon – Minahasa Volcanic Terrain (TMVT), North Sulawesi, Indonesia

Pri Utami[1], Muhammad Sidqi[1], Yeftamikha Siahaan[1], Muhammad G. J. Shalihin[1],

Eben E. Siahaan[2], and Marihot Silaban[2]

[1]Geothermal Research Centre and Dept. of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia.

[2]PT. Pertamina Geothermal Energy, Jakarta, Indonesia.

Keywords: Tomohon, Minahasa, Lahendong, Tompaso, North Sulawesi, volcanic terrain, geothermal system.

ABSTRACT

The Tomohon – Minahasa Volcanic Terrain, North Sulawesi is situated at the elevation range of about 550 to 1800 mRSL. It hosts the productive Lahendong Geothermal Field that currently has a total installed capacity 120 MWe, and supplies electricity to North Sulawesi and Gorontalo Provinces. Our research area is located about 30 km south of Manado, the capital city of the North Sulawesi Province. It covers the Lahendong and Tompaso prospects which are spatially associated with the Lake Tondano, and the active volcanoes.

The volcanic landforms, and the types and distributions of thermal manifestations give hints of the occurrence of both typical high-relief and low-relief volcanic geothermal systems. Our study which is mainly based on geology, distinguishes different characters of the systems within the Lahendong Geothermal Field. This finding can be important input for building the strategy to optimize the development of its geothermal potential.

1. INTRODUCTION

The Minahasa physiographic section of the northern arm of Sulawesi Island that extends from Soputan volcano in the south to Sangihe Islands in the north is highly volcanic (van Bemelen, 1949). Parts of the volcanic terrain that hosts geothermal resources are located in Tomohon City and Minahasa Regency.

Lahendong is the first operating geothermal field in the eastern part of Indonesia. Currently the field has 46 wells and a total installed capacity of 120 MWe, but its resource potential is believed to be larger. Besides producing electricity to supply the North Sulawesi and Gorontalo Provinces, the Lahendong Geothermal Field provides heat energy that is directly utilized in palm sugar production. Many hot springs in both Lahendong and Tompaso prospects are used for bathing.

This paper reports some of the results of our research aiming to obtain a comprehensive understanding of the geology and the characteristics of the geothermal resource in the area referred here to as the Tomohon – Minahasa Volcanic Terrain (TMVT) (Figure 1). We focus our discussion on the Lahendong Geothermal Field that consists of Lahendong and Tompaso prospects. It is mainly based on our field work and subsurface geology studies from 25 wells (i.e., Utami, 2011; Utami et al., 2015; PT. PGE and Geothermal Research Centre UGM, 2013; Savitri, 2016; Yeftamikha, 2017; and Sidqi, 2018) supported by the results of geoscientific work by other workers.

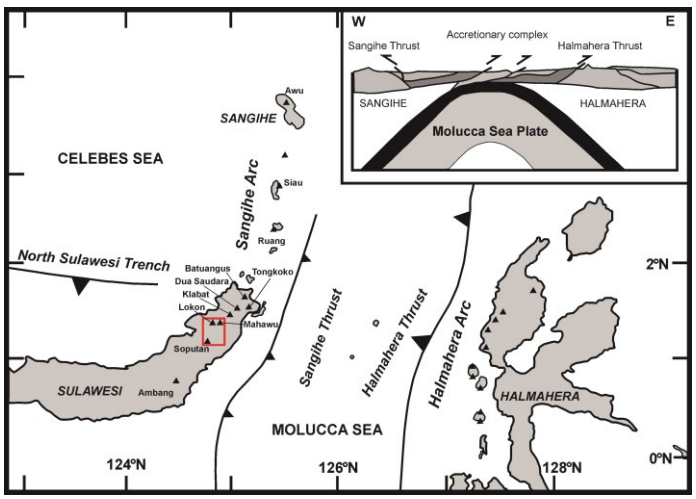


Figure 1: Location of the Tomohon – Minahas Volcanic Terrain (red box) within the simplified tectonic map of the north arm of Sulawesi. Lines with large barbs are subduction zones and lines with small barbs are thrusts (Macpherson et al., 2003). Quaternary volcanoes (filled triangles) along the Sangihe arc are from Morrice et al. (1983). Inset: W – E cross section of the Molucca Sea region showing the Sangihe arc overriding the Halmahera arc (Hall, 2000).

2. GEOLOGY

2.1. Regional Setting

The north arm of Sulawesi is part of the Sangihe volcanic arc, which according to Hamilton (1979, 1988) was formed due to the subduction of Molucca Sea plate to the west, and the Halmahera volcanic arc resulted from the subduction of the Molucca Sea plate to the east. During the Neogene, both arcs consumed the Molucca Sea plate (Cardwell et al., 1980). According to Hall (2000), the consumption of the Molucca Sea plate by both arcs is now ceased and the Halmahera and Sangihe arcs are undergoing orthogonal collision, such that the Sangihe arc is presently overriding the Halmahera fore arc (see Figure 1).

According to Verbeek, c.a. 1908, and Kamerling, c.a. 1925 (in Ganda and Sunaryo, 1982) the oldest volcano in Minahasa is the Lembeyan volcanic complex whose remnants of its caldera wall form hills east of the Lake Tondano. Effendi (1976) mentioned that they are dominantly composed of breccias, lavas, and tuffs of andesitic to basaltic composition, and formed in the Miocene.

During the Late Miocene or Early Pliocene a major volcanic eruption in North Sulawesi produced several hundred cubic kilometers of tuffs, and formed the large Tondano volcano-tectonic depression (Suari et al., 1987). Lécuyer et al. (1997) and Newhall and Dzurisin (1998) refer to this structure as the Tondano caldera. Based on the interpretation of Satellite Pour l'Observation de la Terre (SPOT) image of northeast Sulawesi and field studies, Lécuyer et al. (1997) suggested that the Tondano caldera (20 x 10 km) –now partly occupied by Lake Tondano– formed within a releasing step-over fault zone between two ENE-trending strike-slip segments.

Younger volcanic cones of andesitic composition possibly of monogenetic type emerged within the Tondano caldera, and its immediate vicinity (Sidqi and Utami, 2018). Significant activities also occurred west of the Tondano caldera, spatially associated with Pangolombian horse shoe-shaped structure. These formed the Lengkoan, Kasuratan, Tampusu, Kasuan, and Masarang cones, and the Linow crater (Utami, 2011). The present-day volcanism in TMVT is marked by the activities of Mts. Soputan and Aeseput in the south, and Lokon and Mahawu in the north. At the time this paper was written, the most recently reported activity was the ash of eruption from the Soputan volcano on 22 – 28 May 2019 (Smithsonian Institution: www.volcano.si.edu).

2.2. Geomorphology

The geological processes in the TMVT develop a beautiful landscape that is composed of:

a) Remnant of the old, disected Lembeyan volcanic complex including Maimbeng, Potong, Kawatak, Sosoan, Kaweng and Kamingtan peaks in the southern-southeastern parts.

b) Tondano volcanic and fluvial plain which is spatially associated with small cones of Wowok, Luuk, Umeh, Kanonang, Sinopi, Kokopit, Matatumbak Pinasuan, Semelenduk, and Wawona in the central-eastern parts.

c) Pangolombian horse-shoe-shaped morphology associated with Linow crater, and Lengkoan, Kasuratan, Tampusu, Kasuan, and Masarang cones, forming moderate-relief terrain in central–northern parts.

d) Active Soputan volcano and Aeseput crater, and small cones with craters or collapse structures of Kotamenara, Walewangko, Raringis, Sempu, and Rindengan and Kanonang in the south-western parts.

e) Active volcanoes of Lokon and Mahawu in the northern parts.

Based on identification of the volcanic centres and interpretation of the distribution of their products we conclude that there at least 26 volcanic units in the TMVT. Their stratigraphic relationships are poorly-constrained due to the limited number of age-dated rocks. Age dates taken from PT. Gondwana (1988) were made by K/Ar method. Following the terms used by Suari (1987) they are grouped into the following formations (from the oldest to the youngest):

1) Pre-Tondano Formation: products of the Lembeyan Tertiary volcanic complex, which is dominated by andesite lavas and breccias.

2) Tondano Formation: products of the Tondano volcanic activity, which is dominated by rhyolite tuff.

3) Post Tondano Formation: products of the volcanic centres thought to develop after the formation of the Tondano calderas. They are dominated by basalt and andesite lava and pyroclastics from the small volcanic centres within and in the immediate vicinity of Tondano caldera and the Pangolombian horse shoe-shaped structures (in Figure 2). Obsidian and dacitic lavas are present as the products of the Kasuan and Lengkoan volcanic centres, respectively. The products of the active Soputan, Aeseput, Mahawu, dan Lokon volcanoes are the youngest members of this unit.

2.3. Geological structures

The main structures in the TMVT are the E-NE trending. Two major strike slip faults and their releasing step over fault zones were interpreted by Lecuyer et al. (1997) to control the formation of the Tondano caldera. The thermal manifestations in the Tompaso prospect are mostly associated with the craters or collapse structures. The Pangolombian horse shoe-shaped structure and the Linow crater are thought have been driving fluid flow in the present-day system in the Lahendong prospect. The inferred NE-SW trending faults in the Lahendong prospect may also control the emergence of the thermal manifestations there.

The geologic map of the TMVT (Figure 2) is constructed based on our recent interpretation of the 2019 edition of DEMNAS image (www.tides.big.go.id) and ground checked with reference from the work by Ganda and Sunaryo (1982), Lecuyer et al. (1997), Utami (2011), and Sidqi (2018). The absolute ages indicated in the legend were obtained by K/Ar method, and are taken from PT. Gondwana (1998).

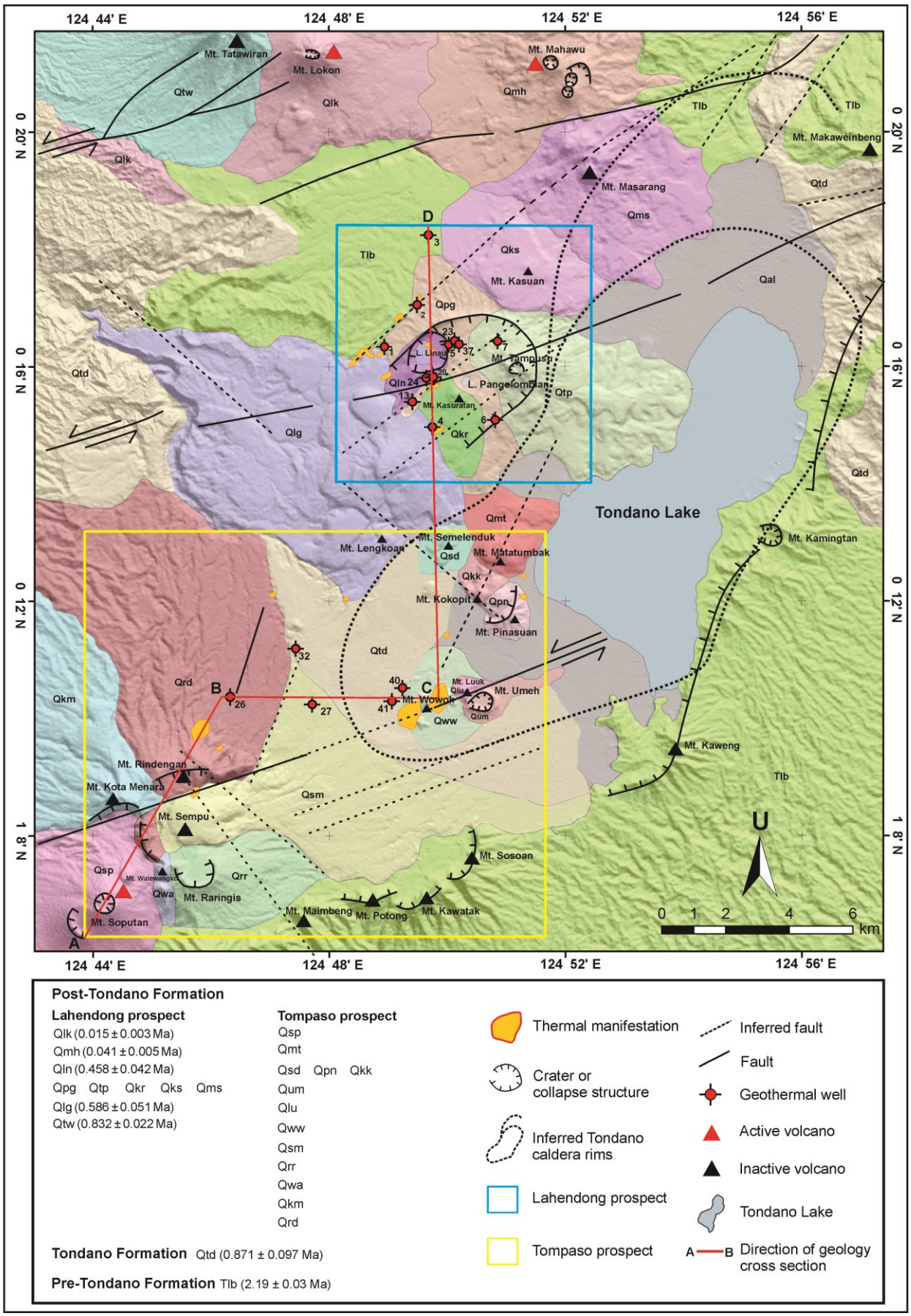


Figure 2: Geologic map of the Tomohon – Minahasa Volcanic Terrain. Blue and yellow boxes indicate the Lahendong and Tompaso geothermal prospects, respectively. Examples of the naming of rock units: Qsp = product of Soputan volcano, Quaternary; Qal = alluvial deposits, Quaternary, Tlb = products of Lembeyan volcanic complex, Tertiary.

3. THERMAL MANIFESTATIONS AND FLUID GEOCHEMISTRY

3.1. Lahendong prospect

Thermal manifestations in the Lahendong prospect are of steam-heated, fumarolic, and solfataric types (Figure 3). The largest thermal area is located in the Lahendong village, and consists of mud pools with mud volcanoes. Another thermal areas are associated with the Pangolombian horse shoe-shaped structure and the Linau crater, and the NE-SW lineaments. They consist of fumaroles, solfataric gas vents, altered and steaming ground (T = 98 ºC at 40 cm depth), and boiling and near boiling acid-sulfate hot springs (T = 70 to 98 ºC, pH = 2-5), mud pots, mud pools, and mud volcanoes.

Plot of the chemical compositions of thermal spring waters and well fluid in the ternary diagram of Cl-SO_4-HCO_3 ternary diagram and in the Giggenbach's $10c_{K+}/(10c_{K+} + c_{Na+})$ versus $10c_{Mg+}/(10c_{Mg+} + c_{Ca+})$ diagram are given in Figure 5.A and 5.B, respectively. Figure 5.A shows that the thermal manifestations in the Lahendong sector are of acid-sulfate type. Some of the deep fluid in this sector, namely those from wells drilled in the immediate vicinity of Lake Linow, fall into the category of volcanic waters. Wells drilled in the eastern parts of the sectors encounter neutral chloride fluids. Calculated reservoir fluid compositions from some wells plot close to the full equilibrium line (Figure 5.B) at about 300 ºC (LHD-8, 11, 12, and 4) suggesting that these deep fluids are close to equilibrium with the reservoir rocks. The samples from LHD-11 and 12, which plot below the full equilibrium line, possibly contains steam condensate. Most of the hot spring waters plot near the composition of the average crustal rock, reflecting their reactivity with respect to the rocks, and dilution with Mg-rich groundwater. Down-hole samples from LHD-1 are far above the equilibrium line suggesting that they are immature.

Jaffey et al. (2004) reported that the $^3He/^4He$ ratios in the gas phase in the thermal springs in Lahendong thermal area ranges from 6.9 to 7.33 RA, i.e., within the range of helium isotopic ratio of 6 to 8 RA, typical for arc-related volcanoes around the circum-pacific region (Poreda and Craig, 1989). These elevated 3He/4He values in Lahendong are thought to be due to extraction of helium from a magmatic body by the crustal fluids.

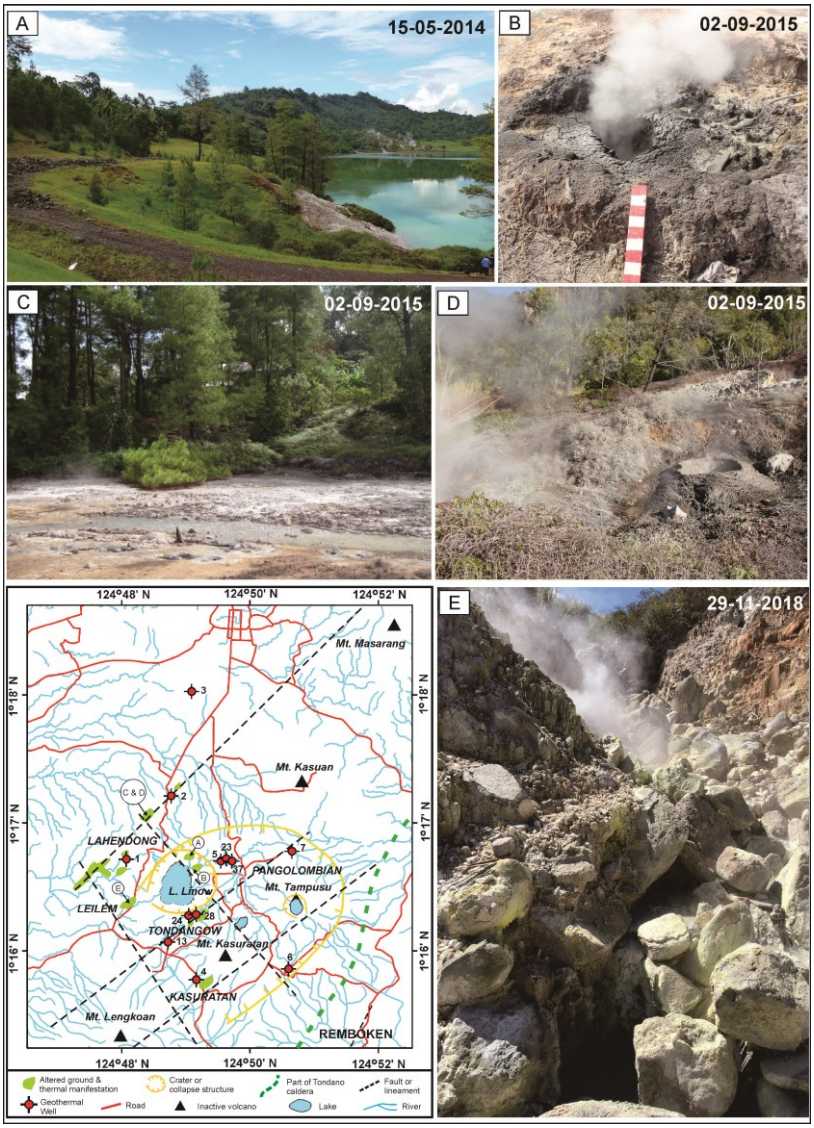


Figure 3: Photographs of representative thermal manifestations in the Lahendong prospect and a location map. Circled letters in the map correspond to the photograph letters. A: Lake Linow with fumaroles in its northern bank; B: Gas discharge in the eastern bank of the lake; C: Mud pools in the Lahendong pine forest; D: Mud volcano as part of the mud pools in Lahendong pine forest: E: Fumarole and solfataric gas vents in Leilem village.

3.2. Tompaso prospect

Thermal manifestations in the Tompaso prospect consist of boiling and near-boiling neutral-pH chloride hot springs (with or without silica sinter), and steam-heated type manifestations (Figure 4). The neutral-pH hot springs (T = 70-90 ºC) manifestations are spatially associated with fumaroles (T = 60-80 ºC), altered and steaming ground (T = 60-85 ºC at 40 cm depth), mud pots, mud pools, and mud volcanoes. Several warm, acidic springs (T = 40-50 ºC) discharge at Pinabetengan, Kayuuwi, Kinali, and Passo villages.

The neutral-pH, chloride fluid type manifestations occur in low-relief terrain at Toraget, Tempang, and Karumenga. A geyser (T = 82-86 ºC) with geyserite deposits occur at the Toraget village. Solfataras, gas discharges (T ~ 96 ºC) with significant amount of sulfur deposit, associated with acidic hot springs (T ~ 95 ºC), and altered, steaming ground (T = 70-90 ºC at 40 cm depth). Solfatara, gas discharges and fumaroles commonly occur at Kanonang Village (Bukit Kasih thermal area) and on the flanks of Mt. Rindengan and Mt. Sempu.

Plot of the chemical compositions of thermal spring waters and well fluid in the ternary diagram of Cl-SO_4-HCO_3 and in the Giggenbach's 10cK+/(10cK+ + cNa+) versus 10cMg+/(10cMg+ + cCa+) diagram are given in Figure 5.A and 5.B, respectively. Figure 5.A shows that the thermal manifestations in the Tompaso prospect are of chloride, chloride bicarbonate and acid-sulfate types. The chloride-type fluids are close to equilibrium with the rocks (Figure 5.B).

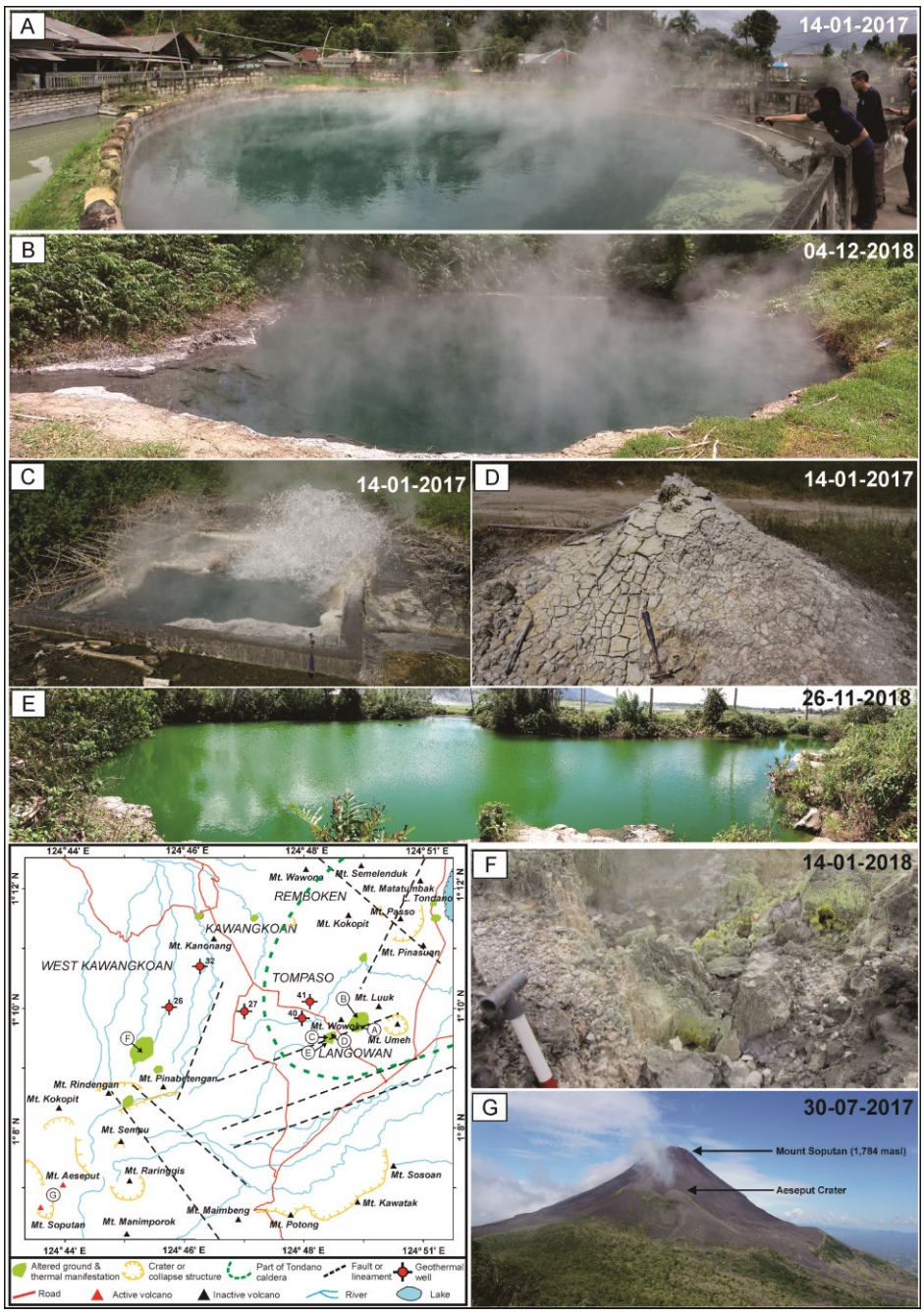


Figure 4: Photographs of representative thermal manifestations in the Tompaso prospect and a location map. Circled letters in the map correspond to the photograph letters. A: Near-boiling chloride hot pool at Karumenga, B: Near-boiling chloride hot pool at Tempang, C: Geyser at Toraget, D: Mud volcano at Toraget, E: Acidic hot pool at Toraget, F: Solfatara at Kanonang/Bukit Kasih, G: Solfataric activity of Mt. Soputan and Aeseput crater.

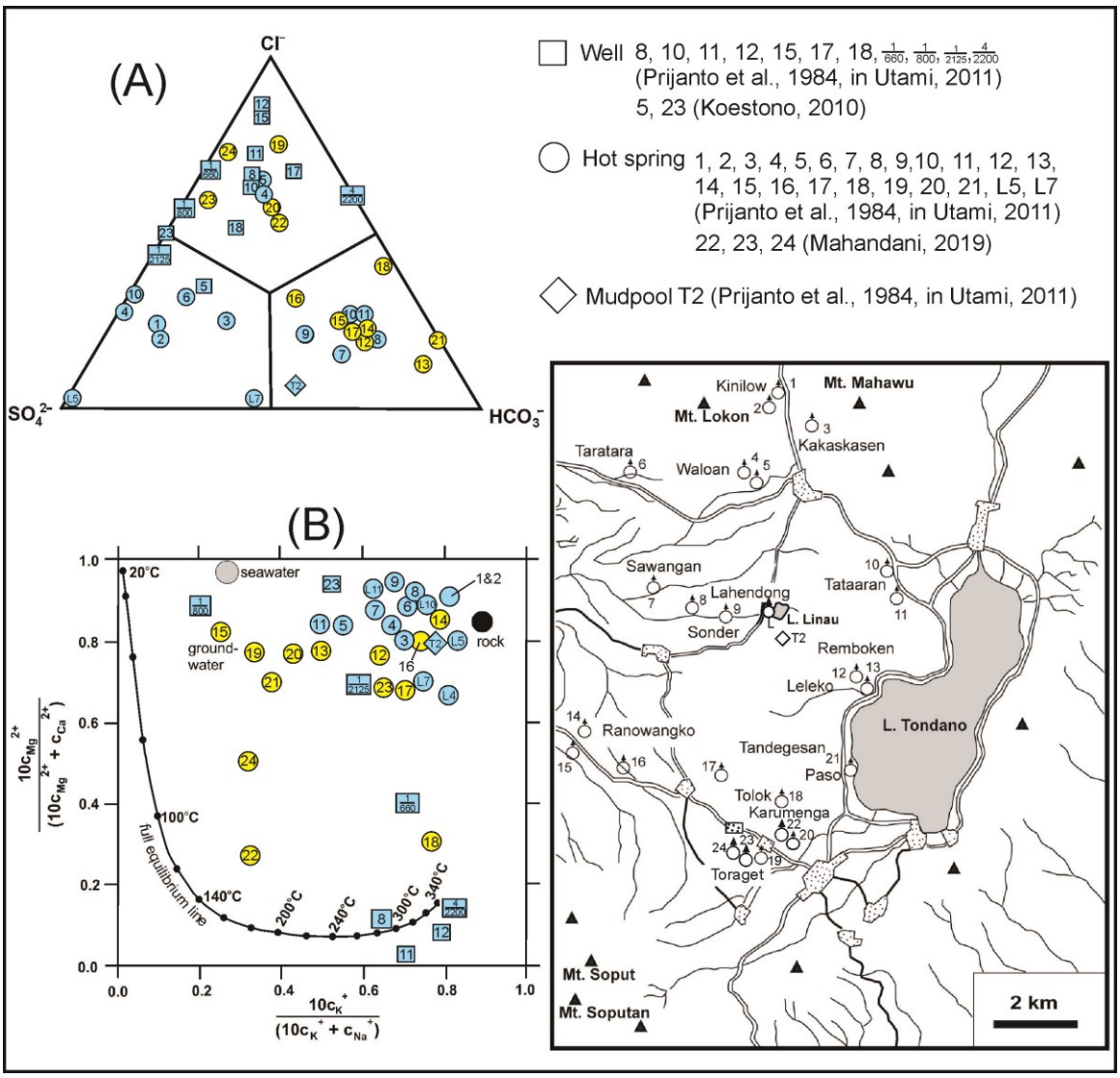


Figure 5: Plot of thermal spring and well fluid sample compositions in Lahendong Geothermal Field on Cl-SO_4-HCO_3 ternary diagram (A) and on the $10c_{K+}/(10c_{K+} + c_{Na+})$ versus $10c_{Mg+}/(10c_{Mg+} + c_{Ca+})$ diagram (B). Number inside symbol indicates number of spring, or well and sample depth. Triangles numbered with L, and a circle numbered with T correspond to thermal springs around L. Linau. Data compiled from Utami (2011), Koestono (2010), Mahandani (2019). Inset: location map of thermal manifestations.

4. HYDROTHERMAL ALTERATION

The hydrothermal alteration in Lahendong and Tompaso are quite similar, in term of the style and mineralogy. The identity and the distribution of the hydrothermal minerals at Lahendong Geothermal Field suggest several clues to the changes in the hydrology of the system including the changes in temperature, permeability, fluid compositions, and the extent of activity.

4.1 Lahendong prospect

The hydrothermal minerals in wall rocks in the deeper parts of the system include calc-silicates (zeolites, prehnite, pumpellyite, epidote, clinozoisite, and actinolite), secondary feldspars (albite and adularia), silica minerals (amorphous silica, chalcedony, quartz), clays (smectite, chlorite, illite, and interlayered clays), and calcite. These formed from near neutral pH-alkali chloride waters. Dolomite, Mg-Fe-rich carbonates, anhydrite, and hematite occur locally. The hydrothermal assemblages deposited in open spaces are generally similar to those replacing the primary phases in the wall rock, suggesting that they were formed from fluids of similar compositions. In the deeper parts (-500 to -1300 mRSL) of wells drilled around Lake Linau, anhydrite occurs as both replacement of primary phases and space-fillings. This formed from sulfate-rich waters, as confirmed by S and O stable mineral isotope analyses of the hydrothermal minerals from the deep parts of LHD-23 and 37. The values of the $\delta^{18}O$ and $\delta^{34}S$ of anhydrite from LHD-37 and 24 are similar to those of hypogene anhydrite deposited in high sulfidation epithermal environment, and those in magmatic-hydrothermal system, respectively.

The past thermal structure of the Lahendong system is deduced from the occurrence of temperature-dependent hydrothermal mineral that replace the primary minerals field-wide. These include actinolite (≥ 300 ºC), epidote (250 ºC), wairakite (220 ºC), mordenite and heulandite (< 200 ºC) and smectite (<150 ºC). Chlorite is ubiquitous as both a replacement and space-fillings mineral. It comprises the early formed veins and was usually the first mineral deposited in multi-mineral veins and other cavities. Textural relations show it was also the first mineral to form through interactions between thermal waters and the primary phases. Space-filling mineral paragenesis suggests that the system has undergone five stages of alteration most notably due to shift and revival of the thermal

activity (Utami et al., 2015). The mineralogy and the measured temperatures show that the present-day thermal foci are located in the areas of Lake Linow, Kasuratan, and Pangolombian, but the latest has not given surface expressions.

4.2. Tompaso prospect

The subsurface hydrothermal mineral assemblage in the Tompaso prospect consists of stilbite, wairakite, prehnite, epidote, adularia, silica groups, and clays (smectite, chlorite, illite, and interlayered clays), and calcite. They indicate the interactions of the rocks with near neutral pH-alkali chloride waters. The hydrothermal assemblages deposited in open spaces are generally similar to those replacing the primary phases in the wall rock, suggesting that they were formed from fluids of similar compositions. There is anhydrite in the deeper parts of all the wells. Dissolution texture in the wall rocks are common in the deeper parts of well LHD-26 drilled near the Kanonang/Bukit Kasih solfataric manifestation area.

Paragenesis of the hydrothermal minerals deposited in the open spaces in the wall rocks suggest that in the early stage of its life the Tompaso prospect had reactive fluids. As the fluid become neutralized in the later stage the minerals such as adularia, calc-silicates, and silicas formed (PT. PGE and Geothermal Research Centre UGM, 2014). Epidote, prehnite, wairakite, and illite indicate high temperatures in wells LHD-26 and 27 in the past. Disagreement of the temperatures they indicated and those measured are interpreted by Savitri (2016) to be due to cooling, i.e., by the down-flowing meteoric water, possibly through a NE-SW trending fault. Yeftamikha (2017) mentioned that wells in clusters LHD-40 and LHD-41, which are located near the thermal area with the near-boiling chloride springs, encounter high-temperature mineral indicators, namely epidote and wairakite at shallower depths, and illite, prehnite and actinolite in the deeper parts. The present-day temperatures in the deeper parts of LHD-41 are almost similar to those indicated by mineralogy, however the well is now used as a reinjection well. Interestingly, the well LHD-44 drilled from the same pad as LHD-40 has been cooling significantly since the hydrothermal mineral geothermometers formed.

5. CHARACTERIZATION OF THE GEOTHERMAL PROSPECTS

Geothermal systems can be defined as heat (and mass) transfer from the deeper parts to the surface or the shallower parts of the Earth crust. Geothermal activity in TMVT is thought to start after the formation of the Tondano caldera. Considering the classification of geothermal systems by Hochstein and Browne (2000), we interpret that the geothermal prospects in the TMVT have characteristics of volcanic, volcanic-hydrothermal, and hydrothermal systems. Figure 6 shows the schematic model of the field according to the cross-section line A-B-C in Figure 2. The thermal structure is interpreted based on the stable temperatures of the selected wells. The hydrology is interpreted from geochemical data of thermal manifestations, limited data of well fluid chemistry, and mineralogy. Nonetheless, our interpretation for the Tompaso prospect is subject to review when the deep fluid chemistry data be available in the future.

5.1. Volcanic geothermal-type system

The hazardous, volcanic geothermal-type character in the TMVT belongs to the Mt. Soputan active volcano in the south, and the Lokon and Mahawu volcanoes in the north (not shown in Figure 6). The volcanoes transfer heat and mass transfer by the explosive and effusive activities in historic time. These active volcanoes therefore are not targets for geothermal development.

5.2. Volcanic hydrothermal-type system

In the Tompaso prospect the volcanic-hydrothermal system manifests in the form of solfataras with significant amount of sulfur deposits, fumarole, and acidic hot spring and mud pots at Kanonang village (Bukit Kasih). These manifestations occupies the high-relief terrain of Rindengan volcano. The presence of the solfataric-type discharges suggest that this part of the prospect may get some contribution of volcanic waters. The Kanonang thermal area is inferred to be the marker of the upflow zone of this type of system. Well LHD-26, drilled toward the area beneath the thermal manifestations, presented high temperatures (≥250 ºC) and high permeability, but showed some indications of the occurrence of reactive fluids, such as rock leaching and anhydrite in the deeper parts of the well. The low resistivity anomaly beneath the thermal area here (PT-PGE, 2008 in Handoko, 2010) may be due to the acidic magmatic fluid feeder. Savitri (2016) interpreted the area has now been affected by down-flowing meteoric water.

The Lahendong prospect that is centered at the Lake Linow is thought to have characteristics of a volcanic-hydrothermal system. They are manifested in the form of solfataras with sulfur deposits, fumaroles, gas discharge with $^{3}He/^{4}He$ values within isotopic ratios of arc-related volcanoes, as well as acid hot springs, mudpots, and leached surface rocks around the lake. Diorite dykes are cut by wells LHD-5 (Utami, 2011), LHD-23 and 28 (Koestono, 2010). The stable S and O isotope analyses made from hydrothermal minerals from wells LHD-24 and LHD-37, drilled toward areas beneath the Linow crater, suggest that this part of the Lahendong prospect received some influx of magmatic fluids. However, production wells drilled outside the Linow area, e.g., those in clusters LHD-4, 10 and 13, produce neutral-chloride fluids.

5.3. Hydrothermal-type system

The hydrothermal-type geothermal system occurs in part of the Tompaso prospect that occupies the low-relief terrain inside the Tondano caldera. It is expressed by the discharge of boiling and near-boiling neutral-pH chloride hot springs depositing silica sinters in Tempang, Toraget, and Karumenga villages. These manifestations, and the distribution pattern of the high-temperature mineral indicators in clusters LHD-40 and LHD-41, may mark the location of an upflow zone, such as that in the Wairakei Geothermal Field, New Zealand. The stable temperatures in well LHD-41 support this interpretation.

6. CONCLUSIONS

Our geothermal studies show that the Lahendong Geothermal Field hosted by TMVT consists of parts with different characteristics and types of system. The Lahendong prospect in the north is situated in moderate to high–relief terrain with Lake Linow in the center. The area with the most vigorous fumarolic manifestations and highest temperatures in the subsurface, is associated with an acidic magmatic fluid feeder as indicated by the fluid compositions and the mineralogy. This part of the prospect has the character of a volcanic-hydrothermal system reservoir with more neutral pH fluid located beneath the Kasuratan area, i.e., further to the south from the center of the prospect.

The Tompaso prospect has both high and low-relief terrain types. In the high-relief terrain the prospect is characterized by volcanic activity of the Soputan volcano, and the volcanic-hydrothermal activity in Kanonang and its vicinity. In the surface the volcanic-hydrothermal activity manifests in the form of solfataras and boiling acid springs, which we thought are related with the Mts. Sempu and Rindengan. More work, especially fluid geochemistry study, is needed to confirm this interpretation. In the low-relief terrain the prospect has characteristics of hydrothermal-type system. The deep chloride fluids manifest in the form of geysers and the numerous near boiling chloride springs depositing silica sinter in Toraget village. Subsurface hydrothermal mineralogy support this interpretation, however deep fluid chemistry data is needed to confirm it.

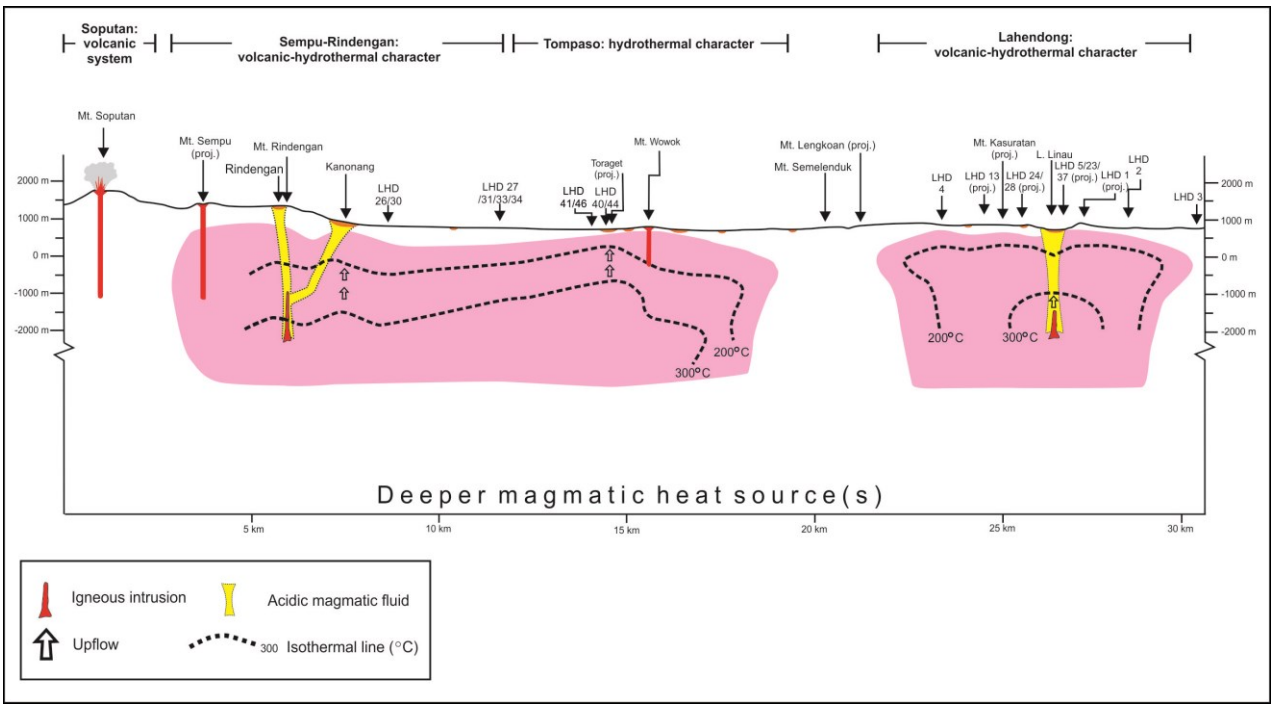


Figure 6: Schematic model showing the volcanic centers, and thermal and hydrological structures of the geothermal prospects in the TMVT.

The diversity of the characteristics of the parts of the field shall be taken into account in building the development strategy. Wells drilled in the area with the volcanic-hydrothermal type need to be further studied and carefully monitored. Part of the Tompaso prospect with hydrothermal-type character may be considered as target of future production area.

In this study we learn that in one Geothermal Working Area located in volcanic terrain the specific type of the geothermal system may vary, possibly due to the type and stage of activity of the host volcanoes. Detailed chemistry analyses of the thermal manifestation fluids are crucial to guide the pre-drilling modelling of the thermal and hydrological structure of field. Careful studies on subsurface hydrothermal alteration and deep fluid chemistry, which are equally important to those of the subsurface temperature and permeability distributions, must be made to analyze the position of each drilled well within the past and present geothermal regimes. Advanced analyses such as age dates and isotopic compositions of suitable subsurface hydrothermal minerals will strengthen the interpretation. Those knowledge undoubtedly will help to increase the success of field management and future development.

ACKNOWLEDGEMENTS

The authors thank PT. Pertamina Geothermal Energy (PGE) for giving the access to the Lahendong Geothermal Field to conduct the field studies and to publish this paper. Work by Savitri (2016), Yeftamikha (2018), Sidqi (2018), and Mahandani (2019), which we cited here, were made possible through the collaboration between PT. PGE and Universitas Gadjah Mada. We thank Septa F. Mahandani for sharing the thermal manifestation data from North Langowan district and drafting the figures. Brenda C. Mauren is thanked for supplying Figure 3F.

REFERENCES

Cardwell, R.K., Isacks, B.L., and Karig, D.E., 1980, The spatial distribution of earthquakes, focal mechanism solutions, and subducted lithosphere in the Philippine and northeastern Indonesian islands in Hayes, D.E., ed., The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, v. 23, American Geophysical Union Monograph, p. 1 - 35.

Effendi, A.C., 1976, Geologic Map of the Manado Quadrangle, North Sulawesi (Scale 1:250,000), Geological Survey of Indonesia.

Ganda, S., and Sunaryo, D., 1982, A Preliminary Report on Geology of the Minahasa Area, North Sulawesi (in Bahasa Indonesia), Internal Report: Jakarta, Pertamina Geothermal Division, 40 p.

Handoko, B.T., 2010, Resource Assessment of Tompaso Geothermal Field, Indonesia, Report No. 30, Geothermal Training Centre, United Nations University, p. 674 - 674.

Hochstein, M.P., and Browne, P.R.L., 2000, Surface manifestations of geothermal systems with volcanic heat sources, in Sigurdsson, H., ed., Encyclopedia of Volcanoes: San Diego, Haraldur Sigurdsson, p. 835 – 855.

Jaffey, L.A., Hilton, D.R., Fischer, T.P., and Hartono, U., 2004, Tracing magma sources in an arc-arc collision zone: Helium and carbon isotope and relative abundance systematics of the Sangihe Arc, Indonesia: Geochemistry, Geophysics Geosystems, v. 4, p. 1 - 17.

Koestono, H., 2010, Lahendong Geothermal Field, Indonesia: Geothermal Model Based on Wells LHD-23 and LHD-28, M.Sc. Thesis, United Nations University, Iceland, 90 p.

Macpherson, C.G., Forde, E.J., Hall, R., and Thirlwall, F., 2003, Geochemical evolution of magmatism in arc-arc collision: the Halmahera and Sangihe arcs, eastern Indonesia, in Larter, R.D., and Leat, P.T., eds., Intra-Oceanic Subduction Systems: Tectonic and Magmatic Processes, Geological Society of London, p. 207 - 220.

Mahandani, S.F., 2019. The Mapping of Geotourism Potentials of the North Langowan District, Minahasa Regency, North Sulawesi Province, Undergraduate Thesis, Universitas Gadjah Mada, Yogyakarta (in Bahasa Indonesia), 220 p.

Newhall, C.G., and Dzurisin, D., 1988, Historical Unrest at Large Calderas of the World: U.S. Geological Survey Bulletin, v. 1855, p. 345-351.

Pertamina UTC and Geothermal Research Centre UGM, 2013, The study of the Evolution of Thermal Structures and the Possibility of Magmatic Fluids Inputs into The Lahendong Geothermal System (in Bahasa Indonesia), Unpublished Report.

PT. PGE and Geothermal Research Centre UGM, 2014, Volcanic Facies and Subsurface Hydrothermal Alteration Studies of the Tompaso Geothermal Prospect, North Sulawesi, Unpublished Report.

Poreda, R., and Craig, H., 1989, Helium isotope ratios in circum-Pacific volcanic arcs: Nature, v. 338, p. 473 - 478.

Savitri, K.P., 2016. Geology and Geothermal Setting of Tompaso Geothermal System, Indonesia, with Comparisons of Andesite Alteration Patterns with Wairakei, New Zealand, M.Sc. Thesis, Victoria University, New Zealand, 120 p.

Sidqi, M., 2018, Geology and Thermal Manifestations of the Tompaso Geothermal Prospect, Minahasa Regency, North Sulawesi Province. Unpublished Undergraduate Thesis, Universitas Gadjah Mada, 348 p.

Sidqi, M., and Utami, P., 2018, The Geology and Geothermal Systems of the Minahasa District, North Sulawesi, Proc. The 6th Indonesia International Geothermal Convention and Exhibition (IIGCE) 2018, Jakarta, 5th – 8th August, 2018, 348 p.

Utami, P., 2011, Hydrothermal Alteration and the Evolution of the Lahendong Geothermal System, North Sulawesi. Ph. D Thesis, The University of Auckland, 449 p.

Utami, P., Widarto, D.S., Atmojo, J.P., Kamah, Y., Browne, P.R.L., Warmada, I.W., Bignall, G., and Chambefort, I., 2015. Hydrothermal Alteration and the Evolution of the Lahendong Geothermal System, North Sulawesi, Proc. World Geothermal Congress 2015 Melbourne, 19-25 April 2015, p.

Van Bemelen, R.W., 1949, Geology of Indonesia. Vol. I.A: General Geology of Indonesia and Adjacent Archipelago, The Hague Government Printing Office, Amsterdam, 732 p.

Yeftamikha, 2017, The Application of Hydrothermal Alteration Study in the Development of "YMS" Geothermal Prospect, Minahasa Regency, North Sulawesi Province (in Bahasa Indonesia), Unpublished Undergraduate Thesis, Universitas Gadjah Mada, 321 p.

Internet resources:

www.tides.big.go.id downloaded 12 July 2019.

www.volcano.si.edu accessed on 22 July 2019.