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Regional Characterization of the Sumatran Geothermal Systems, Indonesia

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ABSTRACT

Coexistence of the dextral strike-slip Sumatran Fault System and subduction-related volcanic arc forms the western half of the island, while the eastern part is dominated by the Tertiary sedimentary basins. Subdivision of the arc into three volcano-tectonic domains is the basis for further characterization of Sumatran volcanic geothermal systems. Compilation of fault kinematics, volcanic facies, and associated geothermal systems is conducted for the Southern Domain where volcanism is concurrent with strike-slip faulting. Series of conceptual models are proposed to represent the influences of tectono-volcanism for geothermal system. Toba Caldera, a large volcanic region with rhyolithic volcanism, dominates the Central Domain. In Northern Domain the volcanism is shifted away from the Sumatran Fault which then affect the nature of associated geothermal systems. Heat flow values in the Central Sumatra Basin are higher compared to average values for continental crust or even to the other two nearby back-arc basins which share a similar sedimentation history. 3D numerical modelling of the lithospheric-scale temperature distribution is conducted to identify the controlling factors of that contemporary elevated heat flow. Lateral variation due to amalgamation of several tectonic terranes is incorporated into the model.

1. INTRODUCTION

Current tectonic setting of the island of Sumatra is oblique convergence, as the Indo-Australia oceanic plate is obliquely subducted beneath the island. It leads to volcanism along the backbone of the island which coexists with a regional dextral strike-slip fault system, the Sumatran Fault. However, the island has experienced long history of plate interaction since Late Palaeozoic, from collision of microplates, rotation, to lithospheric-scale transcurrent deformation (Hall, 2002; Barber and Crow, 2005; Zahirovic et al, 2014). Obviously, each major event during those long and complex deformation history leaved tectonic sutures and basement structures as footprint. Those regional discontinuities then subsequently influence the much younger geologic features, or reactivated under current tectonic setting. Therefore, in addition to the young geologic features i.e. the Sumatran Fault and the Quaternary volcanic centres, the pre-Quaternary inherited basement structures and older magmatic-volcanic zone should be also considered in characterizing the geothermal systems of the island.

This paper is intended as an extended abstract of relating the deep-rooted crustal discontinuities with the occurrence and characteristic of the geothermal systems in Sumatra. It highlights that the pre-Quaternary inherited basement structures influence the latter much younger structures, which then eventually control the geothermal systems. The geothermal systems which are discussed in this paper consist of both the convective volcanic-related and the fault-controlled systems along the Sumatran arc, the conductive systems hosted in the Sumatran sedimentary basins.

2. REGIONAL FRAMEWORK

Since the Late Neogene, the tectonics of Sumatra is dominated by oblique convergence between Indo-Australian oceanic plate and Sundaland, a promontory of Eurasia (Hall, 2002; Barber and Crow, 2005) (Figure 1). It leads to a strain partitioning (McCaffrey, 2008), which the compressive stresses influence the deformation front in the subduction system, the accretionary wedges, and inland compressive structures, while the transcurrent component is accommodated by crustal-scale strike-slip fault system. The inception of the strike-slip deformation i.e. the Sumatran Fault System, was closely associated with the opening of the Andaman Sea to the northwest and increasing subduction obliquity due to the island's clockwise rotation since Mid-Miocene (McCarthy and Elders, 1997).

The overriding Sundaland plate is composed of several microcontinents that were amalgamated during the Palaeozoic and Mesozoic (Pulunggono and Cameron, 1984; Metcalfe, 2000; Barber and Crow, 2003). The geologic inheritances in form of pre-existing basement structures and suture zones then introduce heterogeneities in the overriding Sundaland plate that strongly affect the Sumatran Fault. Some of the basement structures might had been formed prior to emplacement of related tectonic block to Sundaland, hence their orientation can be discordant to the sutures which developed later. However, apparently most of the inherited structures were developed during the amalgamation to Sundaland, either through orogenic phase due to subduction-collision, such as Bentong-Raub Zone (Metcalfe, 2000) and Woyla Suture (Pulunggono and Cameron, 1984), or by regional transcurrent mechanism as like Medial Sumatra Tectonic Zone (MSTZ) (Hitchison, 1994). Consequently, the orientation of the inherited structure is parallel or sub-parallel to the sutures, or at least still in frame of the principle stress directions during the convergence.

The heterogeneities exist in the subducting oceanic plate as well. The Investigator Fracture Zone is a remnant of transform fault that forms a N-S ridge which currently behaves as an indentor, as well as a weak zone. This transform fault separates the younger and rheologically stronger oceanic lithosphere to the west, from the inactive spreading centres that have been weakened by serpentinization (Jacob et al., 2014). These inactive spreading centres tend to resist the subduction and create inward deflection of the trench from a regular arc shape (Figure 1). Seismic tomographic models show that the subducted ridge also lead to the tearing of the slab (Hall and Spakman, 2015), separating steeply subducting plate in the southeast from a more gently dipping plate in the northwest. The slab tearing provides a channel for mantle flow which subsequently impacts the magmatism benath and within the overriding plate significantly (Koulakov et al., 2016). At the same time, the differences in subduction dip angle is responsible for the different volcanic arc location with respect to the Sumatran Fault (Figure 1).

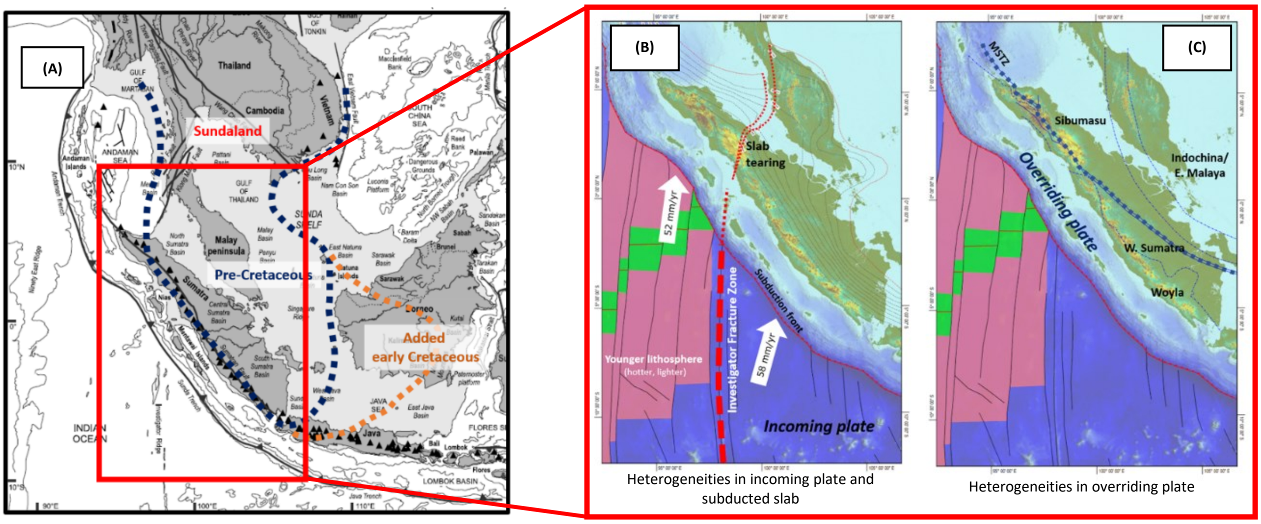

Figure 1: Tectonic setting of Sumatran subduction systems; A. tectonic blocks were amalgamated in Pre- and Early-Cretaceous (modified from Hall, 2011); B. Heterogeneities in incoming plate and subducted slab; note the inward deflection of trench line, and slab tearing which separates southern step and northern gentle subduction; green is inactive spreading centres, grey dashed lines are slab contour; C. Major tectonic blocks build Sumatra, and its suture; MSTZ is Medial Sumatran Tectonic Zone; narrow band between Indochina and Sibumasu is Bentong-Raub Zone (Barber and Crow, 2005)

The Sumatran Fault System (Figure 2A) is a NW-SE regional dextral strike-slip fault, which runs along the island and parallel to the trench, linking the opening of the Sunda Strait in its southern end to the spreading of the Andaman Sea in its northern far end. It is highly segmented with many irregularities along the fault (Sieh and Natawidjaja, 2000; Burton and Hall, 2014), and strongly controlled by pre-existing basement structures (McCarthy and Elders, 1997). Local transtensional or transpressional deformation accommodates the strain between fault segments, or where the fault trace bends. The Sumatra Fault has a close proximity to the subduction-related Quaternary volcanic centres along most of its length. Sieh and Natawidjaja (2000) suggest there is no relationship between young volcanoes and the fault, based on a random distribution of the volcanoes with respect to the surface fault traces. However, other authors (Bellier and Sebrier, 1994; McCarthy and Elders, 1997; Muraoka et al., 2010) proposed an interplay between volcanism and magmatism, and strike-slip faulting. Together, the strike-slip fault system with its subsidiary structures, and the Quaternary volcanic centres form the arc with distinct elevated morphology, known as Barisan range, along most of the western half of the island.

3. GEOTHERMAL SYSTEMS IN THE VOLCANIC ARC

3.1. Volcano-tectonic subdivision of the Sumatran Arc

Based on the spatial relationship between the Sumatran Fault System and Quaternary volcanic centres the Sumatran arc is divided into three domains (Sutrisno et al., 2019, in prep.). This tectono-volcanic subdivision (Figure 2B) resembles the structural domains of Sumatran Fault proposed by Sieh and Natawidjaja (2000). Volcanic geothermal systems in each tectono-volcanic domain have distinct plays (based on Moeck, 2014, classification), therefore the proposed subdivision is essential for further geothermal system characterization.

The Northern Domain is characterized by the shifting of volcanic centres away from the trace of the Sumatran Fault toward the basin to the north. The volcanism in this domain was interpreted as the product of southward subduction of the Andaman oceanic plate beneath Northern Sumatra (Gasparon, 2005). However, images of the subducted slabs beneath Sumatra from seismic tomography disapprove this interpretation (Hall and Spakman, 2015), they show that the shifting of volcanism is related to a gentler subduction dip angle. Volcanic centres have an isolated distribution on top of a fold-and-thrust belt composed of Pre-Tertiary basement units and Tertiary formations. This setting implies that most geothermal systems occur in the flank of the volcanic centres with limited influence from the Sumatran Fault, except in the northern end of this domain where the volcanism shifts back toward the Sumatran Fault and then influenced by the conjugate fault system within the Sumatran Fault.

Toba Caldera dominates the Central Domain. Tearing in the subducting slab provides pathway to channel the upward flow of the asthenosphere It leads to a voluminous magmatism at the base of lithosphere and within the crust as indicated by low velocity zone (Koulakov et al., 2016) and petrologic data (Gasparon and Varne, 1995). Recent regional 2D magnetotelluric survey also confirms the occurrence of large intra-crustal magma chambers beneath Toba, represented by deep low resistivity body between 10-15 km below sea level (Sutrisno et al, in prep.). The regional uplift around Toba Caldera may also be related to the thermal expansion of shallow magma accumulation beneath the region. In this domain geothermal systems are associated with resurgence volcanism around the caldera margins.

Coexistence of the Quaternary volcanic centres and its extrusive rocks with the Sumatran Fault System marks the Southern Domain. Some volcanic centres, both active and inactive, are located close to the main strike slip fault strands, transtensional, or transpressional area between segments of the Sumatran Fault. This spatial proximity between the regional fault zone and volcanism influences the geothermal systems within.

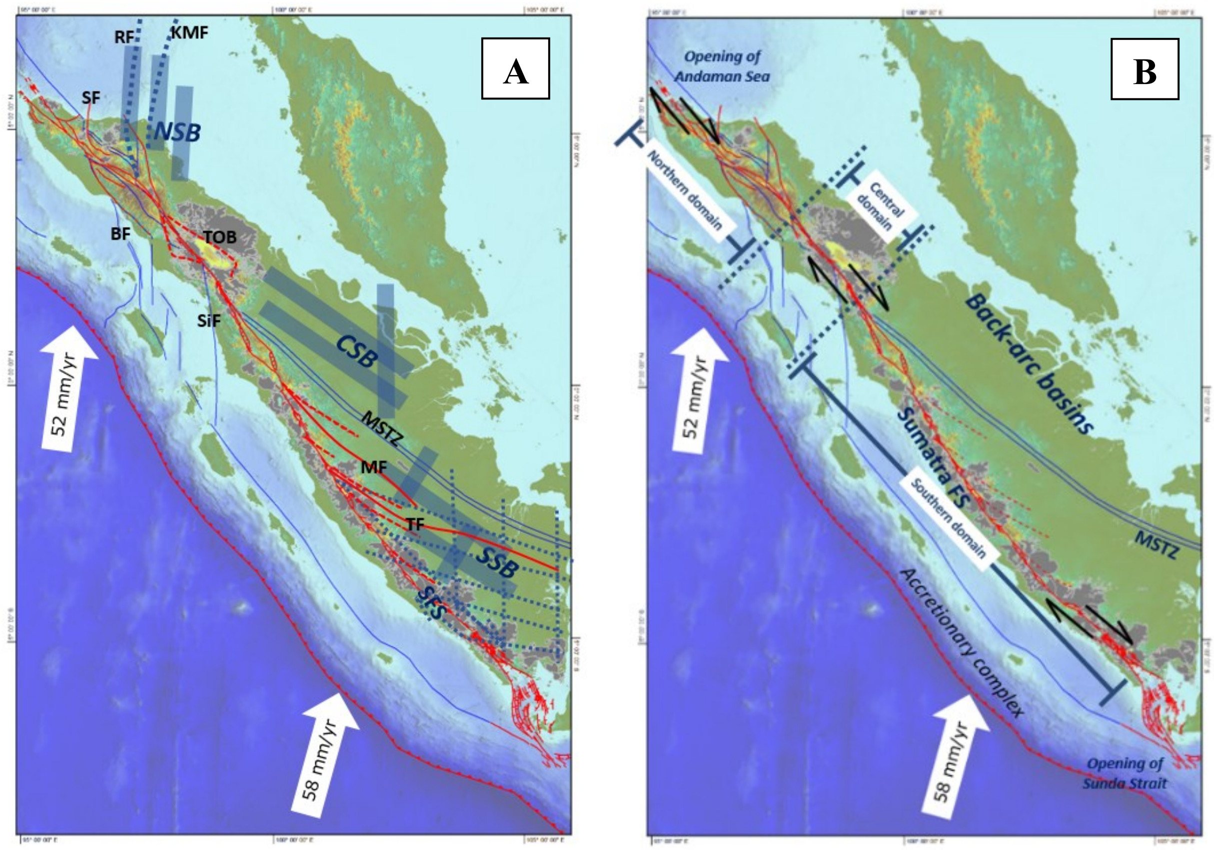

Figure 2: A. The Sumatran Arc consists of the Quaternary volcanic arc (grey shaded area) and the Sumatran Fault System (SFS) (red lines); note the occurrence of series of WNW-ESE splays (red dashed lines), regional lineaments (blue dotted lines) (Pulunggono, 1992), structural trends in the basins (blue shaded bands); RF: Renong Fault, KMF: Klong Marui Fault, BF: Batee Fault, SF: Samalanga Fault, SiB: Siberut Fault, TOB: Toba Caldera, MF: Musi Fault, TF Takung Fault, NSB: North Sumatra Basin, CSB: Central Sumatra Basin, SSB: South Sumatra Basin, MSTZ: Medial Sumatra Tectonic Zone; **B.** Tectono-volcanic subdivision of the Sumatran Arc

3.2. Inherited basement structures

The fabric of basement structures in the Northern Domain is dominated by the N-S trend (Situmorang and Yulihanto, 1985), which slightly curved to the orientation of the Sumatran Fault in the intersection with the fault system. The N-S basement structures are continuation of the Late Cretaceous to Paleogene Ranong Fault and Klong Marui Fault in the southern Thailand (Sautter et al, 2017). These N-S structures are now represented by Samalanga Fault and Lokop-Kutacane Fault in the north western side of the Sumatran Fault, and Batee Fault and Siberut Fault in the south western side (Figure 2A).

There is a possibility that Toba Caldera was controlled by a currently inactive pull-apart basin (Bellier and Sebrier, 1984). The orientation of master faults of the inactive Toba transtensional region are parallel with the dominant orientation of structural grain in the nearby Central Sumatra Basin (CSB) in the southeast (Figure 2A). Dominant orientations of the inherited basement structures in the Southern and Central Domain are WNW-ESE and NW-SE. Those structural fabrics are manifested by the MSTZ, the Late Cretaceous Takung Fault and Musi Fault (Barber and Crow, 2005), the structural trend of the Central Sumatra Basin (Moulds, 1989), and the regional lineaments in the South Sumatra Basin (Pulunggono, 1992). Pulunggono (1992) delineated the regional WNW-ESE lineaments based on the SAR (synthetic aperture radar) interpretation. Combining the structures with the distribution and age of nearby granitoid intrusions, Pulunggono (1992) then interpreted origin of the structures, and its N-S conjugate pair, as remnant of retreating subduction zone from Upper Jurassic to Upper Cretaceous. Intersection angle between the basement structures and the younger Sumatran Fault System are 20-30°, with the tendency of gradual decreasing from the south to the north as the Sumatran Fault System become sub-parallel to the nearby basement structures. Those WNW-ESE and NW-SE basement structures in the vicinity or intersect the Sumatran Fault then reactivated as fault splays (Figure 2A). Unlike Maruoka et al. (2010) who suggests that ellipsoid volcanic cluster around the fault system had been developed under clock-wise rotation, it is proposed that the splay systems subsequently control the occurrence of volcanic cluster around the Sumatran Fault.

Most of the segmentations in the Sumatran Fault System are associated to an intersection with the older basement structures, oriented WNW-ESE and NW-SE in the Southern and Central Domain, and N-S in the Northern Domain. The segments of the Sumatran Fault are connected by either a transtensional or transpresional zone due to overstepping fault segments or fault bends. There are 14 intra-arc pull-apart basins associated with transtensional deformation, and 2 restraining bends due to transpressional deformation along the Sumatran Fault (Sutrisno et al, 2019).

3.3. Intra-arc transtensional deformation

The pull-apart basins tend to be wider towards south eastern-ends. It is observed clearly in Hululais, Sungai Penuh and Muaralabuh Basin (Figure 3). The width of these basins range from 3 km in its NW-end, then widen up to 7-10 km in the SE-end. Considering the irregularity of its shape, it is difficult to apply shape classification proposed by Mann et al. (1983). The size of the pull-apart basins varies from less than 30 km^2 to as large as 500 km^2, with average value is 140 km^2. The depth of these basins ranges from 800 m to more than 2000 m, although available data are very limited to assess exactly the overall depth range. More than half of those basin have length to width ratio (L/W) much larger than 3, the general value for L/W for pull-apart basin as proposed by Aydin and Nur (1982). Therefore, most of the pull-apart basin have elongated shape resembles rhomboidal to stretched rhomboid in classification of Mann et al (1983). The most extreme cases are Ranau (L/W= 0.8) and Sarulla (L/W=14). Small value of L/W ration in Ranau Basin, as well as its peculiar shape which is too perpendicular to the master strike-slip faults raise uncertainty whether it is really a pull-apart basin or mere a collapse caldera which later intersected by strike-slip faulting. Sarulla Basin is in the other extreme side with uncommonly large L/W. It might indicate that this pull-apart basin is very narrow and extensively stretched.

Cross-basinal faults are observed in several pull-apart basins. In Ulubelu, the NW-SE cross-basinal fault acts as permeable pathway for geothermal convective flow and intersected by several productive wells. In Suwoh, the same structure is interpreted from a river flows inside the basin. In Gunung Talang, cross-basinal fault separates two depression lakes. The basins with observed or interpreted cross-basinal fault consistently have small L/W value. It is in agreement with van Wijk et al. (2017) who, based on numerical modelling, concluded that elongated pull-apart basin with large L/W is less likely to form cross-basinal fault which connect the tip of two over-stepping master faults.

In Muaralabuh, the conceptual model which are constrained by the wells and then confirmed by the gravity anomalies, indicates the occurrence of two sub basins separated by a horst in between (Mussofan et al., 2018). This is in agreement with the results from analogue modelling for transtensional setting where the master faults are slightly oblique to the transcurrent movement (Wu et al., 2009).

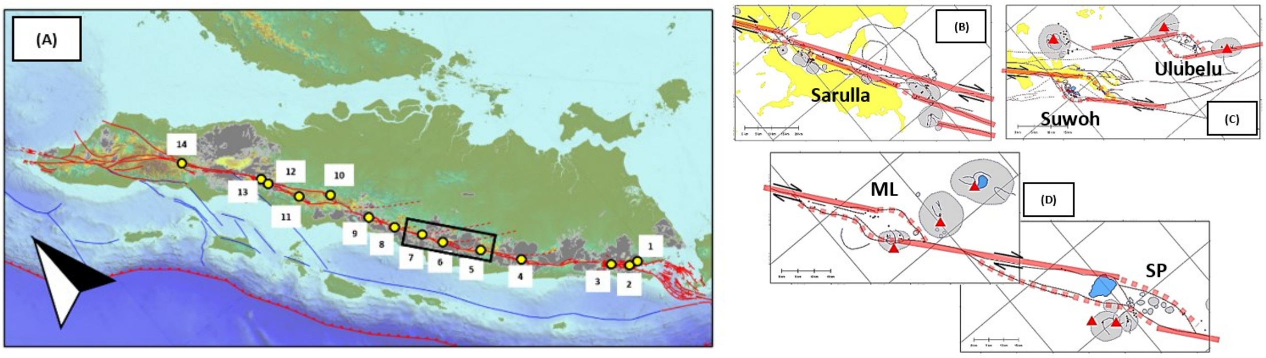

Figure 3: **A**. Location of pull-apart basins along the SFS; Ulubelu (1), Suwoh (2), Ranau (3), Talangkemang (4), Hululais (5), Sungaipenuh (6), Muaralabuh (7), Gunung Talang (8), Singkarak (9), Rao Graben (10), Panyabungan Graben (11), Sarulla (12), Tarutung (13), and Kutacane (14); **B.** Sarulla, an elongated basin with anomalously high L/W; note that it is the highest known geothermal potential in Sumatra; **C.** Ulubelu and Suwoh basin which have small L/W; **D.** Muaralabuh (ML) and Sungaipenuh (SP) with irregular basin shapes as it is widen in SE side; grey circles is stratovolcanoes with red triangle represents eruption centres

3.4. Intra-arc transpressional deformation

At least two transpressional deformations in form of restraining bend are observed in the Sumatran Arc; the Semendo (Sutrisno et al., in prep.) and much smaller Gunung Gadang (Muraoka et al, 2010). The Semendo initially is interpreted as a caldera due to the circular appearance of several domes. Absence of widespread ignimbrite refutes this interpretation (White and Dyaksa, 2015). It is speculated that prominent topographic high in the Semendo volcanic clusters, which is formed by the uplift of positive flower structure and the Quaternary volcanism on top of it subsequently led to the gravitational sliding and deforms nearby sedimentary strata. It is manifested by arcuate thrust-fold belt in Muara Enim, where Gumai Formation acted as decollement, as suggested by Pulunggono (1986).

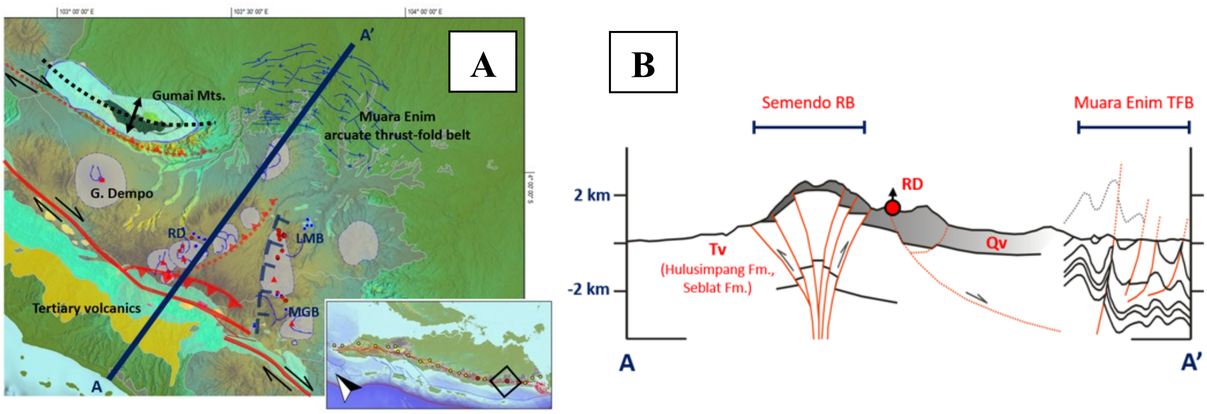

Figure 4: **A**. Location of the Semendo restraining bend; RD: Rantau Dedap, LMB: Lumutbalai, MGB: Margabayur; B. Conseptual cross-section along the line A-A', Muara Enim thrust-fold belt is from Pulunggono (1986)

3.5. Associated geothermal systems

All fumaroles and associated sulfate hotsprings, which represent the upflow are located in the flank of volcanic centres or in the vicinity of small monogenetic domes. In contrast, thermal manifestations along the master faults of a pull-apart basin are typically chloride hotspring, which represent the outflow, or dilute warmsprings which represent either distal outflow or separate deep-circulating system. It is worth to highlight that no thermal manifestations appear in the middle of the basin without any associated fault. All of them are located either in the flank of nearby volcanic centres or along the master strike-slip faults or normal faults outlining the basin.

Van Wijk et al (2017) proposed that elongated pull-apart basins with large L/W and overlapping master faults are least likely to form cross-basinal fault. As consequence, the basin progresses continuously and experiences significant crustal thinning which eventually leads to crustal rupture. Commonly a crustal thinning is associated with elevated heat flow inside the basin. However, significant differences in heat flow between normal and elongated basins with large L/W is not observed along the Sumatran Arc. The heat flow is qualitatively deduced from the occurrence of thermal manifestations, how rigorous they are, or by the subsurface temperatures. Indeed, Sarulla, the basin with extremely high L/W has the highest known geothermal potential in Sumatra, but these geothermal potentials are not distributed evenly within the pull-apart basin. The most prospective geothermal system within Sarulla is Namora-i-Langit, and the domes slightly outside the basin control it. The other systems within Sarulla basin, such as Silangkitan and Donotasik has lower geothermal potential, and lower temperature as well.

Instead of providing porous and permeable stratigraphic units, clay rich basin fill deposits tend to have low primary porosity and permeability. Similarly, basin-fills deposits with substantial volcanic influx, and dominated by competent lava and thick welded ignimbrite, also have low primary porosity and permeability. However, these competent units, which are composed by central to proximal volcanic facies can sustain permeable damage zone around intersecting faults. Conversely, clay rich units tend to form impermeable cores within intersecting faults (Rowland and Sibson, 2004 after Caine et al., 1996). This may explain the absence of thermal manifestation in the middle of the clay rich basin due to the lacks of vertical permeability.

The interior arrangement within the pull-apart basin is important as it creates compartmentalization within the basin. Cross-basinal fault can act as permeable pathway as in Ulubelu, or may act as compartment, as it separates eastern (Srirejo) and western geothermal system (Kalibata) in Suwoh basin. Basement high or horst in Muaralabuh provides permeability for fault-controlled circulating hydrothermal fluids, bounded by eastern and western sub-basins, which are somehow tight.

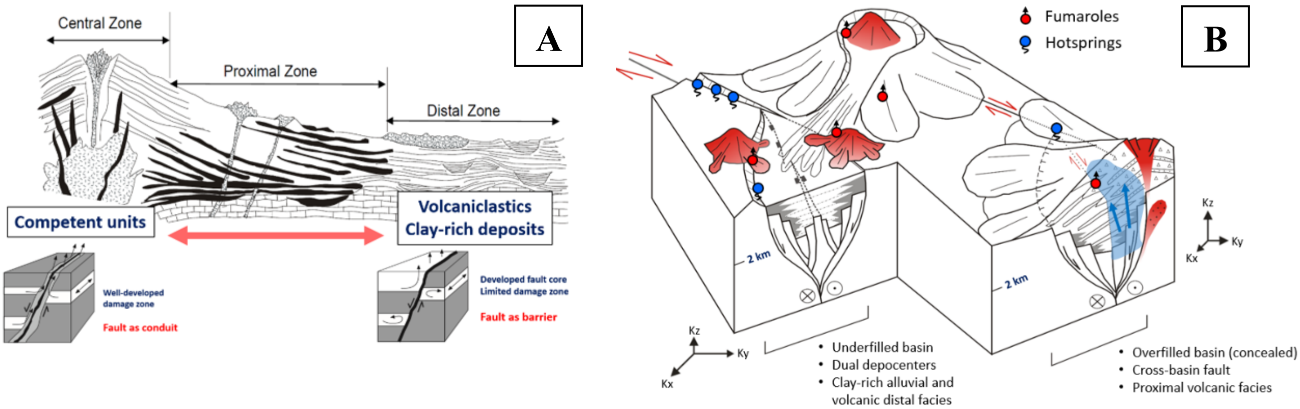

Figure 5: A. Facies model (Williams and McBirney, 1979) and the likelihood of fault permeability (modified from Rowland and Sibson, 2004); **B.** Conceptual model of pull-apart basins, nearby volcanic centres and thermal manifestation; red represents monogenetic domes; Kx, Ky, and Kz are permeability in three cardinal axis

4. GEOTHERMAL SYSTEMS IN THE SEDIMENTARY BASINS

Contemporary heat flow in the Sumatran sedimentary basins, particularly the CSB, is relatively high compared to the average continental condition (Hall and Morley, 2004). Previously, it was interpreted as a consequence of back-arc setting where elevated heat flow follows the crustal thinning (Eubank and Makki, 1981), or due to active volcanism in the nearby arc (Nagoa and Uyeda, 1995). However, seismic tomography does not indicate lithospheric thinning beneath the Sumatra, while there are considerable spatial offset between the basins and the location of active volcanism. Therefore, the source of high heat flow remains uncertain.

The origin of the Sumatran Tertiary sedimentary basins also remains controversial and is a subject for continuous debates (Eubank and Makki, 1981; Tapponnier et al., 1986; Hall and Morley, 2004; Pubellier et al., 2014; Sautter et al., 2017). Since its onset in Late Neogene current arc system divides and separates the basins into the fore-arc and back-arc. This paper only discusses the inland part of back-arc basins, especially the Central Sumatra Basin where significantly high heat flow is noticeable.

The basins generally have identical stratigraphic succession which points out similar origin and diachronous evolution (Barber and Crow, 2005). The striking difference is that the NW-SE and WNW-ESE structural trends which dominates South (SSB) and Central Sumatra Basin (CSB) are much less important in the North Sumatra Basin (NSB), where the N-S structural fabric controls the basin configuration (Figure 2). This is consistent with the aforementioned tectono-volcanic subdivision of the arc. In the two southern basins i.e. CSB and SSB, reactivation of NW-SE and WNW-ESE pre-Tertiary basement structures determines the geometry of initial rifting and subsidence in the Paleogene. Again, it resembles how the same basement structural fabrics influence the Sumatran Fault System along the arc region.

The absence of limestone units in the CSB stratigraphy is another noticeable contrast (Barber and Crow, 2005). Calcareous sediments present in both NSB and SSB, and act as prolific reservoir for petroleum system of the two basins. The distance and spatial position of the basins relative to the uplifted orogeny in the Peninsular Malaysia i.e. the Main Range may control the stratigraphy of infill sediments and the presence of limestone units. The CSB is located just in front of the Main Range, closer than the other two basins. The Main Range is part of the Bentong Raub Zone (Figure 1) where syn-tectonic and post collision granitoid rock dominates the topographic high since the early Paleogene. Erosion from this range provided large amount of continental sedimentary flux into the CSB and inhibited the deposition of limestone. The erosional product from radiogenic granitoid rocks of the Main Range is likely correlate to the higher heat flow in the CSB compared to the other two basins as the Tertiary sedimentary rock in this basin tend to have higher radiogenic heat generation.

To further investigate the hypothesis, we have set up preliminary 3D numerical models of the lithospheric-scale conductive heat transfer of the Sumatran basins. The model incorporates lateral variations in the crustal and lithospheric thicknesses, and also account for differences in composition, thus also in radiogenic heat production. Thermal boundary conditions are based on available observation.

Preliminary result of the modelling (Sutrisno et al., in prep.) demonstrates that the elevated heat flow in the Sumatran basins, in particular CSB, is the accumulating effect of the blanketing effect from the sedimentary strata with low thermal conductivity, and relatively high radiogenic heat generation from continental sediment and crystalline basement constitute the upper crust. The high value of radiogenic heat generation associated to young granite (>150 Ma) (Hantschel and Kauerauf, 2009) is assigned along the MSTZ representing syn-tectonic magmatism along the suture, while lower heat generation (granite >500 Ma) is assigned for the background condition of the upper crust of Sibumasu Terranes. Despite the inversion modelling and data assimilation constrain the model to match with the observation data, in average the temperature of the models tends to be lower than the observation. It might indicate that elevated heat flow in the CSB is partly affected by thermal perturbation from the previous tectonic events. In other word, the basin is still in transient condition and not fully equilibrium. Yet this phenomenon cannot be accommodated by the current static modelling.

5. RESOURCE CLASSIFICATION AND GENERAL CHARACTERISTIC

Table 1 below summarizes the classification of several geothermal types present in the island of Sumatra. The geothermal play is based on the geologic features as proposed by Moeck (2014).

		Geothermal Play (Moeck, 2014)	Temperature	Permeability	Lateral extent
The Sumatran Arc	Volcanic flank	• Magmatic convection dominated system • Conventional volcanic geothermal system	Likely high temperature	Controlled by volcanic facies	Outflow tongue toward topographic low
	Along the strike-slip fault	• Non-magmatic convection dominated system • Deep-circulation system • Possible minor influence from hidden intrusions	Likely low temperature	• Limited around fault corridor • Difficult to predict	• Elongated and narrow around fault corridor • Generally too narrow for geophysical imaging
	Transtensional setting	• Magmatic convection dominated system • Upflows are linked to nearby volcanic centers • Outflows might be modified by the pull-apart basin	• Thermal anomaly is not constrained by basin outline • Higher temperature risk toward outflows	Cumulatively influenced by (i) basin geometry, (ii) basin-fill deposits, (iii) stress field, and (iv) alteration	Compartmented resources within pull-apart basin
	Transpressional setting	• ditto • Outflows might be controlled by restraining bend	Higher risk toward outflows	Matrix permeability is low due to alteration overprinting	Widespread outflows
Tertiary Sedimentary Basin (CSB)		• Conduction dominated system • Non-magmatic geothermal play	• Thermal anomaly is constrained by the basin outline • Low temperature system	Controlled by permeable stratigraphic unit	Regional occurrence over the basin

Table 1. Summary of various Sumatran geothermal system

REFERENCES

Aydin, A., Nur, A.: Evolution of pull-apart basins and their scale independence, *Tectonics* 1, (1982), 91-105

Barber, A. J. and Crow, M. J.: An Evaluation of Plate Tectonic Models for the Development of Sumatra, *Gondwana Research* 6, (2003), 1-28

Barber, A. J. and Crow, M. J.: Sumatra: Geology, Resources and Tectonic Evolution, *The Geological Society*, London, (2005)

Bellier, O. and Sebrier, M.: Relationship between tectonism and volcanism along the Great Sumatran Fault Zone deduced by SPOT image analyses, *Tectonophysics* 233, (1994), 215-231

Daud, Y., Sudarman, S., Ushijima, K.: Integrated geophysical studies of the Ulubelu geothermal field, South Sumatera, Indonesia, *Proceedings of World Geothermal Congress* 2000, Kyushu-Tohoku, Japan, (2000)

Gasparon, M. and Varne, R.: Sumatran Granitoids and their relationship to Southeast Asian terranes, *Tectonophysics* 251, (1995), 277-299

Gasparon, M.: Quaternary volcanicity, in Sumatra: Geology, Resources and Tectonic Evolution, Barber, A. J. and Crow, M. J. (Ed.), 120-130, *The Geological Society*, London, (2005)

Hall, R. and Morley, C. K.: Sundaland basins, in: Continental-ocean interactions within the East Asian marginal seas, Clift, P., Wang, P., Kuhnt, W., Hayes, D. E. (Ed), Geophysical Monograph 149, 55-85, *American Geophysical Union*, Washington DC, (2004) Hall, R. and Spakman, W.: Mantle structure and tectonic history of SE Asia, *Tectonophysics* 658, (2015), 14-45

Hickman, R. G., Dobson, P. F., van Gerven, M., Sagala, B. D., Gunderson, R. P.: Tectonic and stratigraphic evolution of the Sarulla graben geothermal area, North Sumatra, Indonesia, *Journal of Asian Earth Sciences*, (2004), 435-448

Jacob, J., Dyment, J., Yatheesh, V.: Revisiting the structure, age, and evolution of the Wharton Basin to better understand subduction under Indonesia, *Journal of Geophysical Research: Solid Earth*, volume 119, (2014), 169-190

Kaspereit, D., Mann, M., Sanyal, S., Rickard, B., Osborn, W., Hulen, J.: Updated Conceptual Model and Reserve Estimate for the Salton Sea Geothermal Field, Imperial Valley, California, *GRC Transactions* vol. 40, (2016)

Koulakov, I., Kasatkina, E., Shapiro, N. M., Jaupart, C., Vasilevsky, A., Khrepy, S. E., Al-Arifi, N., Smirnov, S.: The feeder system of the Toba supervolcano from the slab to the shallow reservoir, *Nature Communications* 7:12228, (2016)

McCarthy, A. J. and Elders, C. F.: Cenozoic deformation in Sumatra: oblique subduction and the development of the Sumatran Fault System, *Geological Society Special Publications* 126, London, (1997), 355-363

Moeck, I. S.: Catalog of geothermal play types based on geologic controls, *Renewable and Sustainable Energy Reviews* 37, (2014), 867-882

Muraoka, H., Takahashi, M., Sundhoro, 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 of World Geothermal Congress* 2010, Bali, Indonesia, (2010)

Mussofan, W., Baroek, M. C., Stimac, J., Sidik, R. P., Ramadhan, I., Santana, S.: Geothermal Resource Exploration along Great Sumatera Fault Segments in Muara Laboh: Perspectives from Geology and Structural Play, *Proceedings of 43rd Workshop of Geothermal Reservoir Engineering*, Stanford University, Stanford, California, (2019)

Niasari, S. W., Muñoz, G., Kholid, M., Suhanto, E., Ritter, O.: 3D Inversion of Magnetotelluric Data from the Sipoholon Geothermal Field, Sumatra, Indonesia, *Proceedings of World Geothermal Congress* 2015, Melbourne, Australia, (2015)

Pulunggono, A.: Tertiary structural features related to extensional and compressive tectonics in the Palembang Basin, South Sumatra, *Proceedings of Indonesian Petroleum Association 15th annual convention*, Jakarta, Indonesia, (1986)

Rowland, J. V. and Sibson, R. H.: Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand, *Geofluids* 4, (2004), 259-283

Sagala, B. D., Chandra, V. R., Purba, D. P.: Conceptual model of Sorik Marapi geothermal system based on 3-G data interpretation, *Proceedings of IIGCE 2016*, Jakarta, Indonesia, (2016)

Sieh, K. and Natawidjaja, D.: Neotectonics of the Sumatra Fault, Indonesia, *Journal of Geophysical Research* 105, (2000), 28295-28326.

Stelling, P., Shevenell, L., Hinz, N., Coolbaugh, M., Melosh, G., Cumming, W.: Geothermal systems in volcanic arcs: Volcanic characteristics and surface manifestations as indicators of geothermal potential and favorability worldwide, *Journal of Volcanology and Geothermal Research* 324, (2016), 57-72

van Wijk, J., Axen G., Abera, R.: Initiation, evolution and extinction of pull-apart basins: Implications for opening of the Gulf of California, *Tectonophysics* 719-720, (2017), 37-50

Wu, J. E., McClay, K., Whitehouse, P., Dooley, T.: 4D analogue modelling of transtensional pull-apart basins, *Marine and Petroleum Geology* 26, (2009), 1608-1623

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