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Segmented Volcanic Arc and its Association with Geothermal Fields in Java Island, Indonesia

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ABSTRACT

The island of Java (Sunda arc, Indonesia) contains the largest geothermal resources (potential and known reserves) in Indonesia. For example, five out of seven producing geothermal fields in Indonesia are located in this island. In total around sixty geothermal prospects have been identified, in which mostly are spatially associated with Quaternary volcanoes. However, their spatial distributions are not uniformly distributed along the island; rather the bigger prospects (with potential reserve >100 MW) are concentrated in few locations and they can be related with regional to district-scale geologic segmentation of the Quaternary volcanoes.

The Sunda volcanic arc in Java is segmented into the West, Central and East segments that each has distinctive styles of volcanism. Although several geothermal fields are located within large, single stratovolcanoes, the majority of large geothermal fields are concentrated within Upper Neogene to Early Quaternary caldera remnants, in which many Pleistocene volcanic edifices (mostly are monogenic) were emplaced. Most notably is in the eastern part of West Java especially within the volcanic front field. This area is also the most seismically active region and has the highest volcanic density in the whole island. Petrochemical data of Quaternary lavas suggest that volcanism surrounding geothermal system contain some of the most primitive magma erupted in this mature arc. In Central Java geothermal prospects are, on contrary, located within the backarc-side volcanoes. Similarly, the biggest geothermal district in Dieng is also associated with many monogenic volcanoes emplaced within an Upper Neogene-Early Quaternary caldera. Current radiometric data suggest that major geothermal fields are associated with magmas erupted during the Upper Pleistocene, whose ages range approximately 0.5-0.2 Ma. In eastern Java, specific settings for geothermal prospects are less evident in which known prospects are located at both volcanic front and backarc-side stratovolcanoes. The recognition of Upper Pleistocene volcanic edifice is the single most important evidence for the first-pass exploration for geothermal fields.

1. INTRODUCTION

In term of geothermal resources, Java island is the center of geothermal development in Indonesia. Indonesia itself, with approximately 15% of the world active volcanoes located in this archipelago, hosts one of the highest geothermal potentials in the world. The Directorate General of Geology and Mineral Resources estimates the total potential of 27,000 MW. Of this figure, only little more than 800 MWe that have been developed from seven locations, in which five sites are located in Java island. Those are the Darajat (145 MW), Dieng (60 MW), Kamojang (140 MW), Gunung Salak or Awibengkok (330 MW), and Wayang Windu (110 MW) (Ibrahim et al., 2005; Wahyuningsih, 2005). Furthermore, sixty six geothermal prospects have been identified in this island (e.g. Suryantini et al., 2005; Wahyuningsih, 2005) as listed in Table 1.

With such illustration, understanding the Quaternary geologic settings of these developed (and other prospects) in Java island is important in order to help accelerating exploration program in other volcanic islands in Indonesia and beyond. This contribution elucidates the characteristics of known geothermal prospects in Java Island in relation to their geologic environments, with the main focus on major geothermal prospects whose potential reserves exceed 200 MW. Spatial-genetic relationships between large geothermal fields with Quaternary volcanism and other geologic environments will be evaluated. Such relationships may be used as area-selection exploration criteria for exploring new high enthalpy geothermal fields in stratovolcano systems.

2. GEOLOGIC SETTING OF JAVA ISLAND

Java is built up since the early Tertiary through a convergent tectonic margin between the Indian-Australian plates and the southeastern margin of Eurasian continental plate called the Sundaland (Hamilton, 1979). Subduction takes place along the Java trench that reaches the maximum depth of 6.75 km. The oceanic crust is being subducted northward, more or less perpendicular, to the Sunda volcanic arc at a rate of 6-7 cm/yr (Hamilton, 1979; Simandjuntak and Barber, 1996). Between the trench and island is a high submarine forearc ridge and a continuous forearc basin. The subducted oceanic plate is gently dipping to beneath the forearc basin, before it steepens gradually to a depth of a little over 100 km beneath the volcanic arc, beyond which its dip is steeper than 60^o. The Benioff seismic zone currently extends to depths of more than 600 km in Java (Hamilton, 1979; Puspito and Shimazaki, 1995). Tomographic imaging even suggest that the lithospheric slab penetrates to a depth of at least 1500 kilometers (Widiyantoro and Van der Hilst, 1996).

Java is now a part of the volcanic arc of approximately 3,700 km long that extends from the northern tip of Sumatra island through Java to east of Damar island (Hamilton, 1979). This long arc is usually divided in three segments: the Sumatra arc along the Sumatra island, the Sunda arc from Java to Flores islands, and the Banda arc for the islands east of Flores (Fig. 1). The basement crust thins eastward, from approximately 30 km beneath Sumatra to 15 km beneath the Flores Sea (Ben Avraham and Emery, 1973). In Java the crust is 20-25 km thick, with an essentially continental seismic velocity structure. The West Java, and perhaps Central Java, is underlain by a continental basement, while area east of Central Java is an island arc crust.

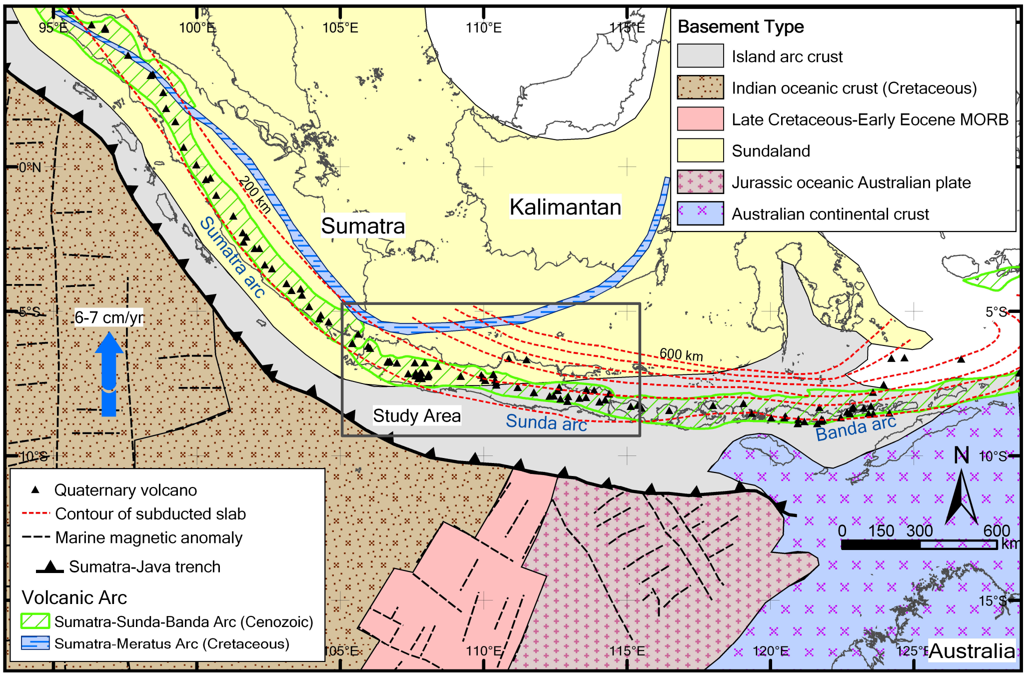

Figure 1: Tectonic setting of Java island, Indonesia (after Setijadji, 2005).

Tectonic development of Java island is divided into two main phases, i.e. the Paleogene extensional and subsidence-dominated tectonics and the Neogene compressional and thrusting-folding events (Simandjuntak and Barber, 1996; Hall, 2002). The structures of pre-Miocene ages trend northeasterly, represented by basins and rises in the Java Sea, including the Karimunjawa Arch and Bawean Trough (Katili, 1975; Hamilton, 1979; Simandjuntak and Barber, 1996) (Fig. 2). The Late Neogene Sunda orogeny affected the segment between West Java and the islands to east (Simandjuntak and Barber, 1996). Mio-Pliocene sedimentary rocks were deformed into tight folds especially in the northern part. This tectonic phase was associated with the uplift of the volcanic arc and the development of a major thrust system.

The current features of geologic structures of Java island can be summarized as follows. The backarc thrust of Barabis-Kendeng thrust crosscut the whole island along its northern part, whose some segments are still active. There are also three main strike-slip faults occur in Java. In West Java, the still active NE-SW Cimandiri fault crosscuts from the southern coast to its northern one. Another strike-slip fault, namely Citandui fault, occurs in West Java with a W-SE trend. The third system occurs in Central Java, namely Central Java fault (e.g., Hoffmann-Rothe et al., 2001) as a NE - SW left-lateral strike-slip fault cross-cut the whole island (Simandjuntak and Barber, 1996). The movement range of Central Java fault is considered very large in horizontal distance and up to about 2 km in its vertical shift (Hoffmann-Rothe et al., 2001).

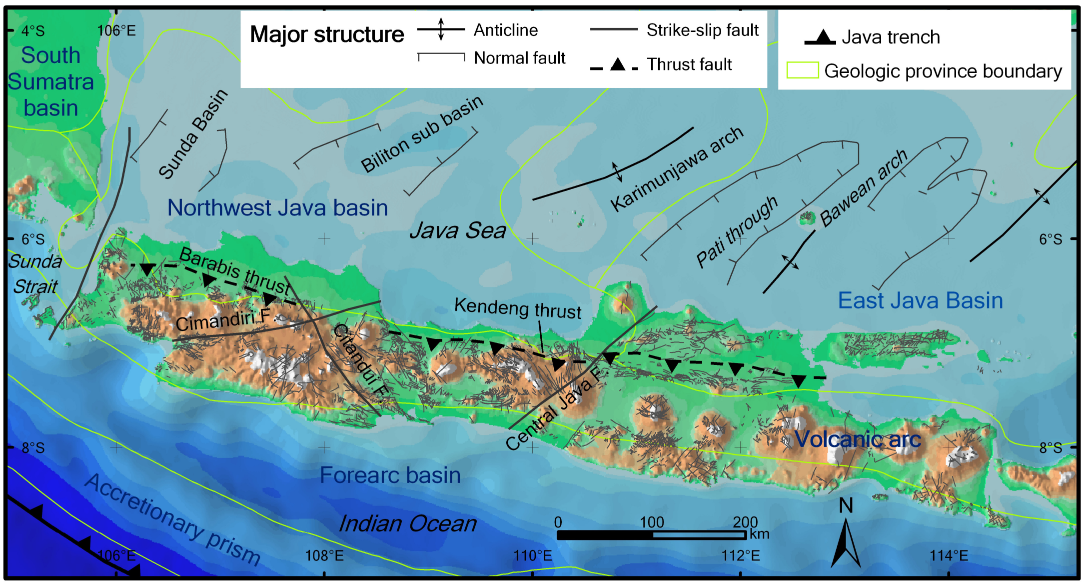

Figure 2: Major geologic structures of Java island. Major geologic structures are compiled from Katili (1975), Hamilton (1979), and Simandjuntak and Barber (1996). All other faults are from published geologic maps. Geologic province boundary is from the USGS Global GIS data.

3. SEGMENTED QUATERNARY VOLCANOES

There are approximately fifty (50) Quaternary volcanoes in Java. Setijadji (2005) classified the Quaternary volcanoes in Java into: 1. Volcanic arc volcanoes whose genetic relationships with subduction is clear, and 2. Backarc volcanoes whose magmatism is not necessarily directly related with subduction. Volcanic arc volcanoes are aither present as single chain or double chain arc. Following the terminology defined by Tatsumi and Eggins (1995), members of double chain arc are further classified into volcanic front, trench-side volcano, and backarc-side volcano (Fig. 3). As a result, we recognize that within the onland of Java island, different types of volcanism are present, i.e., single chain volcanic arc, double chain volcanic arc, and backarc magmatism. We can also see such segmentation of Quaternary volcanoes configuration between West, Central and East Java.

3.1 West Java

In West Java Quaternary volcanoes start with the single chain arc at the westernmost part. This zone consists of the Krakatau volcano complex which is located offshore, and Danau complex that consists of the Danau and Karang volcanoes. Distance between Krakatau to Danau complex is about 60 km. To the east of Danau zone, the nearest volcano zone is the Salak zone which is located about 85 km apart. This zone consists of several single chain volcanoes (Salak, Kiarabere, Perbakti, and Gede). This zone is separated about 60 km from the next cluster of Galunggung-Tangkuban Prahu at the eastern part of west Java. This zone is populated by many volcanoes (16) that form a 90-km double volcanic chain along the arc. Galunggung and some other clustered volcanoes are located along the trench-side volcanic chain, while the Tangkuban Prahu and two other volcanoes (Tampomas and Ceremai) are located along the backarc-side volcanic chain. Trench-side and associated backarc-side volcanoes are in general aligned in NE-SW directions, suggesting a regional NE-SW structural trends that control their emplacement.

The depth of subducted slab underneath the volcanoes decreases from Danau zone to Galungung zone. At Danau zone, the depth of slab is about 130 km beneath the volcanic front that its depth decreases into about 120 km at Salak zone and finally into 110 km underneath volcanic front of Galunggung zone.

3.2 Central Java

Segmentation between West and Central Java volcanoes is very evident. After a highly populated area at eastern part of West Java, the western part of Central Java is very scarcely populated at the Slamet zone. Here there is only one but large stratovolcano of Slamet volcano which is separated about 100 km east of Galunggung-Tangkuban Prahu zone. About 75 km to east, this zone changes into a double chain zone of Merapi-Ungaran at the eastern part of Central Java. This zone consists of two accross-arc volcanic chains of Dieng-Sundoro-Sumbing and Ungaran-Telomoyo-Merbabu-Merapi. These across-arc chains are aligned in NW-SE direction which is different from that of at West Java. Backarc magmatism which is not present in West Java occurs here as the extinct Pleistocene Muria volcano (Soeria-Atmadja et al., 1988; Edwards et al., 1991).

The depths of subducted slab are significantly deeper here than those of West Java, i.e. approximately 175-190 km below the volcanic front volcanoes. Backarc-side volcanoes of Dieng (still active) and Ungaran (dormant) are located about 210-225 km above the slab, while back arc volcano of Muria is about 330 km (Fig. 3).

3.3 East Java

At the western part of east Java, a single volcanic chain of Lawu is accompanied by a double chain of Wilis-Pandan volcanoes. The horizontal distance between Lawu and Merapi (Central Java) is about 80 km, while the distance Lawu-Wilis is about 60 km. The Lasem volcano, which is just east of the Muria volcano, represents the back arc magmatism at this region. Further to backarc-ward, backarc magmatism also occurs at the Bawean island. To the east about 60 km from Wilis, a distinctively regularly-spaced double volcanic chain occurs at the eastern part of Java. At the western part there are Kelud-Semeru as the volcanic front volcanoes and the Penanggungan as the backarc-side one, while at the easternmost of Java there are Lamongan and Raung as the volcanic front and Ringgit and Baluran as the backarc-side ones. The spacing among volcanoes along the arc is only about 20 km apart. Between Semeru and Lamongan, a segmentation of arc is observed in which the volcanic front Lamongan is shifted about 25 km to the northeast from the position of Semeru.

The depths of subducted slab underneath East Java decrease in the segment from Lawu (about 175 km, same as Merapi) to about 150 km underneath Semeru. From Lamongan to the eastern tip, the depth of slab increases again into about 175 km. The locations of backarc magmatism are located about 340 km above the subducted slab for the Pleistocene Lasem volcano, and more than 600 km for the Bawean island. Lavas from the Bawean island are already dated to be Pleistocene, i.e. 0.26±0.04 to 0.84±0.04 Ma (Bellon et al., 1989).

4. GEOTHERMAL FIELDS

Just as the spatial distribution of Quaternary volcanoes, the known geothermal prospects in Java are not evenly distributed in all volcanic arc segments. Some prospects, especially the major and currently productive ones, tend to cluster in few particular areas in which certain geologic conditions seem to control their occurrences.

4.1 Western Java

The western part of Java has the highest population of identified geothermal fields in this island as well as the whole Indonesian regions, i.e., forty prospects (Fig. 4 and Table 1). Geothermal manifestations are very much scattered around the peaks of Quaternary volcanoes. However, large and producing fields are only located in two clustering regions, i.e., the Salak zone (Awi Bengkok) and the Galunggung-Tangkuban Prahu zone (Kamojang, Darajat, and Wayang Windu) (Fig. 5).

The Kamojang, Darajat, and Wayang Windu geothermal fields are located around a cluster of Quaternary volcanic cones, namely the Kendang volcanic complex (Rejeki et al., 2005). These volcanic cones are probably emplaced within the same, older caldera named the Pangkalan caldera whose age is Pleistocene.

The Kamojang geothermal field is the first developed field in Indonesia with recent production is 140 MW from a vapor-dominated reservoir (Utami, 2000; Ibrahim et al., 2005; Kamah et al., 2005). Kawah Kamojang was included in the Catalog of Active Volcanoes of the World (Neumann van Padang, 1951) based on its geothermal activity. The 1.2 by 0.7 km thermal area consists of fumaroles, steaming ground, hot lakes, mud pots, and hydrothermally altered ground. The field is located along a WSW-ENE-trending Quaternary volcanic chain that includes Gunung Rakutak, the Ciharus, Pangkalan, and Gandapura complexes, Gunung Masigit, and Gunung Guntur. This chain is progressively younger to the ENE. Kawah Kamojang is associated with the Pangkalan and Gandapura volcanic centers, along the Kendeng fault, which extends SW to the Darajat geothermal field. Reservoir rocks are composed of the Rakutak basaltic andesite formation (2 Ma) overlain by the Gandapura andesite formation (0.4 Ma) (Sudarman et al., 2000).

The Darajat geothermal field is a vapor-dominated geothermal reservoir which is located about 13 km SW of Kamojang. Hadi et al. (2005) mapped the presence of cluster of more than five volcanic centers, with diameters of less than 2 km, located within a larger extinct caldera complex (diameter of more than 5 km). Within this large caldera, some NE-SW and NW-SE faults control the occurrences of smaller cones. The geothermal reservoir is located within the central part of the extinct caldera at the faults intersection. The dominant NE-SW and NW-SE trending faults which are visible on aerial photographs are the main productive faults. Petrochemical data from the proximity of Darajat geothermal field suggest single calc-alkaline magmatism where a parental tholeiitic (primitive mantle derived) magma erupted with varying degree of fractional crystallization (Hadi et al., 2005). Silica contents of fresh lavas range 47-64 %; indicating some basic lavas are present.

The Wayang Windu two-phase geothermal field is located 12 km west of Darajat. Volcanic facies mapping, geochronology, and petrochemistry in the vicinity of Wayang Windu field suggested that the volcanic complex consists of several volcanic units from several volcanic sources whose ages are Upper Pleistocene (Bogie and MacKenzie, 1998). Among these volcanic rocks there are some primary basalts with elevated Ni and Cr.

The Awibengkok geothermal field is the largest producing field in Indonesia (330 MW) and also among the largest one in the composite andesitic volcanic field in the world (Hulen and Anderson, 1998; Hulen et al., 2000). This liquid-dominated geothermal field is located at the western flank of Salak volcano, one of three overlapping volcanoes (Hulen and Anderson, 1998; Roberts et al., 2000; Suryantini et al., 2005). The Awibengkok geothermal field is hosted principally by Quaternary-age (Upper Pleistocene?), intermediate- to felsic-composition volcanic rocks. Intersected rocks from the production drills consist of andesitic lahar breccia, dacite lava and tuff. There are many thin andesite and dacite porphyry intercepts in the cores that could be subvolcanic intrusive rocks.

Some of the prospects in West Java have high potential to be developed in near future, such as the Patuha and Kahara-Telaga Bodas which are both located near the Kamojang-Darajat-Wayang Windu fields. The Kahara-Telaga Bodas is a vapor-type geothermal system hosted mainly by tuff breccia and minor andesite lavas and quartz diorite intrusions (Raharjo et al., 2002) with an estimated resource is 400 MW (Wahyuningsih, 2005). This prospect is located just about 5 km of the vent of presently active Galunggung volcano (Bronto, 1990; Moore et al., 2002). Other prospective fields include the Danau Complex caldera, Tangkuban Perahu, Ceremai or Kromong, and Tampomas volcanoes (Wahyuningsih, 2005).

Table 2: List of geothermal fields in Java (compiled from Suryantini et al, 2005a,b; Wahyuningsih, 2005)

No	Name	Potential (MW)	Production (MW)
1	Rawa Danau	115	
2	G. Karang	170	
3	G. Pulosari		
4	G Endut Cisatun		
5	Pamancalan		
6	Kawah Ratu	102	
7	Kiara Beres		
8	Awibengkok	600	330
9	Bujal /Jasinga		
10	Cisolok - Cisukarame	133	
11	Selabintana		
12	G .Pancar		
13	Jampang		
14	Tanggeung - Cibungur		
15	Saguling		
16	Cilayu		
17	Cibuni	140	
18	G .Patuha	417	
19	Ciwidey	140	
20	Maribaya		
21	TangkubanParahu	90	
22	Sagalaherang		
23	Ciarinem		
24	G. Papandayan		
25	G.Masigit/ Guntur	70	
26	Kamojang	333	140
27	Darajat	432	145
28	G. Tampomas	100	
29	Wayang Windu	385	110
30	Karaha - Talaga Bodas	400	
31	G. Galunggung		
32	Ciheras		
33	Cigunung		
34	Cibalong		
35	G. Sawal		
36	Cipanas - Ciawi		
37	G. Kromong		
38	Sangkan Urip		
39	Subang		
40	Cibinbin		
41	Banyu Garam		
42	Bumi Ayu		
43	Batu Raden - G. Slamet	185	
44	Guci	100	
45	Mangunan - Wanayasa	92	
46	Candra Dimuka		
47	Dieng	580	60
48	Krakal		
49	Panulisan		
50	G. Ungaran		
51	G. Umbul Telomoyo		
52	Kuwu		
53	G. Lawu		
54	Klepu		
55	Parangtritis	10	
56	Melati		
57	Rajesari		
58	Ngebel - Wilis	120	
59	G. Pandan		
60	G. Arjuno - Welirang	92	
61	Cangar - Tulungrejo	100	
62	Songgoriti		

4.2 Central Java

There are fifteen (15) geothermal fields identified in Central Java (Fig. 4). Currently only one field, the Dieng volcanic complex, has been generating electricity with capacity 60 MW (Wahyuningsih, 2005). The Dieng volcanic complex is the backarc-side of NW-SE trending across-arc Quaternary volcanoes, which include the younger cones of Sundoro and Sumbing to the south. This volcanic complex is composed of many cones and domes that formed inside a collapsed ancient caldera (Van Bemmelen, 1949; Allard et al., 1989). The Dieng volcanic complex consists of two or more stratovolcanoes and more than 20 small craters and cones of Pleistocene-to-Holocene age over a 6 x 14 km area of supposed to be a large Pleistocene caldera (Allard et al., 1989; Siebert and Simkin, 2002).

The caldera was subsequently filled by a series of dissected to youthful cones, lava domes, and craters, many containing lakes. Lava flows cover much of the plateau, but have not occurred in historical time, when activity has been restricted to minor phreatic eruptions. The abundant thermal features that dot the plateau and high heat flow make Dieng a major geothermal prospect. Volcanic products range from andesite to rhyodacite.

Existing radiometric dating by Boedihardi et al. (1991) suggested that pre-caldera volcanic edifices are of Pliocene age (e.g., Prahu, 3.6 Ma). Caldera collapse occurred during the Pleistocene before 0.5 Ma, which was subsequently filled by several volcanic edifices, mostly are of monogenic eruptions. These monogenic volcanoes are aligned in the NW-SE direction and their ages decrease (younger) towards the SE. The oldest post-caldera unit is the Pagerkandang volcanics (0.46 Ma) while the youngest unit being dated is the Seroja volcanics (0.06 Ma). n the last several centuries the volcanism is dominated by phreatic eruptions as displayed by abundant explosion craters. The last eruption in 1979 released enormous amount of almost pure carbon dioxide gas that killed 142 people. The source of carbon dioxide, based on carbon and sulfur isotopes, is magmatic origin derived from mantle (Allard et al., 1989). Therefore magmatic activity actually still continues in Dieng complex until now.

Geothermal fields are associated with the oldest post-caldera monogenic volcanic edifices (cones) of Upper Pleistocene age (i.e. Pagerkandang, 0.46 Ma and Pangonan-Merdada, 0.37 Ma) (Fig. 6). These Upper Pleistocene ages are considered ideal in which mature geothermal systems would have been developed within these geological periods.

Two other locations which are considered most prospective are located in Quaternary volcanic complex of Ungaran and Guci (Slamet volcano) (Wahyuningsih, 2005). The Ungaran volcano, just like Dieng, is a backarc-side volcano from the Merapi-Merbabu-Telomoyo-Ungaran volcanic chain. The ages of these volcanoes are getting younger to the volcanic front, in which only Merapi is currently active. The results of K-Ar dating from Ungaran volcano show that volcanic activities of Ungaran lasted between 1.4 to 0.22 Ma (Pleistocene). Geothermal prospect is located within the Young Ungaran period, i.e. Gedongsongo volcanics whose dated age is 0.27±0.03 Ma (Kohno et al., 2005). In the case of Slamet volcano, despite there is no radiometric data available yet, locations of two geothermal prospects at the NW and SW flanks of Slamet peak clearly show that they are associated with Old Slamet period (e.g. Vukadinovic and Sutawidjaja, 1995).

4.3 East Java

According to Wahyuningsih (2005), eleven (11) geothermal prospects have been identified in East Java but none is now being developed. The most prospective field is located within the Iyang Argopuro volcanic complex. Other locations include the Ngebel-Wilis volcanic complex, Ijen, Arjuno-Welirang and Lamongan volcano.

5. DISCUSSIONS

Relating many aspects of geologic environment of known geothermal fields in Java island, following controlling factors are recognized.

5.1 Genetic Link with Volcanism

Most geothermal fields are spatially associated with Quaternary volcanic complex. As some maps show, the spatial relationship with Quaternary volcanoes is very distinctive (Figs. 7, 8 and 9). Figure 7 shows that the majority of known geothermal fields are located within higher elevation (mountainous areas). Figure 8 demonstrates that there is a trend that the bigger geothermal systems (>100 MW potential) are mainly located at proximal zone (< 10 km from a volcano's peak). An exceptional case occurs at the Cisolok hotspring. Towards the distal zone the geothermal fields are of smaller potential sizes. All but Cisolok geothermal fields which are located beyond 30 km from Quaternary volcanoes are small (<25 MW). The clustering volcanoes are the best sites for their geothermal potentials (Fig. 9). For example, the biggest concentration of geothermal energy found at the eastern part of West Java is located within the highest volcano density in Java. This evidence is associated with the occurrences of many small to medium size, some are monogenic volcanoes clustering within an older caldera crater.

Few exceptional cases are found as the occurrences of hot springs within Tertiary rocks domain without any evidence of Quaternary volcanism in their vicinity. For example, the hotsprings at the Cisolok and Cisukarame are hosted by limestone, and interpreted as the outflow from the Quaternary mountain range to the north (Suryantini et al., 2005). Their estimated potential is considerably high, i.e. 133 MW (Wahyuningsih, 2005). Another case is several hotsprings along the Opak fault zone south of Yogyakarta city, near the Parangtritis beach (Team Geothermal Investigation Java, 2003). The rocks surrounding these hotsprings are Oligocene-Lower Miocene volcanic rocks. Distance to nearest Quaternary volcano (Merapi) is about 70 km to north. Therefore, the genetic relationship with active volcanism is not likely. Rather, these hotsprings seem to be originated from deep-seated fault zone that separates the Southern Mountains zone (whose geology is dominated by middle Tertiary volcanic rocks) and the Yogyakarta Basin which is filled by Quaternary volcanic products of Merapi volcano. This conclusion is supported by the fact that after the Yogyakartta earthquake 2006, one hotspring nearest to the Opak fault zone has been cooling down in its temperature.

Another non-volcanic geothermal field is found at Kuwu village, about 60 km NE of Ungaran volcano. This geothermal activity is likely to be associated with a mud volcano. There are also several minor geothermal occurrences in East Java that cannot be related with active volcanism, e.g., the Melati and Rejosari villages, Pacitan district. As the geologic environments of these fields are within Tertiary volcanic belts, we interpret that geothermal phenomena are associated with another deep heated ater circulation along a geologic structure.

5.2 Ages

As most occurrences can be associated with a Quaternary volcanic complex, the ages of geothermal systems are Quaternary. Especially, the author believes that these high-enthalpy systems were mainly formed during the Upper Pleistocene; the ages of geothermal systems should be around 0.2-0.5 Ma. Some prospects are known to be located very near to active vent, such as such as the Kahara-Telaga Bodas (a vapor-type geothermal system) which is located just about 5 km of the vent of presently active Galunggung volcano (Bronto, 1990; Raharjo et al., 2002; Moore et al., 2002). However, its host rocks are of the Upper Pleistocene volcanic units (Fig. 5).

Upper Pleistocene subaerial volcanic units are therefore critical criteria for exploration of the high-enthalpy geothermal fields. Studying spatial-temporal evolution of arc volcanism during the Quaternary is important. For example, in eastern part of Central Java the geothermal fields are located within the backarc-side volcanoes of Dieng and Ungaran-Telomoyo as in this region volcanism during the Quaternary is migrating southward (towards the trench). On the other hand, the case of Kamojang-Darajat-Wayang Windu shows that geothermal fields are concentrated within volcanic front side as volcanism is migrating northeast-ward (towards the backarc side) during the Pleistoce-Holocene. For geothermal fields located within a more or less single and large stratovolcano such as Slamet, a volcanic stratigraphy study to find location of the Upper Pleistocene edifices is important.

5.3 Regional Seismicity

There is a general relationship between geothermal prospectivity and regional crustal seismicity. Figure 10 shows that the highly prospective West Java regional has also the highest crustal seismicity activities among the whole Java island. However, Kamojang-Darajat-Wayang Windu cluster is not sitting on a high seismicity zone but rather a low seismicity zone surrounded by high seismicity zones. The same evidence is found at Dieng and Ungaran in Central Java which are located at the edge of high seimicity zones.

5.4 Regional Heatflow

Figure 11 shows the heatflow map of Java island. High concentration of geothermal field areas such as West Java and northern part of Central Java are spatially associated with high heatflow region. East Java in overall has low heatflow values, except its backarc volcano zone and its eastern tip.

6. CONCLUDING REMARKS

Despite the generally accepted theory on geothermal systems in stratovolcano environment, the segmented volcanic arc in Java has resulted in a different prospectivity among arc segments. Both regional and local (district) scale segmentations are observed.

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.

At the district scale, spatial-temporal evolutions of Quaternary volcanoes play critical roles. The majority of large geothermal fields form within caldera of presumably Lower Pleistocene age, such as the Pangkalan caldera in Kamojang-Darajat-Wayang Windu cluster and the Dieng caldera in the Dieng geothermal field. The mechanism of geothermal development within these calderas is similar. After the caldera-eruption event took place, a large (>5 km in diameter) of volcanic depression was present. Within this depression, post-caldera volcanism took place during the Upper Pleistocene through the Holocene. Many of the volcanism events are of monogenic eruption type that produced small cones. Volcanism migrated into a certain direction, producing array of conical hills with gradual ages. Considering that a geothermal system needs considerable geologic time to form, the most prospective regions are surrounding the volcanic cones of Upper Pleistocene age. Current radiometric data suggest that geothermal fields are associated with magmas formed around 0.5-0.2 Ma.

For Quaternary volcanic domain that form large stratovolcano shape rather than caldera, understanding volcanic evolution through volcanostratigraphy mapping is critical. Many stratovolcanoes are in fact composed of several stages, e.g. older, middle and younger stages. Elucidating which stage is product of Upper Pleistocene event and identifying its eruption center is critical to select the most prospective region. In relatively well studied volcanic arc in eastern part of Central Java, the author can conclude that the geothermal prospectivity is the highest at the later stage of backarc-side volcanoes. This means the post-caldera stage of Dieng volcano and the young stage of Ungaran volcano.

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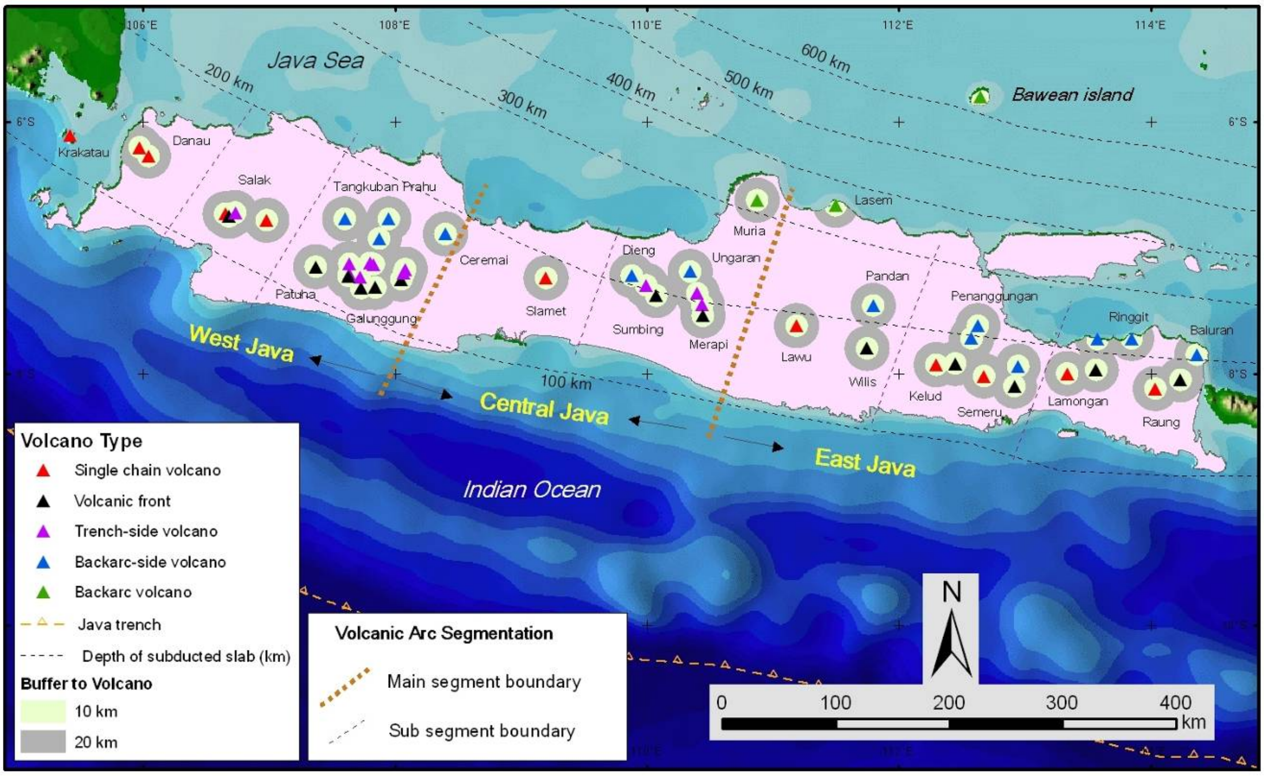

Figure 3: Quaternary volcanoes in Java island, Sunda Arc, Indonesia. Boundary zones of West, Central, and East Java segments, as well as sub segment zones are indicated.

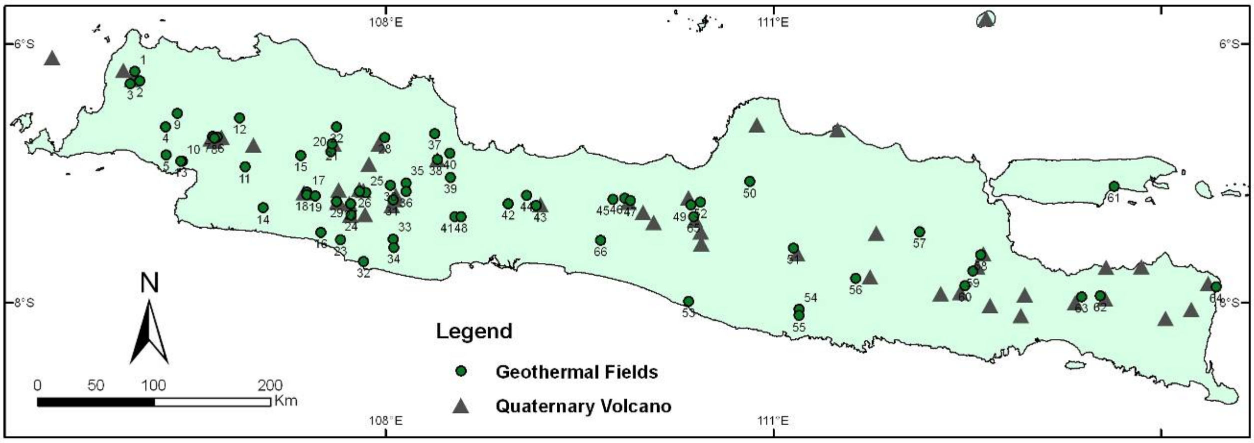

Figure 4: Known geothermal fields in Java. The shown numbers are ID numbers as listed in Table 1.

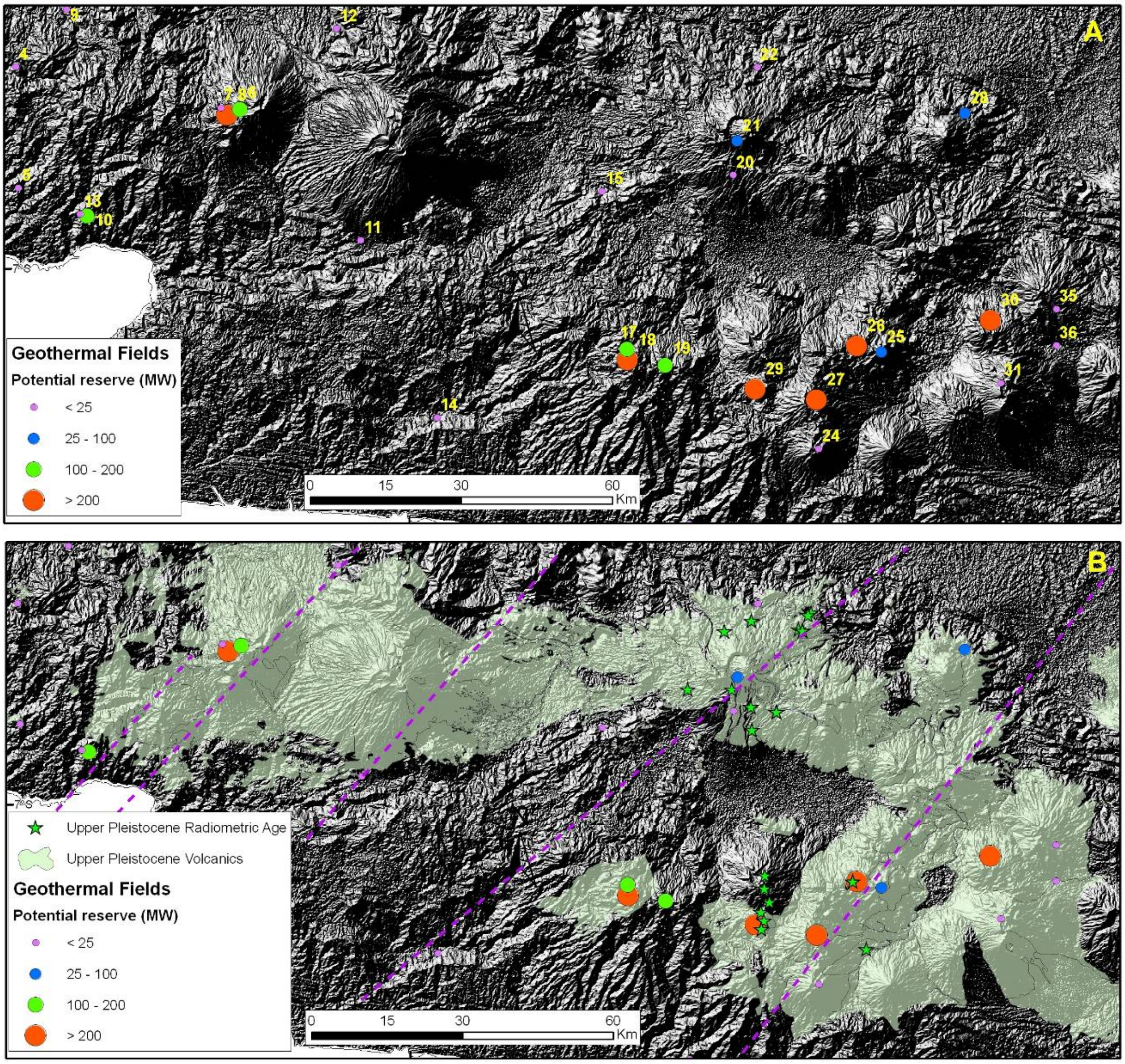

Figure 5: Distribution of major geothermal fields in West Java in relationship with topography (A) and volcanic units, radiometric dating of Upper Pleistocene, and major lineaments (B). Currently operating fields are located at two clusters, i.e. Kamojang (26), Darajat (27) and Wayang Windu (29) within Pleistocene caldera and Awibengkok (7) located at the Salak volcanic zone.

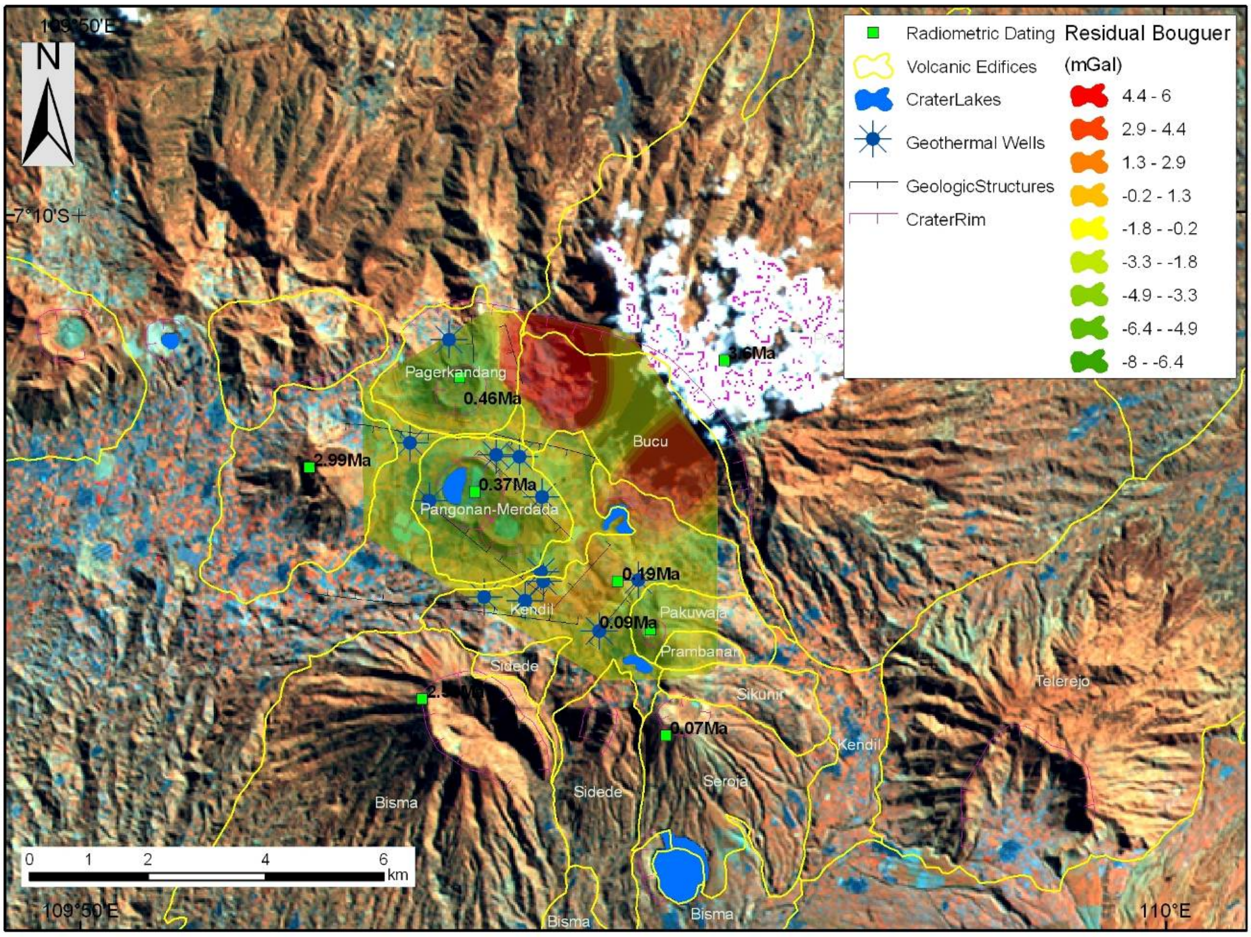

Figure 6: Location of geothermal fields within Dieng caldera suggesting volcanism of about 0.5-0.3Ma (i.e. Pangonan-Merdada and Pagerkandang volcanic events) as ideal age for formation of geothermal fields. Radiometric dates and gravity anomaly are taken from Boedihardi et al. (1991)

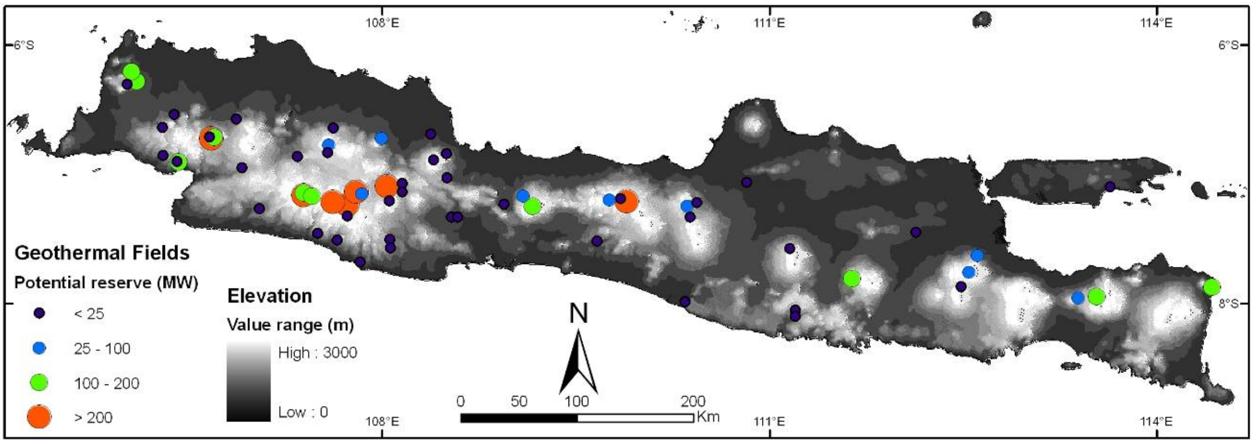

Figure 7: Map showing spatial relationships between locations and potential size of geothermal fields with elevation.

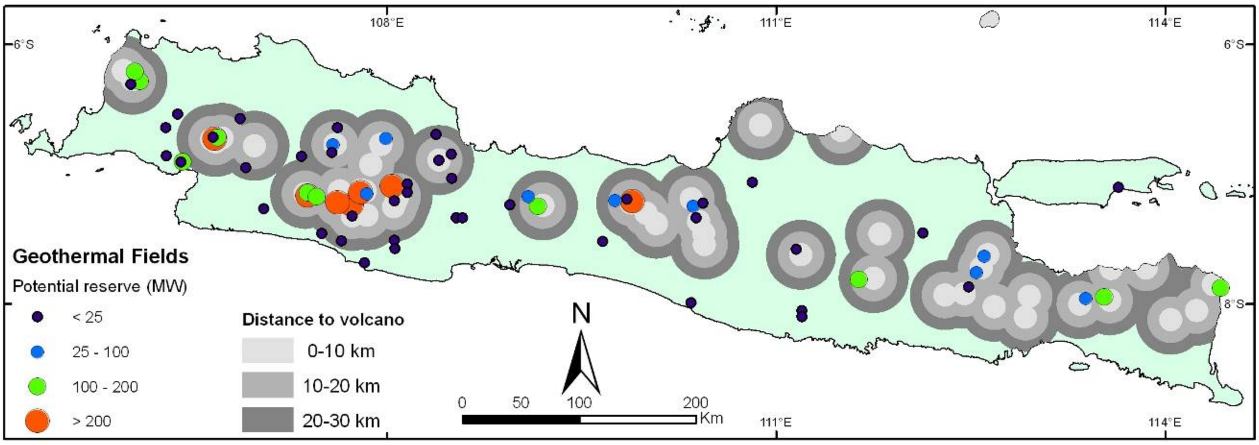

Figure 8: Map showing spatial relationships between locations and potential size of geothermal fields with distance zones from Quaternary volcanoes.

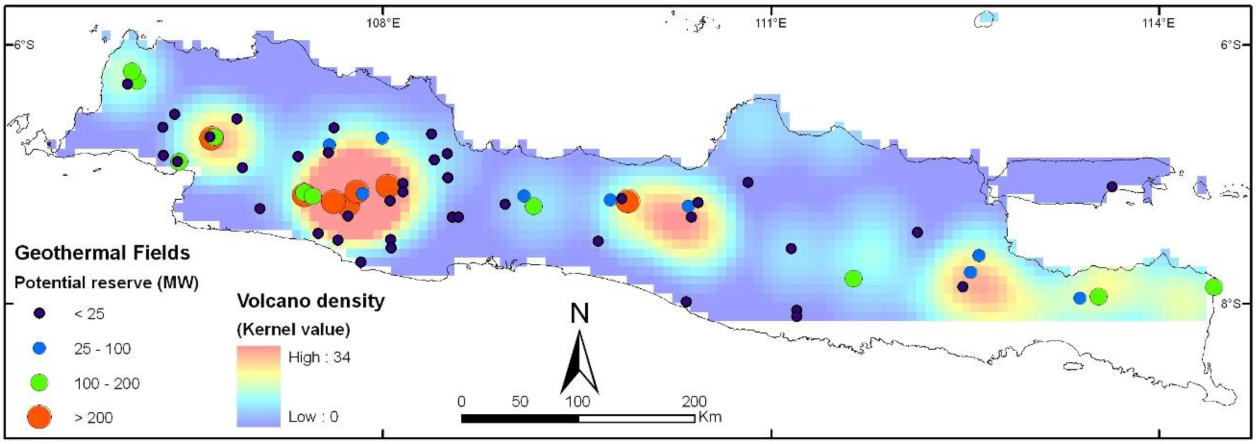

Figure 9: Map showing spatial relationships between locations and potential size of geothermal fields with volcano density values.

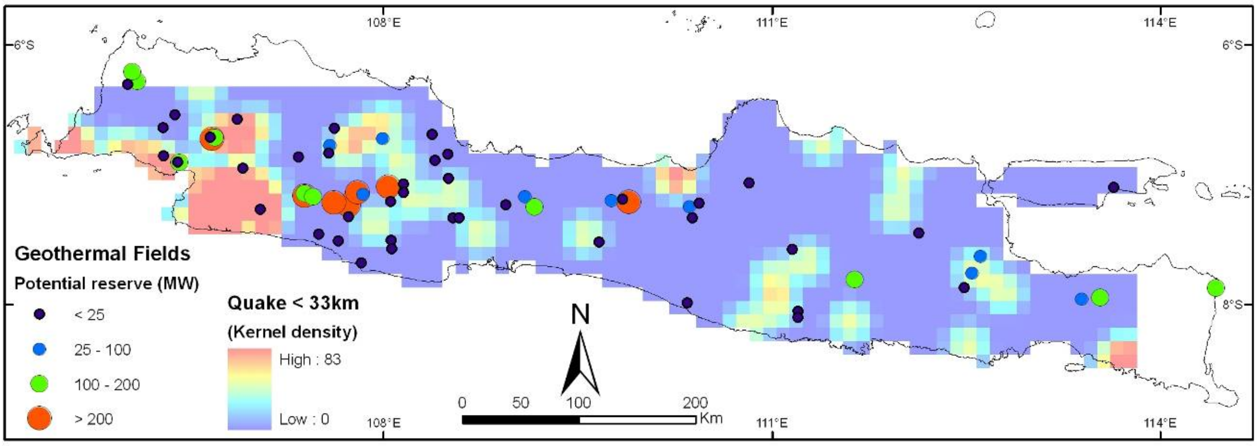

Figure 10: Map showing spatial relationships between locations and potential size of geothermal fields with crustal quakes.

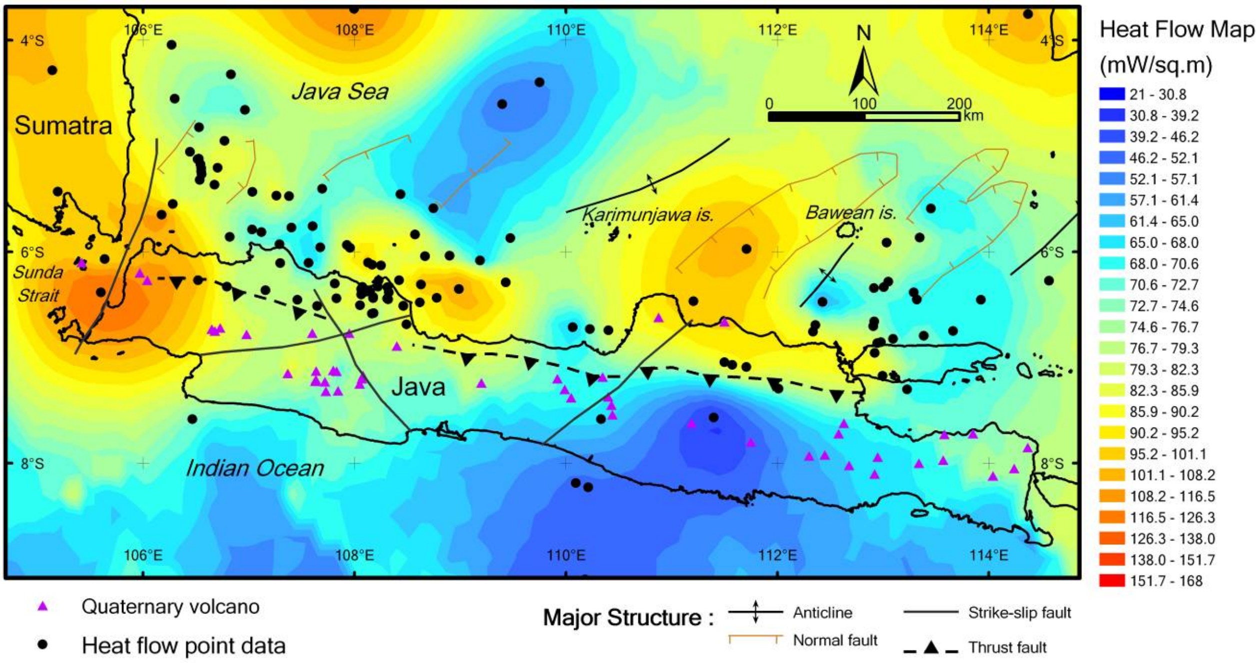

Figure 11: Heat flow map of Java island (after Setijadji, 2005).