

Occurrence of Sarawet hot spring : what affects the outflow?

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Geothermal systems located in volcanic arc are generally influenced by volcanic activities. But at the complex geological setting like Sulawesi the geothermal systems probably is not only influenced by volcanic activities but also structural geology features. Sarawet hot spring in Minahasa, North Sulawesi, Indonesia is a volcanic and fault influenced manifestations. Sarawet hot spring is located in north coast Minahasa. Our study shows that the surface geological-structural analysis in combination with the geochemistry and the heat flow investigation is the essential tools for geothermal systems or manifestation characterization. Tectonics, crust characteristic, heat flow, and surface structural could affect the manifestations and its geothermal systems. Geochemically the water is bicarbonate, peripheral-immature water, and characterized by a meteoric water-line trend. The composition of these thermal springs was controlled by a secondary process during ascent. Based on hydrologic gradient, heat flow characteristic and subsurface structural analysis, the mechanism of Sarawet hot spring is a lateral outflow that affected by dynamically maintained fractures system.

1. Introduction

Minahasa is located in North Arm of Sulawesi in Indonesia. It was one of the major geothermal resources in Indonesia. The hot spring was found within several volcanic and sedimentary rock formations. Sarawet hot spring was located in Sarawet, near Likupang. It was related to sedimentary rock formation, Breccia and Sandstone (Tps)[7]. Different with the other hot spring, the Sarawet hot spring was located in the margin of volcanic system boundary. Thus, the mechanism of how this hot spring and permeability zone was formed is still obscure [10]. This study used surface geological and structural analysis in combination with the geochemistry and the heat flow investigation as the essential tools for geothermal manifestation characterization.

2. Methods

Hot Spring Control System could be determined by several variables such as geochemistry of hot spring manifestation, regional geology and ASTER DEM (figure 1). Water sample was from Sarawet hot spring used for geochemistry analysis and the result was represented into 3 diagrams with different parameters.

The Cl-SO₄-HCO₃ ternary diagram was used to classify geothermal fluids on the basis of the major anion concentrations [8]. It helps to discern immature unstable waters and gives an initial indication of mixing relationships or geographic groupings [6].

The Na-K-Mg triangular diagram was used to classify waters into fully equilibrated, partially equilibrated and immature waters. It can be used to predict the equilibrium temperature. The Na-K-Mg triangular diagram shows attainment of the water-rock equilibrium if the data point plots on the full equilibrium line, or suggests a field of immature water below the "immature water curve" which indicates an initial dissolution of minerals before equilibrium reaction sets in [8]. Lithium was used as a tracer, because it is the alkali metal least affected by secondary processes for initial deep rock dissolution and as a reference for evaluating the possible origin of two important 'conservative'



constituents of geothermal waters, Cl and B. The Cl/B ratio is often used to indicate a common reservoir source for the waters [9]. All of diagrams decide Hot Spring Characteristic after analysis.

Heat Characteristic consists of heat flow, thermal gradient, and conductivity data. All of them shows thermal condition from research area. Heat flow is the transfer of thermal energy from one body to another or a transfer of temperature. The conveyance of heat through the crust is primarily related to rock type and structure [12]. Thermal gradient is defined as a vector that is dependent on temperature distributed in three dimensions (x, y, and z axes). Knowing three-dimensional temperature distributions within the crust is ideal for determining the true vector of the maximum thermal gradient [2]. Thermal conductivity is a measure of the ability of heat to flow through a particular material, and is a function of temperature. Thus, higher thermal conductivity values for a particular lithology indicate a higher allowance for heat flow [4]. Both hot spring and heat characteristic associated with lithology and geological structure, so it can assist in determine the structural control.

ASTER DEM used for establish lineament to create Fault and Fracture Density (FFD) Map. Both of FFD Map and geological structure map help authors to assign structural control, in addition to Heat and Hot Spring Characteristic. Furthermore, structural control either dynamic or kinematic as results can be state hot spring outflow system related with fault occurrence.

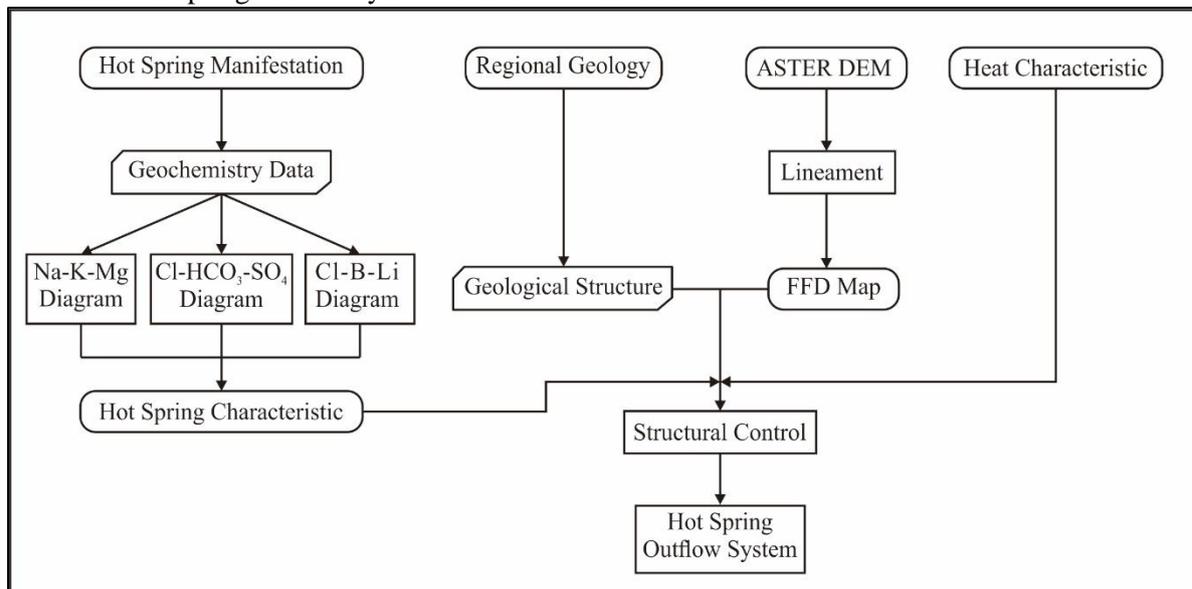


Figure 1. Workflow diagram of structural control identification in outflow.

3. Geological Setting

Minahasa Area consist of Tertiary volcanic and sediment rocks overlain by Quaternary and recent volcanic rocks [7]. The oldest rock formation found in North Minahasa ia Volcanic Rock (Tmw) that consist of breccia, lava and tuff, sandstone, claystone and mudstone which found as intercalation and Breccia and Sandstone (Tps) Formation, consist of breccia and conglomerate intercalated with fine to coarse sandstone, siltstone and claystone. The Quaternary rocks formation of the research area consist of Tondano Tuff (Qtv), Young Volcanic Rocks (Qv), Coral Reef Limestone (Ql), Lacustrine and Fluvial Deposits (Qs), and the youngest is Alluvium (Qal). Qtv consist of coarse volcanoclastic with andesitic composition while the Qv consist of lava, bomb, lapilli and ash with andesit basalt composition that make up the young strato volcano. Ql is distributed in the north coast area and consist of coral reef limestone that mostly found between low and high tide. Not far from the north coast, Qs was distributed as sandstone, siltstone, conglomerate, and marl. And the recent one, Qal, is consist of boulders, cobbles, pebbles, sand and mud

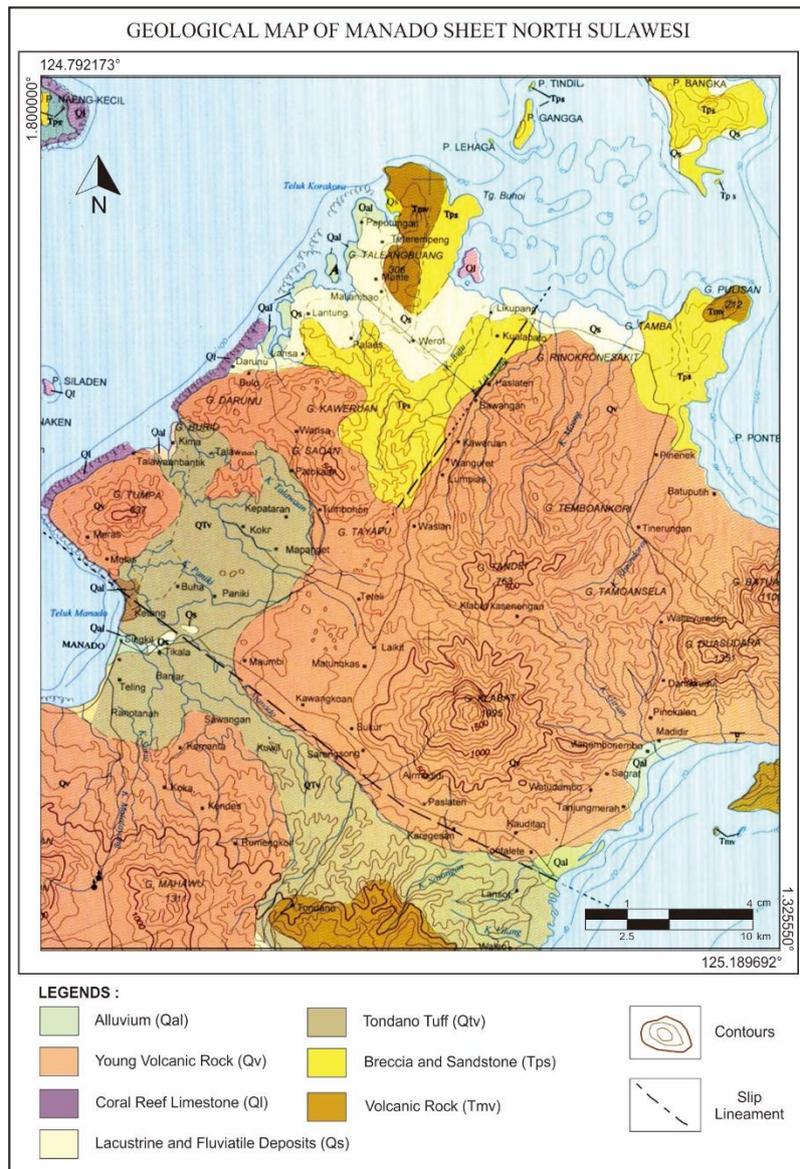


Figure 2. Regional Geology Map of Minahasa showing the distribution of sediment and volcanic rocks and the strike slip of the research area. [7].

The hot springs were not found only within the volcanic area but also on it surrounding areas. In addition, the manifestations were found in the vicinity of a fault that may have leaked the geothermal fluid onto the surface.

Minahasa comprises some fault patterns which are major strike slip fault trending NE-SW, NW-SE and normal fault trending N-S. The fault was created by the movement of Celebes sea-plate. Other geological structure in Minahasa mainly controlled by two major strike-slip fault that cut the North Arms Sulawesi in two places, between Amurang – Malompar in the south and Manado – Kena in the north.

4. Geochemistry

4.1 Cl-HCO₃-SO₄ Diagram

Based on ternary diagram plotting of the major anions Cl^- , HCO_3^{3-} and SO_4^{2-} as seen in figure 3 below, Sarawet hot spring composed of bicarbonate water which located in peripheral - surface water zone with dominant concentration of HCO_3^{3-} . It is interpreted that Sarawet hot spring was associated with CO_2 rich fluids that flowing through permeable zone and then condenses in the shallow aquifer. Sarawet hot water is not classified as reservoir water but it was a product of near surface mechanism due to the mixing of the reservoir water with groundwater or surface water.

4.2 Na-K-Mg Diagram

Na-K-Mg diagram (Figure 4) presented the condition of the geothermal fluids. Sarawet hot spring showed high concentration of Mg and plotted as immature water. Immature water zone and near $\sqrt{\text{Mg}}$ peak point suggest that there were high influence of groundwater in the systems. This is accordance with Cl^- , HCO_3^{3-} and SO_4^{2-} plotting diagram that proved the interaction with groundwater or surface

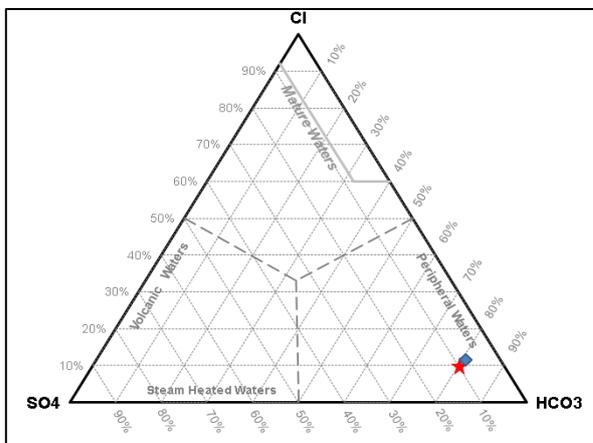


Figure 3. $\text{Cl-HCO}_3\text{-SO}_4$ Diagram.

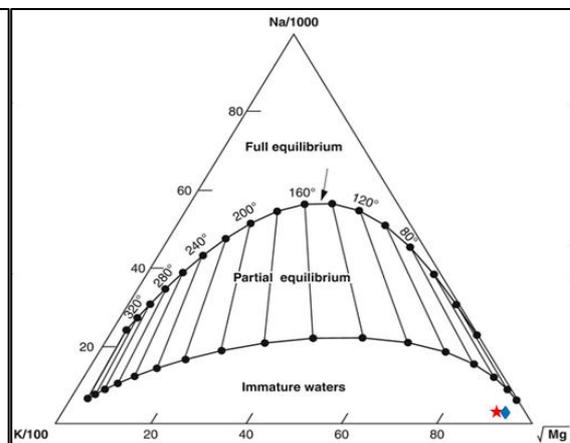


Figure 4. Na-K-Mg Diagram.

water.

4.3 Cl-B-Li Diagram

Figure 5 showed the relatively high Cl content than Li and B at Sarawet hot water. Its indicated the influence of magmatic activity to the hot spring manifestation. The low value of B indicated that the

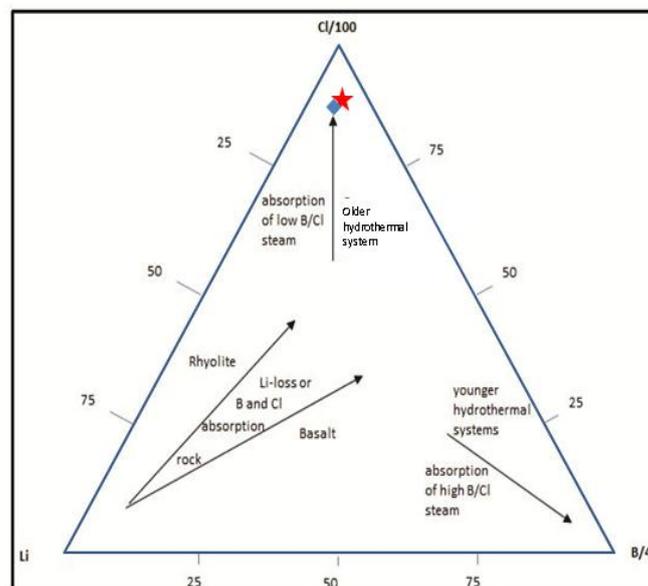


Figure 5. Cl-B-Li Diagram.

reservoir rocks was volcanic rocks, even the manifestation is located in sedimentary formation.

4.4 Isotopes

A previous isotope study from Pusat Sumber Daya Geologi [10] showed that water samples from Sarawet Hot spring experienced meteoric water enrichment. This is indicated by the results of data that located on the meteoric Water Line area. It displayed that the hot spring is just surface water.

5. Structural Geology

The location, shape and size of upwelling zones near the surface reflect their structural control. Fluid flows in active tectonic areas are mainly controlled by fault and fracture. The fault patterns in Minahasa were a result of Celebes Sea Plate movement from the north and Tomini Microplate from the south. Two stresses from North to South caused the north arm of Sulawesi moved eastward and collide with westward movement of Moluccas oceanic plates. Structurally, the Minahasa fault pattern is majorly strike-slip fault trend in NE-SW, NW-SE and normal faults trending N-S [11]. It is considered that structural pattern around Sarawet hot spring were caused by North-South stress. Fracture and fault analysis done by Digital Elevation Model (DEM) and Regional Geology Map showed that Sarawet hot spring was related to high fault and fracture density area. The most intensive fault and fracture area in research area is placed near Sarawet and as displayed in Fault and Fracture Density (FFD) Map below (Figure 6).

Based on hot spring location with respect to fault, there are two primary mechanism of forming and sustaining fracture permeability in the surface, dynamically maintained fracture system and kinematically maintained fracture systems [5]. The fracture system correspond to the breakdown region because of fault interaction and locked fault intersection is called “dynamically maintained fracture system”, while “kinematically maintained fractured systems” refer to slip along fault traces or re-open pre-existing fracture network at slipping fault interaction. This process would affect hydrothermal outflow. We need to analyze data through surface and/or subsurface data to determine the mechanism.

Based on Digital Elevation Model analysis compared with Regional Geology Map [7] (Figure 7), the nearest structure in Sarawet was a pair of NE-SW trending strike slip located in Kualabato (1) and Maliambo (2). Both of them are sinistral. The western-strike slip (1) was trending N60°E and formed as first order and the eastern strike slip (2) was trending N33°E and formed as second order. DEM analysis (Figure 6) showed that those paired of strike slip separated the north compartment of Minahasa to 3 parts; A, B, and C. A was composed of alluvium and Pliocene rocks, B was composed of Pliosen and Quaternary volcanic rocks and characterized by high density of lineament in NW-SE trends and C was composed of Quaternary volcanic rocks. The position of B relatively lower than C.

Dynamic analysis through both sinistral strike slip pattern done by comparing Riedel Shear Model with the main stress in the research area indicated that the western-strike slip is R-Shear and eastern part is P-Shear.

A paired of strike slip would form releasing or restraining step based on its movement. Faults that converge in one direction diverge in the opposite direction [3]. The subsidence of the tip with divergence strike slip faults of the research area could be sketched on Figure 8. Down region was a merged breakdown-region from the interaction of two fault line. The breakdown area has intense fracture and it could be related to the formation of permeability zone. Its form and size were influenced by geometry and kinematics of each fault [5].

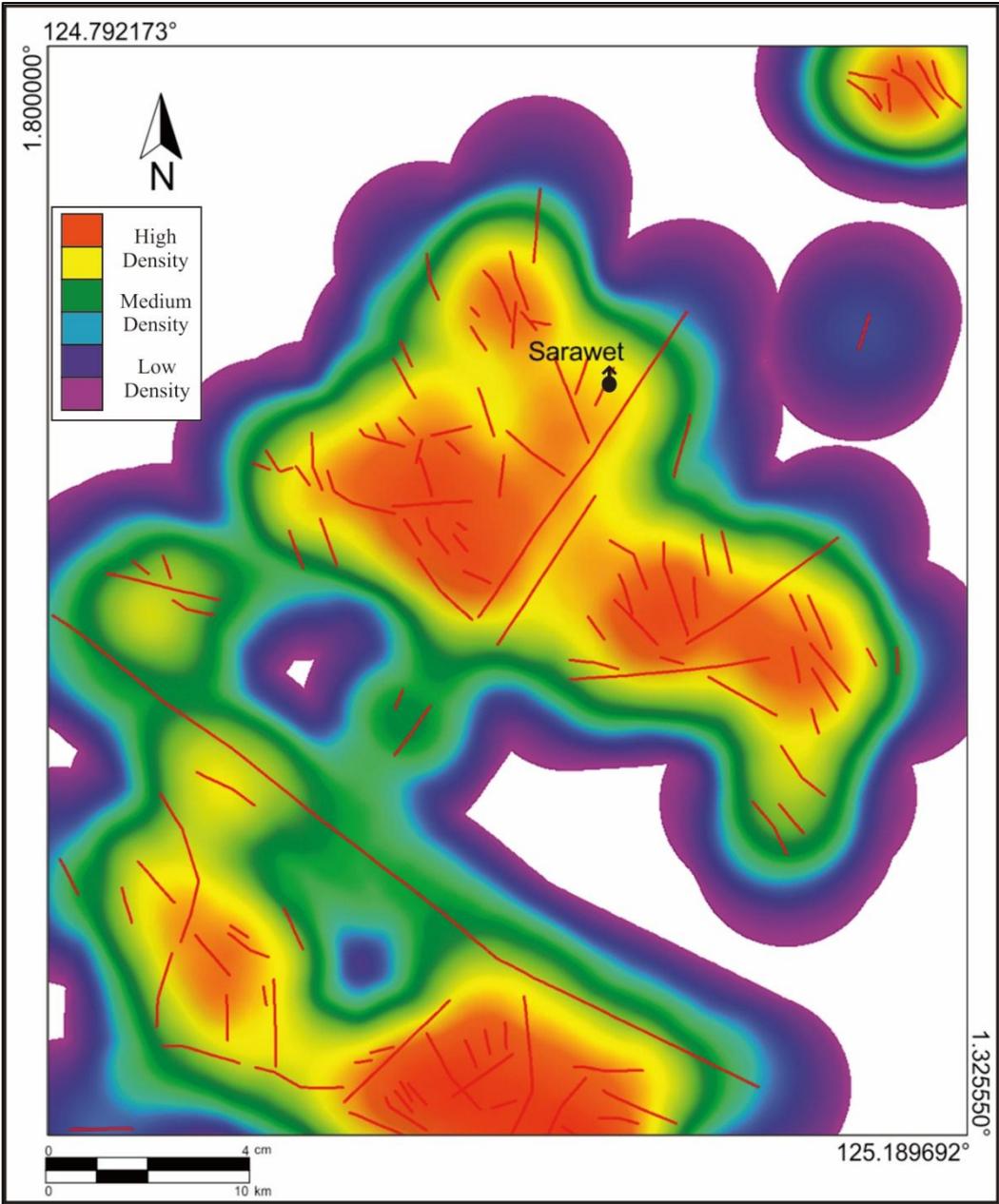


Figure 6. Fault and Fracture Density Map of North Minahasa Area.

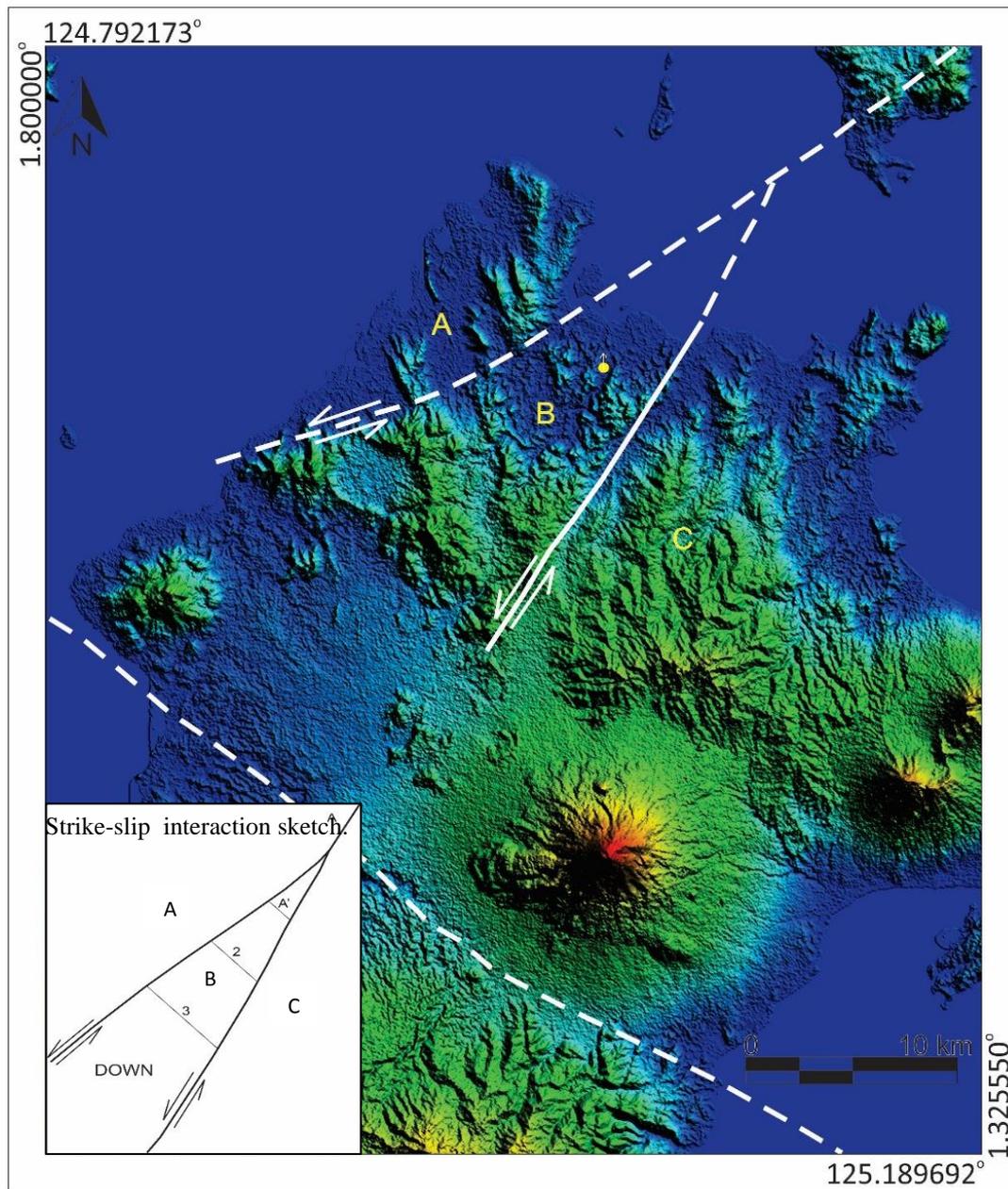


Figure 7. Fault and Fracture Analysis Based on Digital Elevation Model.

6. Heat Characteristic

Heat characteristic figure can be affected by structural systems, for example in discontinuity area near fault system. In this paper, heat characteristic analysis was done to get the relationship between heat characteristic pattern and structural control of the research area. Heatflow map, thermal gradient map, and conductivity map were made based on 4 well data named Lapangan-well, Bor 1-well, Bor.1-well, and Bor 2-well. The location of each well was shown on the map.

6.1 Heat Flow

Figure 8 below showed the heat flow within the research area. Heat flows constantly from the mantle to the surface through conduction. Mean heat flow in Minahasa area was 300 mW/m^2 over continental crust. The heat flow values were significantly higher in the western part and there was anomaly in the centre part of Minahasa. Blue-purple area near LAPANGAN-Well were interpreted as damage zone

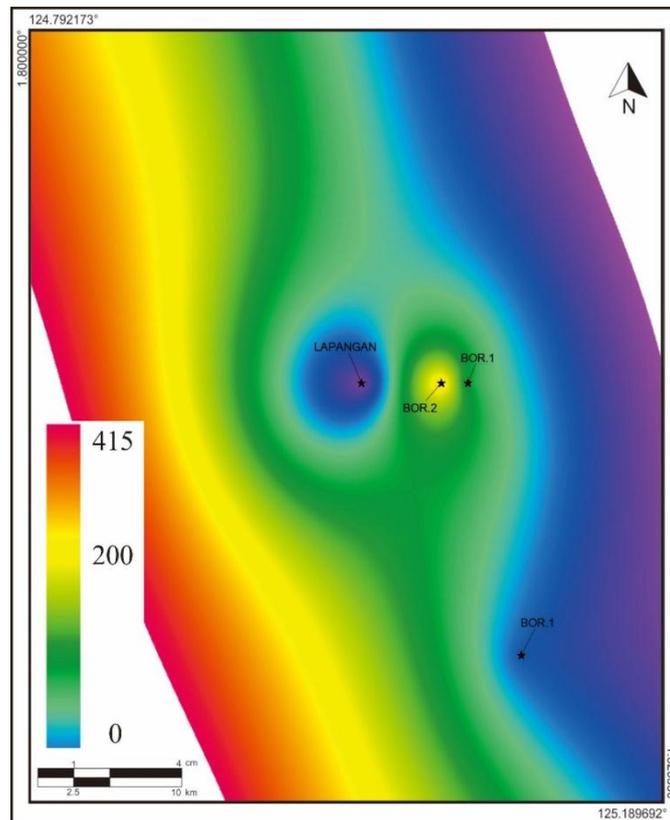


Figure 8. Heatflow Map of North Minahasa area showed the anomaly in the central part near Sarawet hot spring.

were Mode I fracture are concentrated.

6.2 Thermal Gradient

Geothermal gradient is the changes of temperature per depth. Figure 9 showed gradient data from the exploration wells based on “All Heatflow Data” from Royal Holloway South East Asia Research Group [1]. Based on Thermal Gradient Map below, the thermal gradient value was lowered to the South-western part of Minahasa. The distribution of the same thermal values were trending NW-SE but there is small anomaly point which has higher geothermal gradient than its surrounding. The anomaly point was located near the Sarawet hot spring manifestation.

6.3 Thermal Conductivity

Conductivity is an ability of a material to transfer heat energy. Based on Thermal Conductivity Map (Figure 10), the thermal gradient value was lowered to the South-western part of Minahasa. The distribution of the same conductivity values were trending NW-SE. Different with thermal gradient and heatflow map which showed anomaly point near the manifestation, the distribution of thermal conductivity value in the research area was relatively homogen along NW-SE trends.

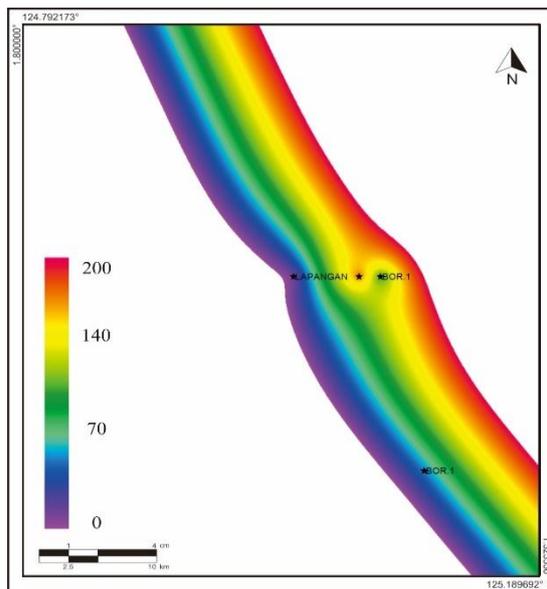


Figure 9. Thermal Gradient Map showed anomaly distribution value near Sarawet hot spring (Between Lapangan dan Bor-well).

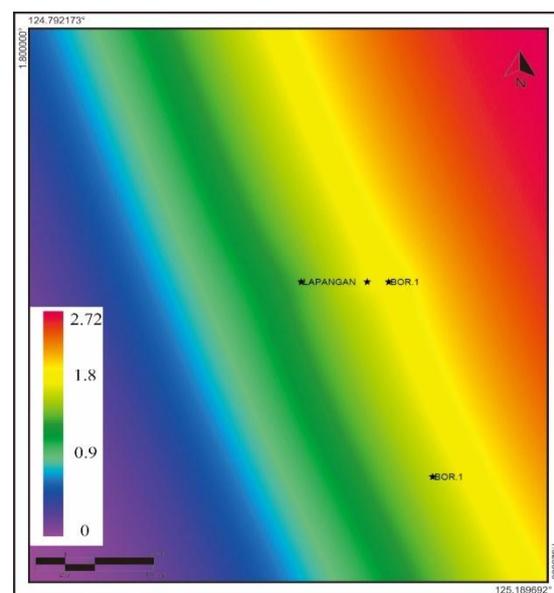


Figure 10. Thermal Conductivity Map showed the NW-SE trending of conductivity value distribution.

7. Discussion

According to the host rocks, geochemistry data and isotope data, Sarawet hot spring was classified to bicarbonate and immature water. The hot spring manifestation was located at Sandstone and Breccia (Tps) [7] formation which predominantly composed of sandstone but geochemically its reservoir was volcanic rocks. It was interpreted that there were near surface reaction between hydrothermal fluids and its surrounding and it showed the possibility of fluid mixing with ground water or surface water. It was consist of 2 fluid components, the meteoric water and groundwater. Volcanic gasses from North Minahasa Volcanic Complex were absorbed by meteoric water and then mixing with groundwater along the path to generate thermal water. The thermal water then flows through its outflow system that conducted by fault and fracture.

It's normal because Sarawet hot spring located in the coastal lowland area with sedimentary rock formation which has higher primary permeability than its surrounding. The origin of this water was composed Sarawet hot spring outflow system was mainly controlled by fault and fracture. Generally, the regional distribution of hydrothermal activity may be controlled by the large scale fault geometry while the local hot spring may be controlled by the fracture or lineament around the main fault. Lateral outflow of manifestations is localized by the fracture in damaged zone. Sarawet hot spring can be referred as local hot spring located between two fault zones. Primarily mechanism of forming and sustaining fracture permeability around the research area were related to breakdown region between two faults. So, it's forming and sustaining fracture permeability system was primarily controlled by dynamic maintained fracture systems related to fault interaction. Fractured formed within the

breakdown region and provide high permeability fluid flow conduits. The formation of hot spring manifestation was related to extension fracture and releasing step.

8. Conclusion

Sarawet hot spring was found in sedimentary host rock but the reservoir was volcanic rocks. The chemical composition of the geothermal water suggested it was bicarbonate peripheral fluid and influenced by groundwater mixing. The lateral outflow of the thermal water were influenced by fault and fracture that produce permeability zone through dynamic maintained fracture systems related to fault interaction and releasing step.

9. References

- [1] All Heat Flow Data (Open Access) Royal Holloway South East Asia Research Group (<http://searg.rhul.ac.uk/current-research/heat-flow/>, accessed Desember 23rd, 2015)
- [2] Beardsmore G, Rybach L, Blackwell D and Baron C 2010 A Protocol for Estimating and Mapping Global EGS Potential *Australian Geothermal Conference 2010* 319
- [3] Christie-Blick N and Biddle K T 1985 Strike Slip, Deformation, Basin Formation, and Sedimentation, *SEPM Spec. Pub* **37**
- [4] Clauser C and Huenges E 1995 Thermal Conductivity of Rocks and Minerals in Ahrens, T.J. ed., *Rock Physics and Phase Relations: A Handbook of Physical Constants* (United States : American Geophysical Union Shelf)
- [5] Curewitz D and Karso J A 1997 Structural Setting of Hydrothermal Outflow: Fracture Permeability Maintained by Fault Propagation and Interaction *Journal of Volcanology and Geothermal Research* **79** 149-168
- [6] Dolgorjay O 2009 Geochemical Characterization of Thermal Fluids from the Khangay Area, Central Mongolia (United States : Geothermal Training Programme United Nation University)
- [7] Effendi A C and Bawono S S 1997 *Peta Geologi Lembar Manado Sulawesi Utara Skala 1:250.000* (Bandung: Pusat Penelitian dan Pengembangan Geologi)
- [8] Giggenbach W F 1988 Geothermal Solute Equilibria; Derivation of Na-K-Mg-Ca Geoindicators *Geochim. Cosmochim. Acta* **52**
- [9] Mnjokava T T 2007 Interpretation of Exploration Geochemical Data for Geothermal Fluids from the Geothermal Field of the Rungwe Volcanic Area, SW-Tanzania (Tokyo : United Nation University)
- [10] Setiawan D I, Mulyadi E, Sundoro H 2012 Penyelidikan Pendahuluan Geologi dan Geokimia Daerah Panas Bumi Kabupaten Minahasa Utara dan Kota Bitung, Provinsi Sulawesi Utara (Bandung : Pusat Sumber Daya Geologi)
- [11] Siahaan E E, Soemarina S, Fauzi A, Silitonga T, Azimudin T, Raharjo I B 2005 Tectonism and Volcanism Study in the Minahasa Copartment of the North Arm of Sulawesi Related to Lahendong Geothermal Field, Indonesia *Proceedings World Geothermal Congress, Turkey*
- [12] Smith D L and Fishkin L 1988 S New Heat Flow Investigations in Arkansas. Contributions to the Geology of Arkansas, *Arkansas Geological Commission. Misc. Pub 18-C III*