Review of subduction and its association with geothermal system in Sumatera-Java

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Abstract. Java and Sumatera have the largest geothermal resources in Indonesia, in which mostly are spatially associated with volcanoes of subduction zones. However, those volcanoes are not distributed in a regular pattern due to the difference of subduction position. Subduction position in Java is relatively more perpendicular to the trench than in Sumatera. In addition, Java has a concentration of large productive geothermal field with vapour dominated system in the western part of Java, which may be caused by the various subduction dip along the island. In order to understand the relationship between the subduction process and geothermal system in the subduction zone volcanoes, we examined several kinematic parameters of subduction that potentially relevant to the formation of geothermal system in overriding plate such as slab dip, subduction rate, and direction of subduction. Data and information regarding tectonic setting of Sumatera and Java and productive geothermal field in Sumatera and Java have been collected and evaluated. In conclusion, there are three condition that caused the geothermal fluid to be more likely being in vapour phase, which are: the subduction is in an orthogonal position, the slab dip is high, and rate of subduction is high. Although there are plenty researches of subduction zone volcanoes, only a few of them present information about its formation and implication to the geothermal system. The result of this study may be used as reference in exploration of geothermal field in mutual geologic environment.

Keywords: subduction zone, slab dip, volcanic arc, vapour phase

1. Introduction

Almost 75% of total productive geothermal power plant in the world are associated with subduction zone volcanoes [1]. Indonesia which is located in Indo-Australian and Eurasian subduction zone, has a line of volcanoes along the subduction zone. Those volcanoes make a number of potential geothermal energy resources, where Sumatera and Java Island have the greatest number of them.

There are two categories of volcano; volcano at the volcanic arc which is genetically associated with subduction, and back arc volcano which its magmatism does not directly relate to the subduction [2]. In a study about relation between volcanic arc and geothermal field in Java Island, Setijadji [3] concluded that the highest prospectivity of geothermal energy is occurred in volcanic arc with genetic association with subduction process.

There is difference density of volcano distribution ratio between Sumatera-Java with 3: 3.5 ratio, which is caused by the difference of the slab dip in each part of the subduction. In spite of having a same subduction zone, there is irregularity trend formed in Java. Western part of Java (referred hereafter as...
West Java) is the most seismically active region and has the highest volcanic density in the whole island [3]. It is also the one and only region where we can find vapour dominated geothermal systems in Indonesia. It has five vapour dominated geothermal fields; Kamojang, Darajat, Patuha, Telaga Bodas, and Wayang Windu. West Java also has the highest contour map of WBF depth which means it has the steepest angle of subduction (referred hereafter as slab dip) below it [4].

There are many researches about subduction and volcanic arc have been published, especially the one in Indo-Australian and Eurasian subduction zone. For instance, there are study about 3D geometry and evolution of the Indo-Australian plate by Richards, S., et al. [5], structural control of arc volcanism by Acocella, V., and Funiciello, F., [6], and geothermal systems in volcanic arcs by Stelling, P., et al., [1], but it is hard to find the connection between subduction process and its implication to the geothermal system.

2. Methods
To understand the association between subduction with geothermal system in volcano subduction zone, we have collected data from various scientific literature about tectonic setting include geothermal system of some productive geothermal fields in Sumatera-Java. We examined some kinematic parameters of subduction which appear to be relevant with geothermal system formed at the overriding plate; slab dip, rate of subduction, and direction of subduction. Providing a simple framework in which to investigate its implications for the geothermal systems, the result of this study could be helpful for better understanding about the nature of volcanic arc and might be used as reference in exploration of geothermal systems in mutual geologic environment.

3. Regional Geology
The island of Sumatera and Java sit atop the Eurasian plate, which overrides the subducting Indo-Australian oceanic plates that converges obliquely at about 50 to 70 mm/yr [7]. The subduction along Sunda trench contributes to the development of Sunda Orogeny in Java and Barisan Orogeny in Sumatera [8]. The orogenies formed in parallel with the subduction is known as Sunda Arc which spreads along northwestern Sumatera to Flores. This northward subduction nearly perpendicular to the arc front in Java and increasingly oblique towards Sumatera [9], which affects the structure formed in Sumatera and Java.

There are several differences in geological setting of Java and Sumatera which affect the styles of geothermal fields there. Sumatera has a continental basement and its subduction style is an active continental margin. Meanwhile, Java is underlain by different basement compositions, from a continental basement in West and Central Java, to an island arc crust in East Java [10].

The potential geothermal field along Sunda arc, especially in Sumatera and Java island mostly has high-enthalpy geothermal system. The densely populated of potential geothermal system in Sumatera and Java island dominantly affected by typical of subduction zone.

Stresses resulting from the oblique subduction have been released periodically by dextral fault movements parallel to the plate margin [11]; these have produced the major Sumatera Fault System (SFS), which runs the entire length of the island [12]. The regional segmentation of West, Central and East Java volcanic arc has directly affected different geothermal prospectivity of each segment. In this case, prospectivity increases from the east to the west. West Java which is the most prospective at a regional scale is spatially associated with the highest crustal heatflow and the highest crustal seismic activities [3].

The geothermal fields in West Java are a major contributor of geothermal energy in Indonesia (figure 1). From 1513.5 MWe installed capacity in Indonesia, which is the number 3 installed national capacity in the world, West Java supplied 77% of it, around 1164 MWe [13].
4. Discussion

Formation of volcanic arc is strongly correlated with the subduction process. With examining some kinematic parameters of subduction, we can interpret its correlation to the geothermal system which is associated with volcanic arc at the overriding plate.

The oldest and the most productive geothermal field in Indonesia are located in West Java. This region have five of eight vapour-dominated geothermal fields of the earth. The factor contributing to the occurrence of the five vapour-dominated reservoirs in West Java are intense heating due to prolonged active volcanism, an absence of shear faulting, and the restrictive permeability range of the host and caprocks surrounding a relatively permeable reservoir [14]. Since vapour dominated geothermal field tends to be more stable and productive, this study is also conducted to review whether there is subduction factor interfere in controlling the formation of vapour dominated system.

4.1. Slab dip

Tatsumi [15] emphasized that pressure controls the magma in subduction zones. Precise earthquake hypocentral locations reveal that the depth to the top of the slab beneath the fronts of volcanic arcs is constant, to within a few kilometres, along individual segments of arc, but varies from 80 km to 160 km between different segments [16]. When the subducting plate reach the certain depth with certain pressure, it could produce magma which would rising and implied to formation of volcanoes at the above overriding plate. The shallower the dip of the slab, the greater the distance of the volcano arc formed from the trench.

We examined the distance of the volcanoes to the trench in Sunda Arc, and found insignificant difference of them (figure 2). In the other hand, from the contour depth of WBF zone, it can be seen that West Java has the steepest slab dip among the Sunda Arc [4]. From this sight, the relation between slab dip and the volcanic arc is not clearly seen.

England and Katz [16] have studied about location of volcanic arc formation which said that the mechanism whereby the melt reaches the Earth’s surface are controlled by the dynamics of the wedge. Hence, the arc front is located somewhere above the region in which the temperature in the wedge exceeds a condition called as anhydrous solidus (the state where water contents are about ten times lower than the concentrations estimated for wet melting), because the degree of hydrous melting increases rapidly there. It supports the previous study by England and Wilkins [17] which said that the locations of the arc controlled by a strongly temperature-dependent process either at the top of the slab or in the

![Figure 1 Indonesia geothermal potency and installed capacity (modified from Geological Agency, Ministry of Energy and Mineral Resources of Indonesia, in Directorate General of New, Renewable Energy, and Energy Conservation, 2016)](image-url)
wedge of mantle beneath the arcs, while the temperature depends on the convergence rate, $V$, and dip, $\delta$, of the slab.

Since they are counted as inseparable parameters, we would review the rate of subduction and its influence to the subduction process and volcanic arc to understand the relation between two of them to the temperature of the wedge.

**Figure 2** Subduction zone in Sumatra and Java (modified from Richards, et al., 2007) [5].

**Figure 3** Definition of rate of subduction in scheme. Convergent velocity ($V_c$) is sum of subducting plate velocity ($V_{sup}$) and overriding plate velocity ($V_o$) (modified from Acocella and Funiciello, 2009) [6].

### 4.2. Rate of subduction

The rate of subduction could be defined as convergent velocity ($V_c$) which is sum of subducting plate velocity ($V_{sup}$) and overriding plate velocity ($V_o$) [6] (figure 3).

The subducting plate velocity ($V_{sup}$) which is included in rate of subduction ($V_c$) has been observed together with depth beneath volcanic arc to study about factor controlling the location of volcanic arc, using a simple mathematical model [16]. It was a further study of previous research about temperature structure in subduction zones which was concluded that temperature of the slab and the mantle wedge which controlled the location of the arc, depend on a single dimensionless distance $V_r \delta^2/\kappa$, where $V$ is the rate of plate convergence (or $V_c$ based on previous description), $r$ is distance from the corner of the wedge, $\delta$ is the dip of the slab and $\kappa$ is thermal diffusivity (figure 4). In this scaling, the maximum temperature in the mantle wedge $T_r$ is given by equation 1:

$$
T_r \approx T_0 \exp \left[ -B \left( \frac{V_r \delta^2}{\kappa} \right)^\beta \right]
$$

(1)

where $T_0$ is a scale temperature, and $B$, $\beta$ and $\gamma$ are constants, the values of which depend on the details of the flow near the top of the slab.

The study has calculated the steady state wedge, $T_r$, plotted against $V_r \delta^2/\kappa$, and it is confirmed that $T_r$ is proportional with the dimensionless distance (figure 5).
The greater the number of $V\delta$, the more the temperatures it needs to reach the condition of melting slab to produce magma and form the volcanic arc.

![Diagram of subduction zone](image)

**Figure 4.** Schematic of subduction zone (modified from England and Katz, 2010)

**Figure 5.** Maximum temperature in the wedge, $T_r$, as a function of dimensionless distance from the wedge corner, $Vr\delta^2/\kappa$, where $V$ is convergence speed, $\delta$ is dip of the slab, and $\kappa$ is thermal diffusivity [6].

### 4.3. Direction of subduction

Plate motion vectors can be used to predict deformation which produced as subduction outcome. Where subduction is strongly oblique and steep, arc-parallel strike-slip faults can form. These frequently run along the volcanic arc and have associated with permeable secondary structures whose orientations can be determined similarly [18].

According to Hochstein and Browne [19], reservoir permeability in vapour-dominated system is $>10$ mD and surrounded by impermeable rock which has permeability $<1-3$ mD to prevent flooding from the outside. Generally, fault has strong impact in creating secondary permeability in reservoir. In Kamojang, the outer zone of reservoir has low permeability, 0.02 mD and in the inner zone is 150 mD [20]. Meanwhile, the outer zone of Darajat reservoir is about 0.04-0.16 mD [21]. The occurence of strike-slip which is affected by shear stress will generate transtension which could enrich the permeability of reservoir. Therefore, the absence of shear faulting could support the vapour dominated system to be occurred.

Great Sumatera dextral strike-slip was formed parallel with the arc. Gunderson, et al., [22] and Santoso, et al., [23], have mapped north striking faults and identified half graben and graben structures. Intensive structure in Sumatera caused the high permeability of reservoir and surrounded rock. It generates the high rates of water inflow and produce liquid phase in reservoir. Study about exclusivity of the vapour dominated geothermal system in West Java concluded that shear stress on faults that cross through the reservoir and associated enhanced permeability possibly play an important role in preventing a vapour-dominated system from developing [14].

Moving south from Sumatera to Java there is a change from oblique to perpendicular subduction. While geothermal system in Sumatera are highly affected by Great Sumatera Fault, West Java geothermal system have not been associated with regional faults like Sumatera’s. West Java can be considered to be located at the transitional zone between oblique subduction in Sumatera and frontal subduction at the eastern part of West Java [24]. In West Java, oblique subduction occured during Cretaceous while orthogonal subduction during Tertiary periods (figure 6). Each of subduction activity
has formed different structural pattern, depending on the position of subduction track at that time [25]. These two kinds of subductions in Java tectonic were accommodated by wrench faults in the upper crust in NW direction.

Figure 6. Evolution of subduction zones and magmatic arc of West Java [26].

The West Java Fault as a major structure has two main NW trending of fault splays that formed Garut circular structure or Garut Basin by negative flower structure. A research about regional structure in West Java by Corbett and Leach [27], was conducted to know about deep seated structure and surface
structure relationship and resulted that the N-S to NNE-SSW trending surface structure is the surface manifestation of NW-SE to WNW-ESE deep structures extensional system in West Java is N-S.

Movements along laterally offset basement faults generate popup structures and pull-apart grabens in restraining and releasing bends, respectively [28]. If the vertical component is normal, faults tend to be listric and to form a negative flower structure, which forms a depressed area [28]. The upper part of negative flower structure is a pull-apart basin which is bounded by faults. This regional major deep seated structure’s role in localizing magmatic heat source in an arc-volcanism and secondly, extensional setting of structure that provide the favourable condition for secondary permeability in fluids interaction and accumulation [27]. It can be argued that the oblique subduction has a important role in generating the pathway for intrusion and enhancing the permeability.

On the other hand, the Indo-Australian plate is subducted under the Eurasian plate northwardly at N20°E and at rate of 6-7 cm/yr in West Java area [30]. This orthogonal subduction since Tertiary period accomodate the appearance of 4 structure pattern in West Java, N-S, N-E, E-W, and N-W trending. The fault structures of NE-SW trending are associated with oblique subduction activity during Cretaceous period and has been reactivated during the Early Tertiary tectonic period with compression forces of N-S trending. This trend has generated fault structures of NS striking as an extensional fault and fault pattern with NNE-SSW direction as Synthetic Riedel Shear. It can be argued here that West Java Fault probably the remnant of previous structure style when West Java was in oblique subduction.

There are NE and N-S striking faults found in 5 vapour dominated fields which act as favourable fault in providing permeability zone. It is interpreted that these structures control the permeability in reservoir while not intensify the surrounded permeability. That fact is supported by the absence of shearing faulting which occured during Cretaceous period. It caused the permeability in reservoir is much higher than surrounding so they are able to produce vapour phase fluid. The transtension zone which controlled the localizing of heat source also support the occurrence of intense heating.

It is confirmed that direction of the subduction affected the structure formed at the overriding plate which can support the act of the geothermal fluid in a geothermal system. The oblique subduction in Sumatra generates NW-SE striking strike slip which enhance the permeability and caused high rates water inflow. Its condition is suitable to create the liquid phase reservoir. The other way, transition subduction that occurred in West Java caused the lacking of shearing fault and enhance the higher permeability in reservoir than surrounding. It support the vapour dominated reservoir to develop.

5. Conclusion

If the multiplicative value of slab dip and rate of subduction of Java is higher than Sumatera, the heat source in Java tends to be higher, although there is uncertainty in this deduction since they are not the only factors to be considered in this correlation.

The higher the obliqueness of direction of subduction, the higher the permeability formed in overriding plate. It is caused by oblique subduction which generally forms extension in transtension zone with permeable character. The permeability in Java is generally lower than in Sumatera due to the absence of shearing fault in West Java. It has generated certain geological setting which makes some area in West Java have significant differences between permeability of reservoir and surrounding rocks. Coupled with intensive heating from the heat source, it leads vapour dominated geothermal system to developed in West Java.

However, the precise correlation between kinematic of subduction process and geothermal system at overriding plate remains unclear. This may be caused by lack of data on exact value of slab dip, rate of subduction, and distribution of permeability of geothermal system. In order to understand more about implication of subduction to the geothermal prospectivity, research about act of slab dip and rate of subduction in structure formation at overriding plate, and further study about localization of vapour dominated geothermal system in West Java are needed.
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