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Structurally Controlled Fluid Flow in a High-Enthalpy Geothermal System – Case Study Lahendong, Sulawesi (Indonesia)

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ABSTRACT

This study investigates a magmatic structurally controlled geothermal reservoir in North Sulawesi (Indonesia) combining structural geology, hydrochemistry including isotopes as well as geochemistry and permeability determination. The integration of all data into a thermal-hydraulic model allows prediction of reservoir behavior and supports the sustainable use of it.

Methods used throughout the study are structural mapping, fault plane analysis, field based determination of physicochemical properties of well and spring waters, discharge measurements in rivers, analysis of major and minor elements as well as isotopes of waters and rocks in the laboratory completed by investigations on permeability of rocks. Modeling of hydrochemical water properties was done using PHREEQC and subsequently a thermal-hydraulic modeling was carried out with Feflow.

Hydrogeological and geothermal relevant tectonic structures in this volcanically active area include two fault zone patterns, joints, and fractures at different scales. Discharge of several thermal springs is mostly connected by the fault zones while subsurface fluid flow is presumably controlled by fractured striking NW-SE. The study area is therefore highly differentiated with respect to hydraulic properties and chemical composition of the fluids. There are two types of fluids that can be roughly classified into acid and neutral waters. Isotopes suggest a meteoric origin of geothermal groundwater. Variable trace element concentrations are subject to differences in weathering regime and geochemical equilibrium conditions in the aquifer.

The main rock types in the Lahendong area are andesite and breccia. The thin sections from the surface rock material of the springs along with the cores from well indicate different stages of alteration. Temperature calculations by geothermometers are in good agreement with in situ measured temperature data, ranging between 232°C and 341°C.

A compartmentalisation of the reservoir was derived from stress field analysis of the tectonic elements in combination with hydrogeological interpretation. Temperature anomalies and loss of river water suggest surface water infiltration into fault zones. The Lahendong geothermal field is subdivided into two sub-reservoirs by horizontally less permeable fault zones and permeable fracture patterns parallel to the strike of the main fault. Our study shows that geological-structural analysis in combination with hydrothermal- and geochemical investigations are the essential tools for geothermal reservoir characterization and sustainability prediction of geothermal energy exploitation.

1. INTRODUCTION TO LOCATION AND GEOLOGY OF THE STUDY AREA

Our study area is located in Lahendong, North Sulawesi - Indonesia. Basins hosting lakes and volcanoes characterize the topography dominated by abundant vegetation. In this tropical climate zone the temperature is 25.9°C in average throughout the year and annual rainfall remains round about 2,662 mm (DWD, 2012).

The Lahendong geothermal field, owned by P.T. Pertamina Geothermal Energy, has 80 MWe production capacity provided by 8,300 tons of steam through 10 production wells. Vertical and inclined wells provide steam directly to be used for electricity generation and water, which is reinjected at the Northern boundary of the area. Production fields are located below

Lake Linau and the flank of Mount Lengkoan (Fig. 1). True vertical depth reached by production wells range between 1,460 and 2,499 m, which corresponds to 605 m to 1,643 m below sea level (Brehme et al., 2014). The reservoir is a two-phase-system, however, the Northern section of the reservoir has a lower steam proportion compared to the South. Temperatures in this high-enthalpy-reservoir range from 200°C to 340°C (Koestono, 2010).

From a tectonic point of view Sulawesi is located at a triple junction connecting the Eurasian, Australian, and Philippine plates, accommodating a plate motion ranging between 7.5 – 9 mm/year (Walpersdorf et al., 1998). The island consists of four parts originating from different components of surrounding complex subduction and faulting processes.

Minahasa, the Northeastern peninsula of Sulawesi rotated clockwise, before the volcanic activity started in Plio-/Pleistocene, as verified by paleomagnetic and geophysical investigations(Hamilton, 1979; Otofuji, Sasajima, Nishimura, Dharma, & Hehuwat, 1981; Silver, McCaffrey, & Smith, 1983; Surmont et al., 1994) (Otofuji et al., 1981; Surmont et al., 1994; Hamilton, 1979; Silver et al., 1983). Subduction processes characterize this part of Sulawesi. One subduction slap is dipping towards West beneath the island while the North Sulawesi Trench is pushing from the North.

During the Miocene volcanic rocks and marine sediments were deposited at this northern active volcanic arc. A combination of regression and accelerated volcanic activity caused the Tondano eruption (1.3 – 2 Ma years ago), and later led by the Pangalombian eruption during the late Pleistocene (Siahaan et al., 2005). Rock types are predominantly basaltic andesites and volcanic breccia (Pre-Tondano series, ~2.19 Ma), rhyo-dacitic tuffs intercalated by diorites (Tondano series, ~0.87 Ma) and pumice, tuff, volcanic breccia and basaltic andesite (Post-Tondano series, (Koestono et al., 2010; Utami et al., 2004).

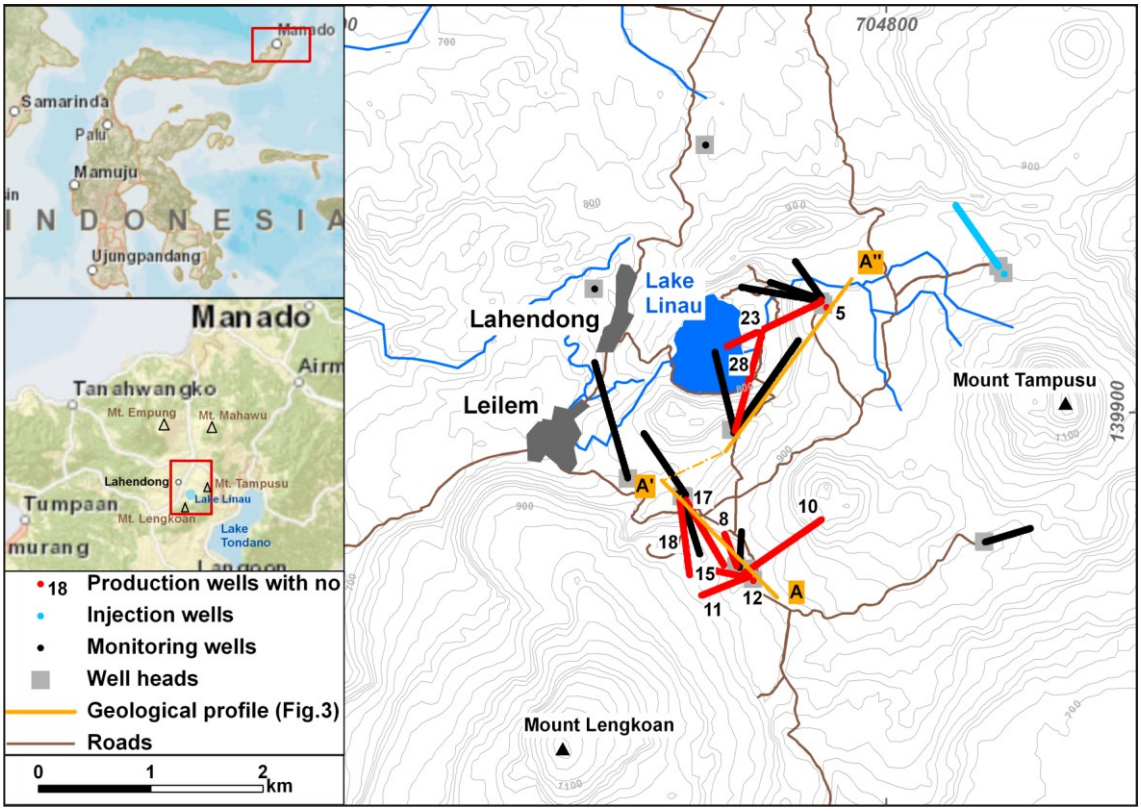

Fig.1: Location of the study area and wells. Deviated wells are shown as lines, vertical wells as dots (from Brehme et al., 2014).

2. METHODS

Methods used throughout the study are structural mapping and fault plane analysis with a focus on subsurface fluid circulation. We measured orientation (strike and dip) of faults and joint planes as well as the slip direction (indicated by slickensides). Relevant elements to determine subsurface fluid flow are fault orientations, discontinuities and joints, location of thermal springs, and the hydrogeochemical composition of groundwater from wells and hot springs.

Physicochemical properties were measured on-site by hand-held instruments at wellhead, in hot springs, rivers and lakes (i.e. pH, temperature, and electrical conductivity. Discharge measurements in rivers and investigations on the permeability of rocks revealed possible fluid pathways in rocks and faults.

Eventually, modeling of hydrochemical water properties was done using PHREEQC revealing possibly precipitating mineral phases (Parkhurst & Appelo, 2013). The thermal hydraulic conditions of the geothermal system are described by a thermal-hydraulic model using Feflow (Diersch, 2013).

3. RESULTS

3.1 Hydrotectonics

Based on hydrochemical investigations the Lahendong geothermal field is subdivided into two sub-reservoirs consisting of acid and neutral type waters, respectively. Brine water with a pH of 3 characterizes the acid reservoir in the North and a moderate pH of around 4 – 7 is predominant in the South (Fig.2). The occurrence of the two water types in very close proximity suggests subsurface fluid flow barriers, e.g. fractures/faults. On the other hand permeability of fault zones was observed by infiltration of surface water from creeks showing a considerable discharge drop while crossing the fault. Temperature isoline-deflections around this fault verify a downward cold-water intrusion from the surface.

These observations let conclude that faults and fractures act either as pathways or barriers and therefore explain fluid flow to different reservoir volumes leading to strong variety of water types (Brehme et al., 2014). In detail results show that fault zones represent horizontal flow barriers due to sealing of the fault core as well as conductive pathways in the damage zone sub-parallel to the fault strike. This physical setup should be taken into consideration as the fault core can be 103 - 104 times less permeable than the surrounding damage zone (Evans et al., 1997; Faulkner et al., 2003).

Permeability properties of faults in the Lahendong area were studied in outcrops and manifestations, where the orientation, aperture width and possible sealing by mineral precipitation are reasonably visible. Generally, two basic stages of fault development have been identified in the region of interest. The relatively older strike-slip faults are NE-SW oriented and dip between 72° and 81° towards SE. Riedel shears and slickensides indicate left-lateral movement. A second fault pattern is identified in a set of N-S and E-W striking normal faults. The dip range between 78° and 88° into ESE or SSW. Both types of faults act as barriers in the reservoir and have a certain permeability in the surrounding of the fault core most obvious W and SW of Lake Linau (Brehme et al., 2014).

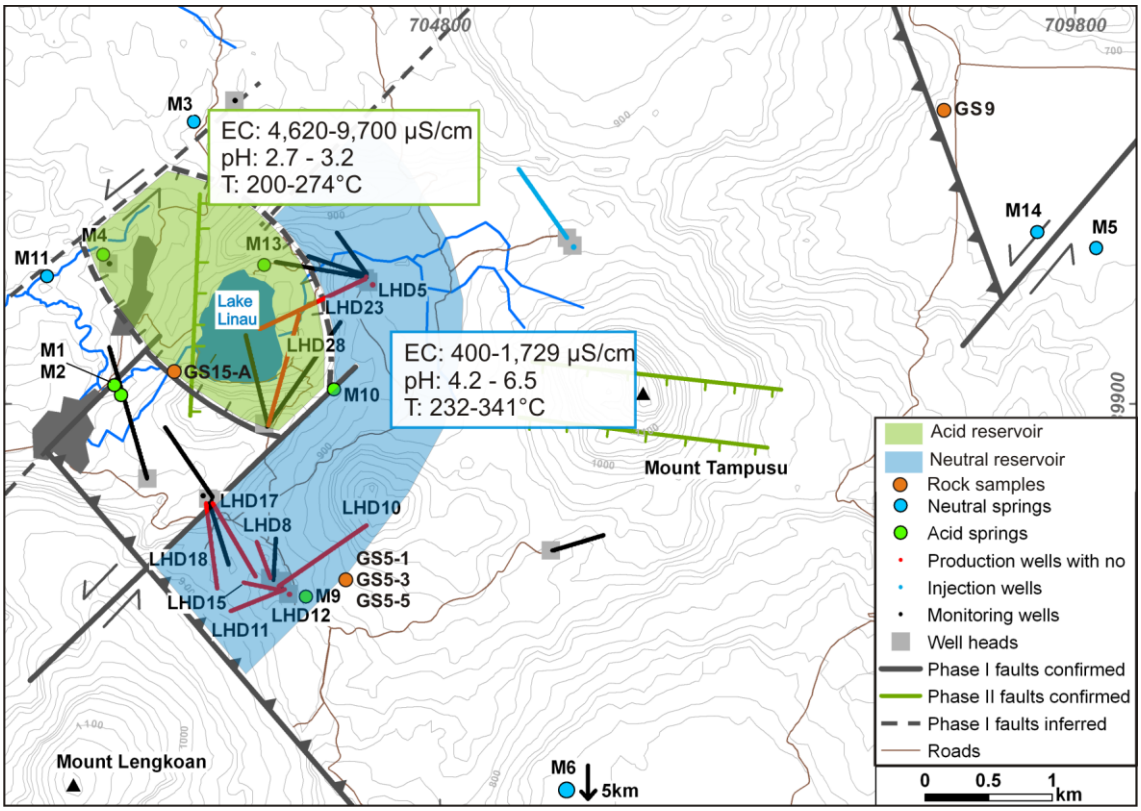

Fig.2: Hydrotectonic conceptual model showing the different reservoir compartments in Lahendong (acid: green color and neutral: blue color) and sample locations

3.2 Geohydrochemistry

An existing comprehensive geohydrochemical database consisting of fluid and rock analyses was completed by additional studies during field campaigns in 2010–2012. Existing pattern could have been confirmed by additional fluid and rock samples.

This database has been used to validate two models running for the geothermal system (hydrochemical and thermal). The aim of the hydrochemical model is the prediction of possible supersaturated minerals and resulting mineral precipitation as well as dissolution using the numerical code PHREEQC. The thermal regime has been evaluated using several geothermometers.

The basic hydrochemical feature in the Lahendong geothermal system is its clear subdivision into two reservoirs hosting acid and neutral water as observed in wells and hot spring samples. The origin of acid water is the contact of fluids with gases (H_2S and CO_2) emanating from an old magma chamber, i.e. today's heat source beneath Lake Linau. Neutral water is predominantly observed in close proximity NE and SE of Lake Linau. Major ions in reservoir and hot spring water are SO_4

and Cl. In hot spring waters Cl content is much lower than the level observed in the reservoirs, probably due to dilution by shallow groundwater. SO_4 concentrations are extremely different owing to the continuous reaction with rising gas and subsequent acidification (Brehme et al., 2014).

For both types of reservoirs, the host rock is volcanic breccia consisting mainly of rock fragments and minerals i.e., quartz, plagioclase and epidote embedded in a fine microcrstalline matrix. Minor mineral phases are chlorite, pyrite, clays and sulphate containing minerals. They vary with the type of fluid hosted due to dissolution and precipitation processes. The PHREEQC model reveals supersaturation of clays, chlorite and sulphate-mineral phases (i.e. pyrite, alunite) in hot spring as well as reservoir waters and additionally iron-mineral phases (i.e. hematite, siderite) supersaturated in hot spring samples.

Na/K- and Quartz-geothermometer calculations have been performed based on well and hot spring samples. The best results have been obtained for the acid well samples, calculating 264 – 273°C with an error of maximum 3 – 4% for the reservoir temperature and 0 – 16% for maximum measured temperatures. Neutral well samples reveal temperatures of 220 – 336°C (error range: 0 – 35%). Hot spring geothermometer calculations show maximum temperatures of 207 to 348°C and reservoir temperatures between 158 and 334°C for nearby wells in a similar error range (1 – 38%).

Both models have been verified using real observed data from this and previous studies. A good agreement is attained between supersaturated mineral phase calculations in the reservoir and observed alteration minerals in core samples as well as surface samples and their corresponding supersaturations. Temperatures obtained by geothermometry using reservoir samples provide the best results. Variations in hot spring samples are interpreted to be due to enhanced reaction with surrounding rocks during upflow.

3.3 Thermal-hydraulic modeling

The Lahendong area accommodates three different types of bedrock, namely, andesite, volcanic breccia and tuff. These horizontally intercalated formations have been generated by several volcanic eruptions. Andesitic rocks are the least permeable and therefore represent boundaries between different permeable horizons. Permeable reservoirs rocks are mainly presented by breccia-layers. Two faults dip below the Lake Linau and separate two reservoir systems (Fig.2). The neutral reservoir is located NE and SW of Lake Linau and has an average temperature of 319°C (thermal gradient 145°C/km) and a reservoir pressure of 121 bar. The acidic reservoir located between the faults is characterized by a pressure of 117 bar and an average temperature of 237°C (thermal gradient 200°C/km) (Brehme et al., 2014).

Porosity of andesite is 3.7%, of tuff 7.7% and of breccia 10.5%. Heat conductivities range between 1.615 W/m/K for tuff and 1.782 W/m/K for andesite. The permeability values of rocks in the Lahendong geothermal system are beneath 0.1 mD, which lead to the assumption that subsurface fluid flow is dominated by second order permeability, i.e. conductivity of faults and fracture zones. Therefore, an approximate hydraulic conductivity of 1*10-4 [m/s] is assumed for the permeable layers (breccia); 1*10-3 [m/s] for the fault zones, and 0.01*10-4 [m/s] for the andesite units. In Lahendong, subsurface fluid flow is generally from SW to NE.

A thermal-hydraulic model was generated with Feflow (Diersch, 2013) representing natural state conditions before production start in the Lahendong geothermal field. Fluid flow is dominated by higher water tables, presumably due to infiltration in the SW and lower hydraulic heads in the NE resulting in a fluid flow from SW to NE (Fig.3). Surface water infiltration is interfering with the subsurface fluid flow by cold water infiltration via the northeastern fault and fluid rise via the southwestern fault (Fig.3).

The temperature field is mainly dominated by a temperature gradient of 26 – 380°C set at the southwestern border of the model (Fig.3). Additional heat flow rises from a magma chamber structure set to a temperature of 350°C as measured in nearby wells. Temperature distribution is dominated by convection resulting in higher temperatures in the SW of the study area and beneath Lake Linau (due to rise of fluids). Lower temperatures of 100 - 200°C are characteristic for the northeastern domain. Downhole measurements from wells show a good agreement with modelled thermal and hydraulic conditions.

Furthermore, a 2-phase model has been constructed using TOUGH2 in order to evaluate fluid conditions considering temperature and pressure states. Results show increased temperatures beneath Lake Linau due to fluid rise in the area. The study area is dominated by liquid water, except on top of the magma chamber. A zone of super-critical state is located beneath a 2-phase area that is vertically extending between the faults reaching Lake Linau from the bottom. This 2-phase input into Lake Linau could be observed in the field by bubbles rising in the southwestern part of the lake.

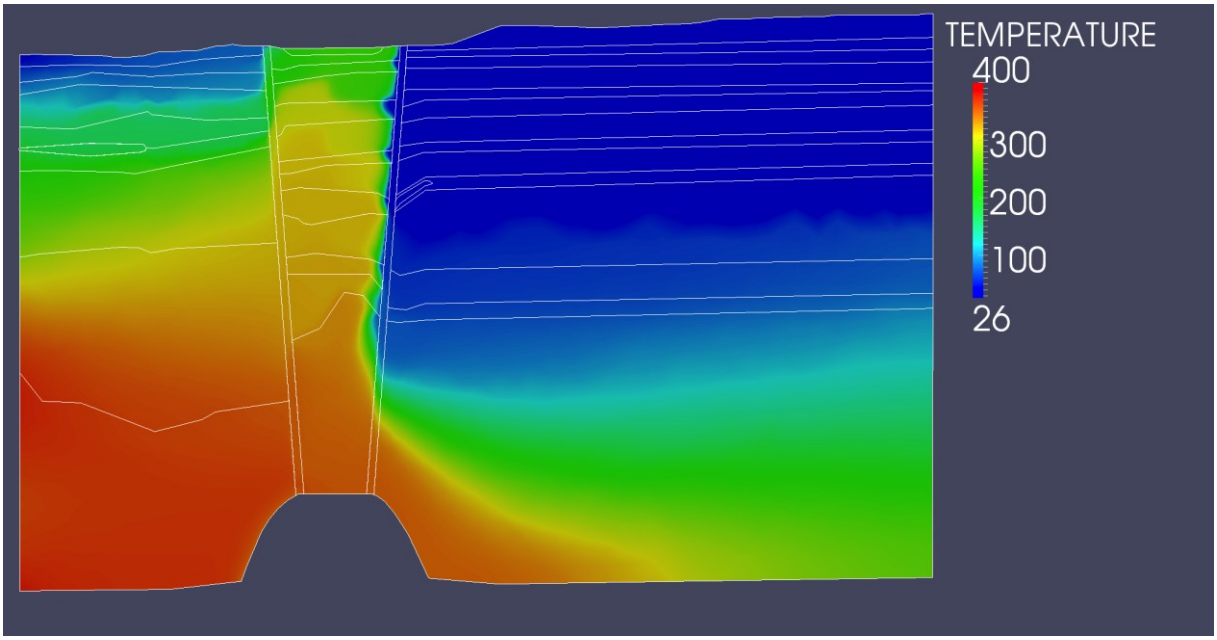

Fig.3: Temperature distribution simulated with a thermal-hydraulic model showing a SW-NE cross-section with two faults and a magma chamber structure.

4.CONCLUSION

The high-enthalpy geothermal system Lahendong in Indonesia has been investigated focusing on subsurface fluid flow and geohydrochemical processes. Detailed analysis of rocks (thin sections, XRD/XRF) and fluids (major/minor ions), structural mapping, geothermometer calculations and hydrochemical and thermal-hydraulic modelling have been used to provide insights into physical processes affecting the geothermal system.

Two fault regimes, strike-slip and normal faulting, subdivide the field into different parts. Independent of fault type they act as barriers perpendicular to the strike and separate two hydrochemically different reservoir types. At the same time fluid flow was observed parallel to the strike of faults.

Extensive geohydrochemical studies allowed the validation of a water-rock-interaction model, which revealed mineral phases supersaturated at reservoir or surface conditions. Mostly attracted for precipitation are clays, chlorite, sulphate- and iron-mineral phases. Geothermometer calculations based on well samples show the best results for acid conditions. Neutral well samples and hot spring waters lead to error ranges of 0-38%. Average reservoir temperatures are 319°C for the neutral and 237°C in the acid reservoir.

The thermal hydraulic model combining all results from the study reveals a fluid flow through permeable breccia layers from SW to NE and along the strike of faults. Heat distribution is controlled convective leading to higher temperatures in the SW and between the faults. Fluid flow is furthermore influenced by 2-phase prevalence beneath the lake.

Our innovative multidisciplinary approach is characterized principally by the combination of structural geology, hydrogeology, rock/water geochemistry and numerical simulations. The numerical models simulate different scenarios in the geothermal system and are verified with a database of downhole measurements. These models describe thermal and hydraulic evolution of the field, 2-phase-flow and geohydrochemical processes, i.e. precipitation and dissolution due to water-rock interaction. They represent reference models for comparable geothermal systems.

Geological-structural analysis in combination with hydrothermal- and geochemical investigations is the essential tool for geothermal reservoir characterization and sustainability prediction of geothermal energy exploitation. They are complementary to geophysical assessments.

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REFERENCES

Brehme, M., Moeck, I., Kamah, Y., Zimmermann, G., & Sauter, M. (2014). A hydrotectonic model of a geothermal reservoir – A study in Lahendong, Indonesia. Geothermics, 51, 228–239.

Diersch, H.-J. (2014): Feflow Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media, Springer, pp 996.

DWD, Deutscher Wetterdienst 2007. Offenbach/Main, http://www.dwd.de/ (accessed June, 2012).

Evans, J. P., Forster, C. B., & Goddard, J. V. (1997). Permeability of fault-related rocks, and implications for hydraulic structure of fault zones. Journal of Structural Geology, 19(11), 1393–1404.

Faulkner, D. ., Lewis, a. ., & Rutter, E. . (2003). On the internal structure and mechanics of large strike-slip fault zones: field observations of the Carboneras fault in southeastern Spain. Tectonophysics, 367(3-4), 235–251.

Hamilton, W. B. (1979). Tectonics of the Indonesian Region (p. 345). U.S. Govt. Print. Off. (Washington), 1078, 345p.

Koestono, H. (2010). Lahendong Geothermal Field , Indonesia : Geothermal model based on wells LHD-23 and LHD-28. Master-Thesis at University of Iceland.

Koestono, H., Siahaan, E. E., Silaban, M., & Franzson, H. (2010). Geothermal Model of the Lahendong Geothermal Field , Indonesia. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.

Otofuji, Y., Sasajima, S., Nishimura, S., Dharma, A., & Hehuwat, F. (1981). Paleomagnetic evidence for clockwise rotation of the northern arm of Sulawesi, Indonesia. Earth and Planetary Science Letters, 54, 272–280.

Parkhurst, D. L., & Appelo, C. A. J. (2013). Description of Input and Examples for PHREEQC Version 3 - A Computer Program for Speciation , Batch-Reaction , One-Dimensional Transport , and Inverse Geochemical Calculations. Modeling Techniques, book 6 (p. 497). U.S. Department of the Interior, U.S. Geological Survey.

Siahaan, E. E., Soemarinda, S., Fauzi, A., Silitonga, T., Azimudin, T., & Raharjo, I. B. (2005). Tectonism and Volcanism Study in the Minahasa Compartment of the North Arm of Sulawesi Related to Lahendong Geothermal Field, Indonesia. Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.

Silver, E. A., McCaffrey, R., & Smith, R. B. (1983). Collision, rotation, and the initiation of subduction in the evolution of Sulawesi, Indonesia. Journal of Geophysical Research, 88(B11), 9407–9418.

Surmont, J., Laj, C., Kissel, C., Rangin, C., Bellon, H., & Priadi, B. (1994). New paleomagnetic constraints on the Cenozoic tectonic evolution of the North Arm of Sulawesi, Indonesia. Earth and Planetary Science Letters, 121, 629–638.

Utami, P., Siahaan, E. E., Azimudin, T., Browne, P. R. L., & Simmons, S. F. (2004). Overview of the Lahendong geothermal field, North Sulawesi, Indonesia: A progress report. Proceedings of the 26th NZ Geothermal Workshop 2004 (pp. 1–6).

Walpersdorf, A., Vigny, C., Manurung, P., Subarya, C., & Sutisna, S. (1998). Determining the Sula block kinematics in the triple junction area in Indonesia by GPS. Geophysical Journal International, 135, 351–361.