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Structural Control on the Thermal Manifestations in South Sulawesi, Indonesia

Mochamad Nukman, Ade Anggraini, Pamungkas Yuliantoro

Geophysics Study Program, FMIPA, Gadjah Mada University. Sekip Utara, Yogyakarta 55284, Indonesia

E-mail: moch_nukman@ugm.ac.id

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ABSTRACT

A field campaign for updating thermal manifestations information and their structural pattern at South Sulawesi, shows that all (three sites) of geothermal prospects indicate that the discharging hot springs are associated with the faults that bounded the thermal system. The discharging thermal springs have temperatures range of 38-72ºC, mostly neutral pH, and a combined ~8 l/s of fluid discharge. The springs are located at the wrench fault system, i.e. NNE-SSW left lateral of East and West Walanae Faults, which are those in parallel relationship forming a depression zone. The field findings (fractures pattern, veins & fault breccia) show that fracture striking NNE-SSW is mostly occurring at the vicinity of discharging springs. With referring to E-S regional compression, the attitude of measured joint at three locations (Lejja, Sulili and Massepe), i.e. NNE-SSW and N-S, are likely a dextral or antithetic component of major sinistral fault of the Walanae Fault system. The earthquake swarms are occurring in the western part of the interaction fault zone, where the hottest springs (i.e. Sulili complex) are discharging. The cluster of deep earthquakes (EQ) at the northern part of West Walanae Fault, is indicating the possible location of a deep heat source associated with faults acting as conduits transferring heat to shallower levels. Among other thing, our findings show that not all geothermal fields in Indonesia are hosted in volcanic settings, but also controlled by crustal heat systems.

1. INTRODUCTION

Structural setting of an area that hosts a geothermal system plays a role to the distribution pattern of the thermal features, which later will affect our understanding of the pattern of thermal flow and the features of the geothermal system. The structural setting also can predict the occurrences of the system along the interest zone (Curewitz & Karson, 1997; Faulds et al., 2006). In broad views, the tectonic settings of Indonesia geothermal fields are of three types. From the west to the east of Sundaland, the geothermal systems are located: 1) along the volcanic arc Sunda (Sumatra-Java-Bali-Flores); 2) along the volcanic arc of Eastern Sundaland (i.e. Sulawesi); and 3) the Banda Arc (Maluku) (Radja, 1985; Hochstein & Sudarman, 2010). Those three types of volcanic arcs are controlled by two different subduction types, i.e. low angle oblique (for #1) and high angle orthogonal (for #2 and #3) (Hamilton, 1979). That somehow affects the occurrence of high temperature systems (>225ºC) along the arc.

In a slightly smaller scale the magma emplacement, as the heat source of the thermal system, mainly occurs in extensional or/and transtensional regimes. The conduit-zone opening of those systems allows the heat at depth be transferred to the shallower levels (Curewitz & Karson, 1997; Muraoka et al., 2010; Fauld et al. 2010). Most of the geothermal fields along the western and southern margin of Sundaland are hosted by such extensional (volcanic arc along Java to Flores) and transtensional regimes (in Sumatra arc, i.e. Sumatra Fault System). Volcanism located at the margin of pull-apart structures along 1500 km of the Sumatra Fault System, are related to several high temperature geothermal systems (Muraoka et al., 2010).

This paper aims to discuss and propose the structural control of the discharge of three complex springs in western South Sulawesi, where the absence of active volcanism (in South Sulawesi; Smithsonian Database, 2020) offers an opportunity to investigate the control of thermal system at a known discharging spring. Three springs among 18 spring's complexes in South Sulawesi are namely Lejja, Sulili, and Massepe, discharging at the zone where two prominent faults are present, i.e. East Walanae Fault (EWF) and West Walane Fault (WWF). The result of this work would contribute to elucidate one of several reasons about the absence of potentially high temperature geothermal systems in South Sulawesi, comparing to other parts of Sulawesi (central and northern arm). The work is based on field observations and measurements on structural geology, physical properties of hot springs (pH and temperature), available earthquake database (lab work), and some reviews on previous work.

Geological data includes joints and fractures measured at rock outcrops at the vicinity of the hot springs of Lejja, Sulili, and Massepe in the northern district of South Sulawesi. Updating locations and measuring the pH and temperature of the hot springs was also conducted in July 2019. Subsurface geological data was obtained from the available earthquake (EQ) dataset of the ISC (International Seismological Center) catalogue for 55 years (1963-2018).

2. REGIONAL TECTONICS

Sulawesi Island is situated at the eastern convergence margin of Sundaland plate against Eastern Indonesia blocks (Figure 1). The convergence margin is marked by the rifting of the Makassar Strait in the NNE-SSW opening trend. Three tectonic complexes occur at the eastern zone of the Makassar rifting, i.e.: 1) subduction among east Sulawesi Block against Eurasian plate, 2) subduction of Molucca sea against Eurasia plate, 3) collision of east Sulawesi block vs west Sulawesi block. These three tectonic events occurred in multiples phases (Silver et al, 1983) forming four arms and one neck that currently shape the Sulawesi Islands, i.e. North, East, South East, and South arms, and the Central Sulawesi neck (Hamilton, 1979). In subsequent order, the North arm of Sulawesi was/is formed by the subduction type #1 (Hamilton 1979; Hall and Wilson, 2000). This subduction is controlling the E-W trend of the volcanic arc from Toli-Toli to Manado City (in subsequently trend) and N-S trend of the Sangie Volcanic Arc.

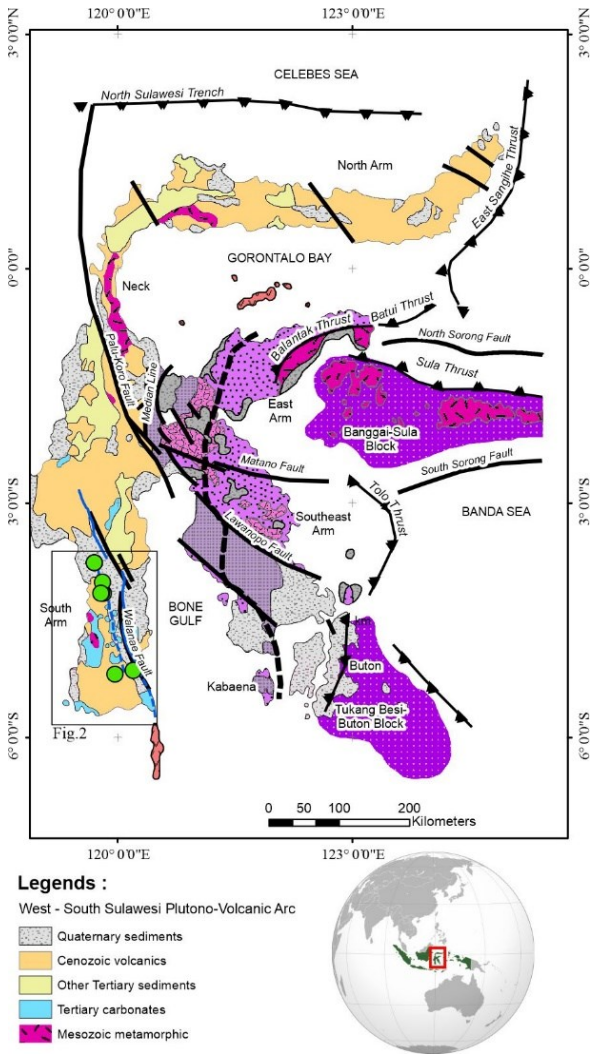


Figure 1: Tectonic Setting of Sulawesi (Hall & Wilson, 2000).

The uplift of the East and South Arms of Sulawesi was controlled by at least two continent-continent collisions in Early Miocene (Hall & Wilson, 2010) or even earlier in Neogen times (Wakita et al., 1996). The collision was a consequence of the westward movement of the microcontinent of north Papua Bird Heads through the large sinistral strike slip of South Sorong Fault (Hamilton, 1979; Wakita et al., 1996). The collisions then were arranged by the formed sinistral strike slip of Lawanopo Fault & Matano Fault at the SE arm, and sinsitral strike slip of the Palu-Koro Fault at the neck of central north Sulawesi. Several folding and thrust faults trending N-S also formed at the eastern arm and south arm (Sukamto, 1972).

The oldest rocks at the west arm of Sulawesi are sedimentary, ultramafic, metabasites, and metapelite of Jurassic to mid-Cretaceous ages, exposed at Bantimala and Barru (Sukamto 1982, 1982; Wakita et al., 1984; Parkinson et al., 1998). The distribution of volcanic rocks of Miocene age (e.g. Camba Fm) trending N-S along the western part of South Arm, suggests melting of subducted slab (Dhuri and Sudjatmiko, 1974).

3. THERMAL MANIFESTATIONS IN SULAWESI

Thermal features in Sulawesi widely spread in all of the arms. Bemmellen (1949) and Radja (1970) were two of several first attempts to classify the distribution of hot springs in the four arms of Sulawesi. Temperature of the springs and their regional, and some local, structural controls were described. A recent resume of geothermal potential in Sulawesi is described by Idral (2010) presenting a list of prospects containing their updated locations, temperature, estimated thickness of reservoir, and heat potential. Location of some springs at South Sulawesi were missed in those tables that were used in this current work. In this paper, the current updated locations are listed in Table 1.

The Linau caldera is the most extensive thermal manifestation at the NE of north arm Sulawesi. The well-known geothermal field of Lahendong is a high temperature field type, which has been producing 120 MWe (Utami et al., 2020). The subduction from the east and north at this north arm of Sulawesi produces the late Pleistocene–Holocene volcanism. From a structural viewpoint, a right step over a NE-SW sinistral fault at the vicinity of Linau Lake might control the systematic permeability pattern in Lahendong thermal system (Brehme et al., 2014).

Active volcanism is absent in the mainland neck of Sulawesi and Eastern Sulawesi. The only active volcanism is the stratovolcano Mt. Colo, situated at the Gulf of Tomini in the Una-Una Island (Figure 1), but there is no report regarding its geothermal potential. Hot springs at the Sulawesi neck (central) are associated with the pull-apart structure of Palu-Koro left lateral fault, with no volcanism

associated. T-springs complex, namely Pulu, Mapane, Kabuliburo, Sibalaya, Lima, Walatama and Simoro, are discharging at the east and south-west end of Palu Graben, with temperature range of 40–95ºC (Bakrun et al., 2003).

Left lateral fault setting with poorly defined stepover occurs at the Lawanopo fault, located at the east arm of Sulawesi, where there is a low temperature spring (T. max. 47ºC) with neutral pH widely spread in 1-1.5 km along the coast (Nukman et al., 2019). The hot springs are characterized by unboiling springs. The hot springs in the neck and the eastern arm of Sulawesi are not related to active volcanism.

3.1. Thermal manifestations the central-southern part of South Sulawesi

The are 18 warm springs listed in the previous report by Idral (2010) located at South Sulawesi. We visited the thermal features located at the central and southern part of South Sulawesi's arm. There are three thermal areas central-west of Sulawesi south arm, namely Lejja, Sulili, and Maseppe springs, oriented from north to south (Figure 2).

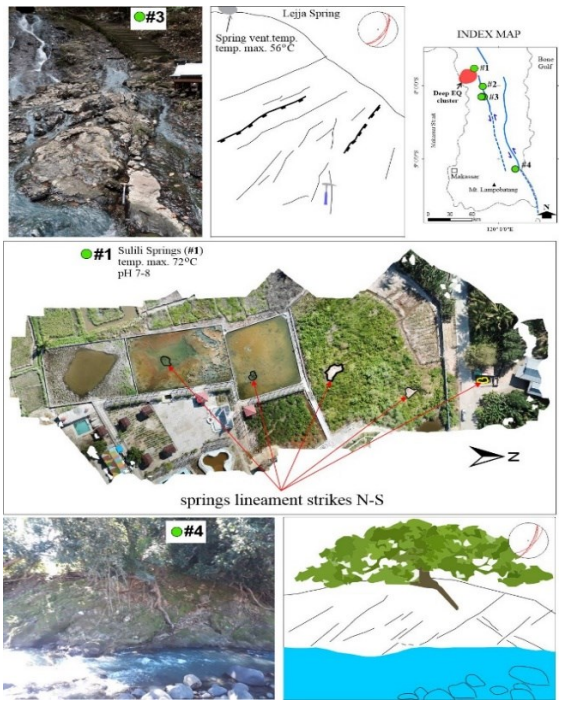


Figure 2: Outcrop of fracture on autoclastic lava: #3. Lejja springs, #1 Sulili springs, #4 Vicinity of Wapalae spring. Note : the Wapalae spring is located at southern part of East Walanae fault (in prep,)

The highest temperature is 72ºC measured at Sulili springs, which is 20ºC higher than previously measured by Idral (2010), with neutral pH (Table 1). Four warm and hot spring vents are aligned in N-S trend (Figure 2 #1), the highest site is associated with sulfur odor and kaolinite. The springs are located at flat topography and low elevation (21–22 masl) in recent alluvial and colluvial deposits, known as Walanae depression.

Toward 40 km south from the Sulili springs, we observed a hot spring with 65ºC of temperature, pH 7, fluid flow rate of ~1 l/s, and associated with silica sinters and sulfur, namely Massepe springs. This Massepe spring wasn't reported by Idral (2010), but its updated coordinates are included in Table 1. The hot spring of Massepe is discharging out at fractured breccias, striking in NE-SW. Due to limited time, we didn't visit the other Massepe springs.

Lejja Spring is located 20 km toward south of Massepe springs (188 m.a.s.l). Large discharge rate (3-5 l/s) of ~56ºC and pH 6-7 of thermal water is used as a public spa by the locals. Fractured autoclastic lava (andesite-basaltic in composition) striking NNE-SSW controls the discharge pattern of the springs. Opening fractures are in rage of 5-15 cm with 40-60 cm of fracture spacing. Cooling fractures are somehow cut by the tectonic fractures intensively.

At lower elevation than Lejja, a strongly altered rock, possibly of pyroclastic origin, crops out at the road cut (112 m.a.s.l). This altered rock is associated with zeolite, sparsely distributed at the outcrop. There are traces of sulfur near the vein. The measured vein orientation is N-S and NE-SW, indicating NNE-SSW of principal maximum stress. At lower elevation (i,e 108 m.a.s.l) shear joint striking NNE-SSW forming fault breccia cropped out at the western side of Lejja spring, also consisting calcite vein. Thess shear joints indicate a left lateral movement. During our trip, Waepelae spring located at the East Walanae fault, far southeast of Lejja-Sulili-Massepe springs (Figure 3 & 5), was also visited. The spring has temperature 56ºC, 6 of pH, with ~ 0.1 l/s of fluid discharge.

3.2 Seismicity at south arm of Sulawesi

There were 1514 seismic events recorded in various magnitude occurred in South Arm of Sulawesi (ISC catalogue used in this work). The event of Mw 7,5 Palu earthquake on September 28, 2018, followed by a series of strong aftershocks, confirms that the Palu-Koro is an active fault. However, there are no reports that this event triggered some activity of Walanae Faults. A deep cluster of earthquakes

(deduced from the 55 years catalog of recorded EQ) is located at the end of West Walanae Fault (Figure 3). Other seismic events are scattered at this South Arm of Sulawesi, but still apparently related to the faults of West and East Walanae.

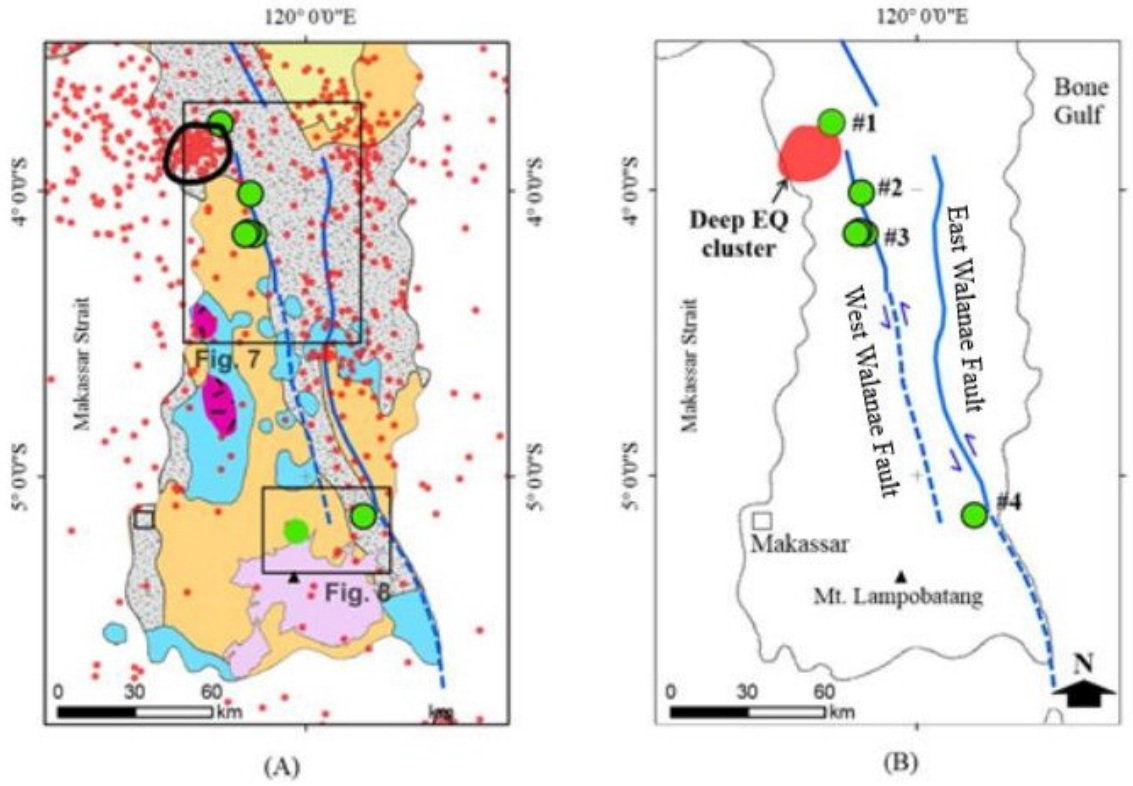


Figure 3: Seismic events at South Sulawesi (from earthquake catalogue of ISC). #1 Sulili springs, #2 Massepe springs, #3 Lejja springs, #4 Waepelae spring.

Table 1: Database of visited hot springs at South Sulawesi: Lejja, Massepe, and Sulili springs.

No	Site Name	X (lat)	Y (long)	Z (m.a.s.l)	Fracture Bearing (dip.dir/dip)					Remarks
1	Lejja Outcrops	119.8192	-4.1530	112	290/68, 150/65, 263/70, 265/68,263/70					pyroclastic, oxidized veins
2	Lejja Outcrops	119.8004	-4.1466	109	110/70, 115/85, 110/75, 115/80					fault brecciation on andesite-basaltic
						Temp. (ºC)	pH	Flow Rate (1 l/s)	TDS (mS/cm)	
3	Massepe Springs	119.8069	-4.0117	24	-	65	7	1	5.3	silica sinters, sulphur
3	Lejja Springs	119.7880	-4.1528	188	124/65, 126/ 58, 122/58,102/52	56	8	3	0.3	fractured volcanic breccia
3	Waepelae - Kampala Spring	120.2022	-5.1413	37	135/66, 116/66, 116/74,115/75	56	6	0.1	3.9	small bubles gas observed, dicharging out from the river clift
3	Sulili Springs #1	119.7022	-3.7661	21	Trend in N-S	39-40	7	0.1	3.5	kaolinite
3	Sulili Springs #2	119.7021	-3.7657	22		70	7	0.1	5.1	kaolinite
3	Sulili Spring #3	119.7021	-3.7652	21		48	8-Jul	0.5	3.59	buble gas, no kaolinite
3	Sulili Spring #4	119.7021	-3.7655	21		72	7	0.2	4.5	kaolinite

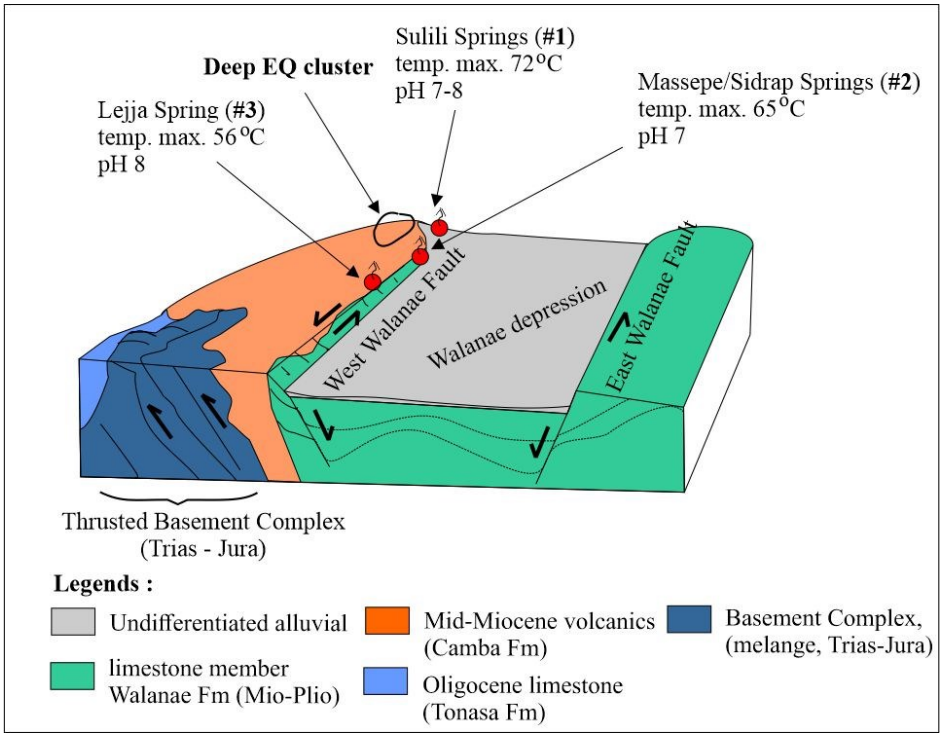


Figure 4: Schematic diagram (unscaled) of geology framework at the vicinity of discharging springs at South Sulawesi. Geological information is based on Sukamto (1982).

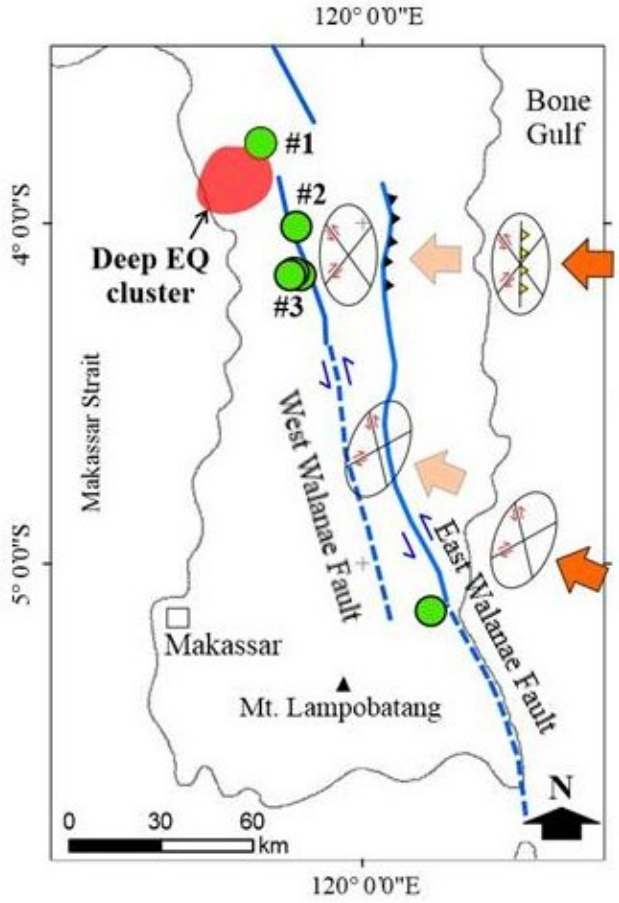


Figure 5: Strain ellipsoid model along Walanae Fault System, based on measured structural data and also referred to geodetic measurement of Sarsito et al. (2018)

4. DISCUSSION

The current regional maximum stress in the South Arm of Sulawesi is reported to be E-W, as derived from the measured kinematic along Walanae Faults, based on geodetics (Sarsito et al., 2018). We consider that this E-W regional stress varies along the Walanae faults, as the kinematics of the faults are sinistral fault system in NNW-SSE, and almost N-S at the northern part of East Walanae (Figure 5). Geodetic measurements show that the kinematic of the Walanae Faults has two strain partitions, i.e. sinistral strike slip at the southern part, and a kinematic couple of sinistral and thrust kinematic at the northern part (Sarsito et al., 2018). This different strain partition along the same fault system could be due to the change of the fault strikes. The southern part of East Walanae Fault strikes NNW-SSE, which is at optimum angle to slip if the maximum stress is NW-SE (Figure 5). The northern part of East Walanae Fault strikes N-S, which is not at the optimum angle to slip, but the stress will generate more thrust fault (referring to relationships of stress and faulting of Anderson, 1951)

The East Walanae Fault has consistent attitude than the western one, i.e. striking NNW-SSE. The E-W maximum stress will impose to the NNW-SSE fault plane and triggering slip in strike slip pattern, i.e. sinistral, rather than thrust fault. This strike slip system will generate opening zones and control permeability more than a thrust fault system. With referring to regional E-S compression, however, the attitude of measured joint at 3 locations (Lejja, Sulili and Waepelae) i.e. NNE-SSW and N-S (Figure 3) indicates the antithetic component of a major sinistral fault of Walanae Fault system, which is still compatible to accommodate the current regional stress. The significant of Waepelae is that a structural outcrop was exposed and measured (listed in Table 1) in form of joints striking NE-SW. This structure trend shows the antithetic component of the sinistral of East Walanae Fault.

The absence of young or dormant volcanism at the northern arc of South Sulawesi, where are located the hot springs (up to 72^{o}C), suggests that the heat source is located at a very deep depth. This seems to be confirmed by the location of the EQ cluster of seismic events with magnitude (Mw) 4.0 – 4.9, occur at estimated depth 5 km (12 events), at depth 10 -25 m (~ 20 events) at 30 km (26 event). This EQ cluster is possibly due to the fault activity. In association with the occurrences of thermal manifestations at the surface and the absence of young volcanic, this shallow fault might also be deeper than we thought, which will allow deep crustal heat transferring to the shallower level.

5. CONCLUSION

The thermal system in South Sulawesi is classified as non-volcanic system, supporting previous work by Radja (1971), Hochstein & Sudarman (2008), Idral (2010). It is a structural controlled system of a deep heat source, since the faulting system is clearly defined based on field observation. The study of structural geology at this area (at the vicinity of Sulili spring, the hottest spring) is challenging, since the outcrops is strictly exposed at the depression area where the rock outcrops is limited.

6. ACKNOWLEDGEMENTS

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REFERENCES

Anderson, E.M.,: The dynamic of faulting and dykes formation with applications to Britain. Edinburg. London, 1951.

Brehme, M., Moeck, I., Kamah, Y., Zimmermann, G., Suter, M.: A hydrotectonic model of geothermal reservoir-A study in Lahendong, Indonesia, Geothermic, **51**, 2014, 228-239.

Curewitz, D., Karsom, J.A.: Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction, Journal of Volc. Geoth. Res. 79, 1997, 149-168.

Dhuri, Sudjatmiko, 1974 : Geologi Lembar Majene dan Palopo bagian barat Sulawesi Selatan, Direktorat Geologi, Bandung.

Faulds, J., Moeck, I., Drakos, O., Zemach, E.: Structural assessment and 3D geological modelling of the Brady's geothermal area, Churchill country (Nevada, USA): A preliminary report, Proceeding, Thirty Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, California. SGP-TR-188.

Hall, R., Wilson, M.E.J.: Neogene sutures in eastern Indonesia, Journal of Asian Earth Sciences **18**, (2000), 781-808.

Hamilton, W.: Tectonics of Indonesian region. USGS Professional Paper **1078**, 1979, 345pp.

Hochstein, M.P., Sudarman, S., 2008. History of geothermal exploration in Indonesia, Geothermics **37, 2008.** 220-226.

Idral, A.: Potency of Non Volcanic Hosted Geothermal Resources in Sulawesi-Indonesia, *Proceeding,* World Geothermal Congress, 2010, 25-29 April, Bali, Indonesia.

_____ISC catalogue : International Seismological Centre, http://www.isc.ac.uk/iscbulletin/search/catalogue/ (downloaded in 2019).

Muraoka, H., Takahashi, M, Sundoro, H., Dwipa, S., Soeda, Y., Momita, M., Shimada, K.: Geothermal Systems Constrained by the Sumatran Fault and Its Pull-Apart Basins in Sumatra, Western Indonesia*, Proceeding*, World Geothermal Congress, 2010, 25-29 April, Bali, Indonesia.

Nukman, M., Suryanto., Kurniawan, A., Alfiansyah, D.: Why do we consider travertine? Reviews on travertine of Sipoholon (Tarutung), Sumani (Singkarak), & Wawolasea Thermal Area, Indonesia, *Proceeding,* 8th ITB International Geothermal Workshop, Bandung, Indonesia/

Parkinson, C.D.: Emplacement of the East Sulawesi ophiolite; evidence from subophiolite metamorphic rocks, Journal of Asian Earth Sciences 1998, 13-28.

Radja, V.T.: Geothermal energy prospects in South Sulawesi, Indonesia, In : U.N. Symposium on the Development and Utilization of Geothermal Resources, Geothermics**, Special Issue 2**, pp. 136-149,

Radja, V.T. : Status of geothermal energy development in Indonesia up to year 200. GRS Trans **9**, 487-497.

Sarsito, D.A., Susilo, S., Rudyawan, A., Muhammad, N.A., Andreas, H., Pradipta, D.: Walanae fault kinematic deduced from geometric geodetic GNSS GPS monitoring, E3S Web of Conferences **94**, 04008, 2019, ISGNSS. (https://doi.org/10.1051/e3econf/20199404008).

Smithsonian Institution : Natural Museum of Natural History, Global Volcanism Program, volcano list/database: https:/volcano.si.edu/ (downloaded in 2020).

van Bemmelen, R.W.: The Geology of Indonesia. Government Printing Office, Nijhoff, the Hague **2nd**, 1979, 732pp.