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Regional Structure Control on Geothermal Systems in West Java, Indonesia

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ABSTRACT

Indonesia has been recognized to have large geothermal potential, possibly up to 4000 MWe. The resources are distributed at 256 geothermal areas and among of them, 40 locations are located in West Java Indonesia. Geothermal installed capacity in West Java is 839 MWe out of 1197 MWe of all geothermal capacity in Indonesia. Regional structure is very important in the geothermal system in providing conduits for magma ascent. In addition, the structure also provides the secondary permeability for the hydrothermal fluids, meteoric water, to be migrated, interacted and finally accumulated in the geothermal reservoir. Unlike geothermal fields in Sumatra that are controlled by the Sumatra Fault Zone, the geothermal locality in Java seems to be distributed randomly. No single regional structure has been associated with geothermal system in West Java. However, the enhanced regional Bouger anomaly of Java compiled with Regional Geology show that there are major structures, which are associated with the geothermal fields in West Java. The major structures in West Java that controlled the geothermal system are a Major Arc Parallel structure of West Java Fault trending at NW-SE and circular structures. These major structures controlled and associated with volcano-magmatic product in West Java. Those structures also correlate spatially with recent active hydrothermal activity, and also correspond with a fossilized geothermal system as indicated by hydrothermal mineralization occurrences in West Java associated with the structures. The kinematic analysis of regional structure reveals the extensional condition in West Java at NNW-N-NNE trending. The consistency of extensional setting in active and fossil geothermal system indicates that the structure control in geothermal system in West Java, is driven by regional structure.

1. INTRODUCTION

Structure plays important role in localizing geothermal fluid circulation. Structures provide conduits for magma to ascend to the upper crust that may act as the heat source in geothermal system (Corbett and Leach, 1998). Structures also generate the secondary permeability where the heat transfer, hydrothermal fluids, meteoric water, interact and accumulate in a geothermal reservoir. Some of the structure will breach the system and accommodate geothermal fluids to be exposed on the surface as geothermal manifestations. It can be generalized that the structure is involved in pre, syn and post genetic of the system. The explanation above also indicates that the control corresponds to different crustal levels. The role for localizing deep intrusions is controlled by deep-seated structure, whereas localizing hydrothermal fluids is controlled by the thin skinned structure.

Despite the importance of structure control, the geothermal system in West Java has never been associated with a major regional fault. In general, geothermal prospects in Java are highlighted to be associated with active arc volcano-magmatic (Hochstein and Sudarman 2008; Setijadji 2010). Carranza et al. (2008) also noted a close relationship of geothermal spatial distribution and regional-scale faults and lineaments, but the regional lineament was seen to be a regional surface structure. The issue of tectonic driven and kinematic of major structure in Java, especially related to geothermal system in West Java, is still open for discussion. This study proposes a delineation of major structures using different crustal identification, which are deep seated structure by regional Bouger anomaly and thin skinned structure from regional geology map. Then the proposed delineation of major structure is developed, to explain spatial correlation and kinematic characteristic of structure control in geothermal locality in West Java.

This study utilized the published geological map and anomaly Bouger map rather than remote sensing analysis or previous study or remote sensing lineament (e.g. Carranza et al., 2008), because the maps were produced from careful data inventory and research including both field geological mapping and remote sensing analysis. The advanced technology, especially computer applications, has opened the possibility to compile the large data sets for this study.

2. METHODS AND DATA SETS

For Java, there are about 55 regional geology maps (systematic geological map) and 55 systematic Bouger anomaly maps published at a scale 1: 100000 by Geological Research and Development Centre/Geological Survey of Indonesia. All map sheets has been scanned into registered digital raster files. The registration process and vector digitation of all data sets have been prepared using a computer software, MapInfo, in GIS laboratory of Research Center for Geotechnology, LIPI. The digital data sets consisted of vector and attributes of Geological Map and Regional Gravity Map of Java were use as base data for this study. In addition, the geographic map from Bakorsutanal was used for drainage pattern analysis to support the surface structure features. The geothermal locality for spatial correlation was collected from Hochstein and Sudarman (2008) included volcano locations (Smithsonian Institute and VSI) and hydrothermal mineralization localities (Sukirno, 1991 and various sources).

The basic concept for the analysis is to depict whether there is a correlation between the deep seated structure and surface structure, which can develop the general explanation on structure control on geothermal systems in West Java. The analysis conducted in this study include lineament's delineation, grouping of structure type, rose diagram analysis, and model comparison of tectonic-structure style. Lineament were delineated by visual interpretation on shaded relief anomaly Bouger of Java that is expected to be a representation of deep seated structure. The advantages of relief shaded visualization is to highlight a gradient of Bouger anomaly which can be assumed to be the sudden change of density caused by faulting. The application of shaded relief maps is proven to be beneficial in delineation of buried active fault (Yamamoto, 2003). The surface structure is represented by geological structure or faults from regional geology map. The analysis of surface structure also supported by the analysis regional drainage pattern of Java (base scale at 1:1000000). The polyline drainage patterns were thinned to have a lineament-like pattern. All lineament from regional Bouger anomaly, faults from regional geology map, and drainage pattern were extracted and imported into Rockware, a computer program, to be analyzed about the trending and pattern in rose diagrams. Structure characteristics, geothermal localities and volcano-magmatic products will be compiled to synthesize the general pattern of regional structure control in geothermal systems in West Java.

3. GEOLOGIC SETTING AND GEOTHERMAL SYSTEM OF WEST JAVA

Java is located at the southern part of Sunda Land of Eurasian Plate, where the Indian-Australian plate is subducted beneath Eurasian plate. Active plate convergence has produced arc volcanism and intrusion since the early Oligocene along the Sunda Arc. The plate convergence along the subduction zone can be divided into oblique subduction (western part of convergence) on Sumatra and adjacent area and frontal subduction (eastern part of convergence) that produce Java, Bali and Sumbawa islands (Hall, 2012) (Figure 1). West Java can be considered to be located at the transitional zone between oblique subduction in Sumatra and frontal subduction at the eastern part of West Java. The Indo-Australian plate is subducted under the Eurasian plate northwardly at N20^{o}E and at rate of 6-7 cm/yr in West Java area (Hall, 2012) (Figure 1).

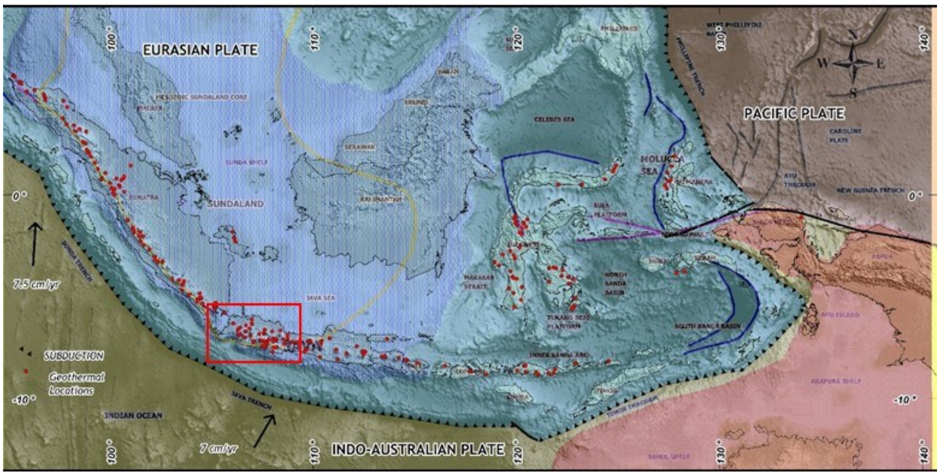

Figure 1. Present day tectonic setting of Indonesia (modified after Hall, 2012)

West Java can be divided into five different tectonic provinces, namely the: 1) Northern basinal area, 2) Bogor through, 3) Modern volcanic arc, 4) Southern slope regional uplift and 5) Banten block (Darman and Sidi, 2000) (Figure. 2). The Northern basinal area is composed of Eocene – Miocene sediment and covered by younger shallow sedimentary deposit in N-S trending rift basin; Bogor through consist of Tertiary deep water sediment, where the E-W anticline occur due to the Northwardly compression; The modern volcanic arc is composed by andesitic volcanism product that related to subduction process; Southern slope regional uplift or Southern Mountain (Bemmelen, 1949) consist of Eocene – Miocene sedimentary rock, Old andesite Formation (OAF) and complex structure; and Banten Block which is the western part of West Java can be divided in to three parts : the Seribu carbonate plat form, Rangkas-bitung Sub-basin and Bayah High (Darman and Sidi, 2000).

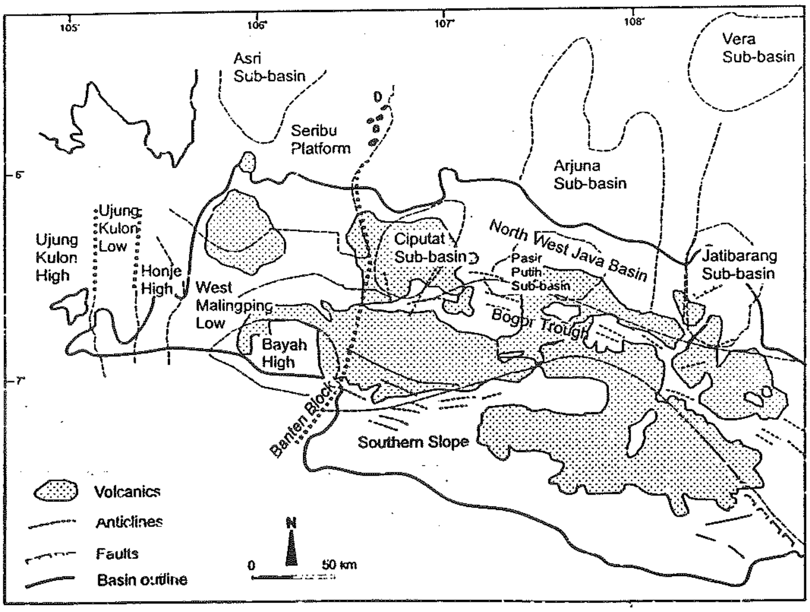

Figure 2. Summary of West Java Tectonic Provinces (from Darman and Sidi, 2000)

The volcano-magmatic arc in West Java is a subduction-related product that was developed since the early Tertiary. The Tertiary magmatic arc can be divided into two phases. The first phase took place at 40 Ma to 18 Ma, consist of tholeiites and some shoshonitic characteristics, while the second phase is took place at 12 Ma to 2 Ma and consist of tholeiites, medium-K calc-alkaline and high-K calc-alkaline magmatism (Soria-Atmadja et al. 1994). The latest magmatic arc was succeeded by Quaternary volcanism of Sunda Arc that composed of calc-alkaline to high-K calc-alkaline. The Quaternary volcanism was subdivided into young volcanic and old volcanic (Bemmelen, 1949), where young volcanic is late Pleistocene in age while the old volcanic is early to middle Pleistocene in age (Sunardi and Kimura, 1997). In West Java, there are two volcanic ranges, namely: volcanic front and rear arc (Sendjaja and Kimura, 2010). Based on geochemical characteristic from Tertiary and Quaternary volcanoes – magmatic product e.g. lava, the Sunda Magmatic arc in West Java has been in a steady state for the past 10 Ma. Such a steady state mechanism is required a sustained subduction system that continue unchanged over the past 10 Ma (Sendjaja and Kimura, 2010).

Structure patterns in Java can be divided into four groups which are: N-S trending of Sunda pattern, N-E trending of Meratus pattern, E-W trending of Java pattern and N-W trending of Sumatra pattern (Pulunggono and Martodjojo 1994, Untung and Sato 1978, Satyana 2007). The age of the structures are varying from Late Cretaceous (Meratus Pattern), Late Cretaceous to Paleocene (Sumatra Pattern), Eocene to Late Oligocene (Sunda Pattern) and Early Miocene (Java trend). Sumatra, Meratus and Sunda patterns comprise of strike slip and normal fault while the E-W trend of Java is thrust-reverse fault and folds (Satyana, 2007). From all structure patterns in Java, West Java area is highly dominated by N-W, strike-slip fault of Sumatra Pattern (Untung and Sato 1978 and Satyana 2007).

The West Java geothermal system is located in the western part of the Java Arc, which is one of five active arcs that have been associated to geothermal in Indonesia (Hochstein and Sudarman, 2008). There are 71 geothermal localities in Java (Hochstein and Sudarman, 2008 and VSI, 1998) distributed in West, Central and East Java (Figure 3). The population of geothermal localities in West Java province is 45 locations, which is the highest locality in Java and Indonesia in general (Setijadji, 2010). However, according to the geothermal field classification, introduced by Hochstein and Rossetti (2010), only 22 locations can be classified as a geothermal field in Java, while 14 of the fields are situated in West Java. Among of the localities, 4 fields have been classified as producing geothermal field ("brownfields") namely : Kamojang, Darajat, Wayang Windu and Awibengkok, while 6 fields has been classified as proven geothermal fields which are Citaman, Kawah Ratu, Cisolok, Cibuni, Patuha and Karaha. The geothermal fields in West Java are a major contributor of geothermal energy in Indonesia. From 1197 MWe installed capacity in Indonesia, which is the number 3 installed national capacity in the world, West Java supplied 86 % of it, around 1039 MWe (Bertani, 2012).

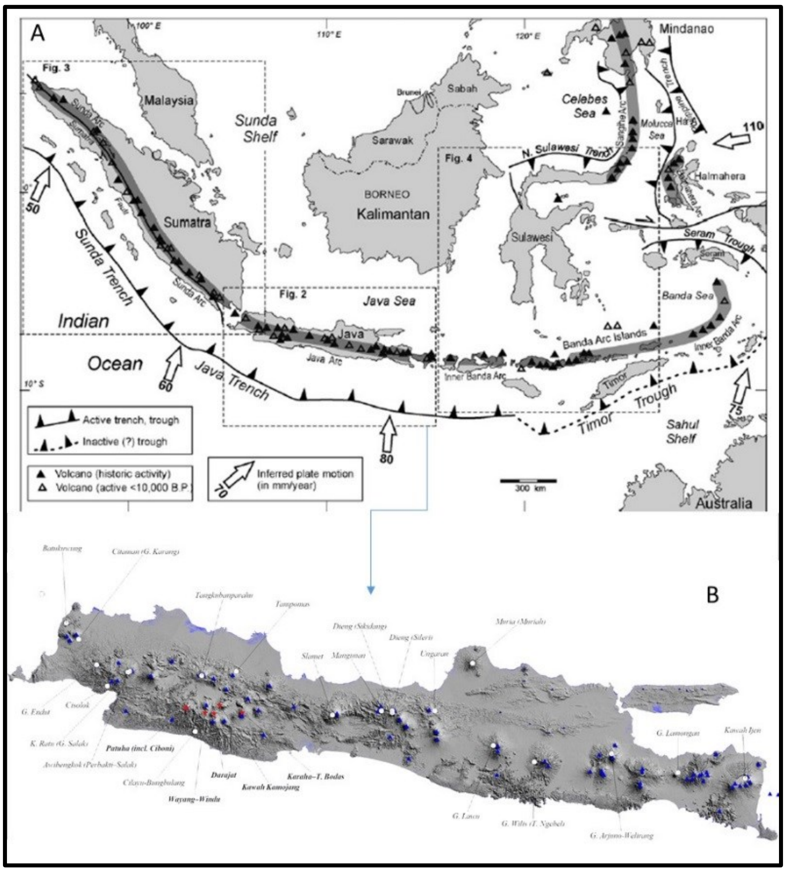

Figure 3. A. The active volcano-magmatic arc in Indonesia that associated with geothermal locations (Hochstein and Sudarman, 2008). B. The occurrence of geothermal field in Java, Based map is DEM of SRTM 30, geothermal field locations is adapted from Hochstein and Sudarman, 2008

Geothermal systems in West Java occur in vapor and liquid dominated systems. The geothermal vapor dominated system are included Kamojang, Darajat, Wayang Windu, Patuha and Karaha-Talaga Bodas (Raharjo, 2012) while the other fields such as Awi Bengkok, Tangkuban Parahu etc. are liquid dominated system. The occurrence of vapor dominated systems in West Java is unusual; there are only 8 locations in the world defined as vapor dominated systems, and 5 of them are located in West Java, especially clustered in central part of West Java. Vapor dominated systems require high potent and intensive heat source (Raharjo, 2012). The high potent of magmatic ascend require deep seated and tectonic driven as conduits (Corbett and Leach, 1998). Since the magmatic activity and structure is related, the structure has to be involved in localizing the thermal regime in West Java.

However, West Java geothermal systems have not been associated with regional faults like Sumatra's geothermal field. Furthermore, the conceptual of regional geological structure in Java is still open for discussion. Some studies of Java structure have been done with different results e.g. Situmorang (1976), Satyana (2007), Hall et.al (2007) and Clement et.al (2009). Conjugate faults of NW and NE trending that cross Java were proposed by Situmorang (1976) and Satyana (2007), while a thrusting fault model was proposed by Hall and Clements. More generally, theories regarding tectonics of Java also evolved when the occurrence of micro plate beneath East Java was indicated by Smyth et.al (2007) and Sribudiyani et.al (2003). Tectonic reconstruction from Hall (2012) that show Java used to have a similar elongation to Sumatra before rotated counter-clock wise; this, along with supporting paleomagnetic evidence (Ngkoimani, 2006) raised new questions regarding the structural evolution in Java and West Java in particular.

4. RESULT AND DISCUSSION

Analysis of Regional structure control was conducted on two main data sets: 1). surface structure from regional geology map and major drainage pattern and 2) regional Bouger anomaly for deep crustal level. The basis of the analysis is an application of a simple analogue of deep seated structure and surface structure relationship as resulted from the rigid base and clay of Riedel's clay model experiment (Tchalenko and Ambraseys, 1970; Tchalenko, 1970 and Bless and Feuga (1986) in Corbett and Leach, 1998) (Figure 4). The basic model analogue will be based on strike slip deformation due to the fact that both oblique and frontal subduction setting that might contribute in Java tectonic will be accommodated by wrench faults in the upper crust.

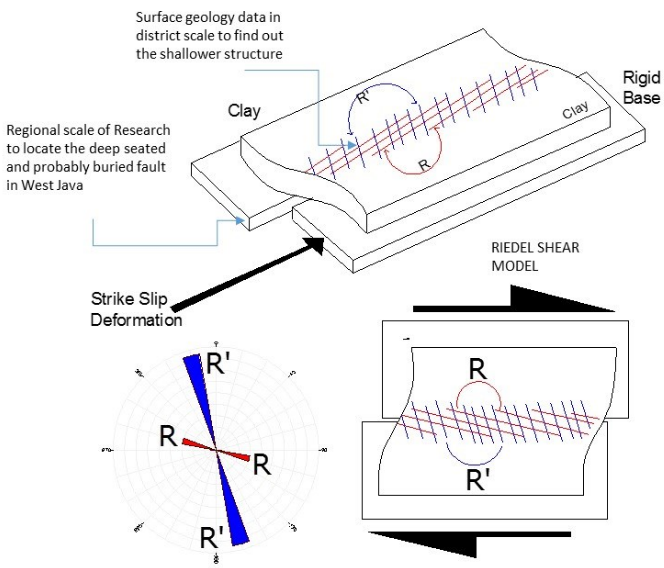

Figure 4. The concept for sub surface and surface structure based on Riedel clay experiment (modified after Tchalenko and Ambraseys (1970) in Corbett and Leach, 1998)

4.1 Surface Structure Characteristic

An analysis of surface structure was based on review of the regional geology map and drainage pattern in West Java. The structural map, consisting of fault and fold, was digitized from a compilation of registered regional geology map sheets. More than 55 sheets have been digitized for further research (Figure 5, 1 to 3). A half of all data, which cover West Java, is analyzed for surface structure study. The main reason for use of fault lines from the regional geology map, published by Geological Survey of Indonesia, is because the mapping was conducted using a systematic geological research process.

In general, geological structures in Java can be divided into fold and fault. Folds in West Java, consist of anticlines and synclines, have a major trend in E-W or about N 90^{o}E to N115^{o}E; N270^{o}E to N285^{o}E (Figure 5). Based on the frequency shown from rose diagrams, structures in West Java are dominated by faults. Faults in Java occur in all direction of rose diagram quadrants, however the maximum trend of fault is NNE-SSW or ranging from N0^{o}E – N20^{o}E. The structure from regional geology map indicates the major trend for the surface structure. This characteristic also supported by drainage pattern which shows a similar rose pattern to the fault rose diagram (NNE-SSE trend).

4.2 Structure Identification from Regional Bouger Anomaly Map

More than 55 sheets of Systematic Bouger Anomaly Map, that cover all of the Island of Java, have been registered and the Bouger anomaly contour lines of the map have been digitized. During the vector tracing, the value of Bouger anomaly in mgal has been assigned in the contour line as attributes. Therefore the nodes extraction of the contour line will have attributes x, y and Bouger value as z value. The nodes extraction was applied to maintain the exact shape of Bouger anomaly contour in the gridding process, where gridding process was conducted using Oasis Montaj Software. After the grid file has been produced, relief shaded display utility was applied in N-S lighting. The series of relief shaded Bouger anomaly process is shown in the Figure 6 (A to D). The process of regional Bouger anomaly has been presented to determine the spatial correlation of hydrothermal mineralization and deep seated structure in Java (Ismayanto et.al, 2007).

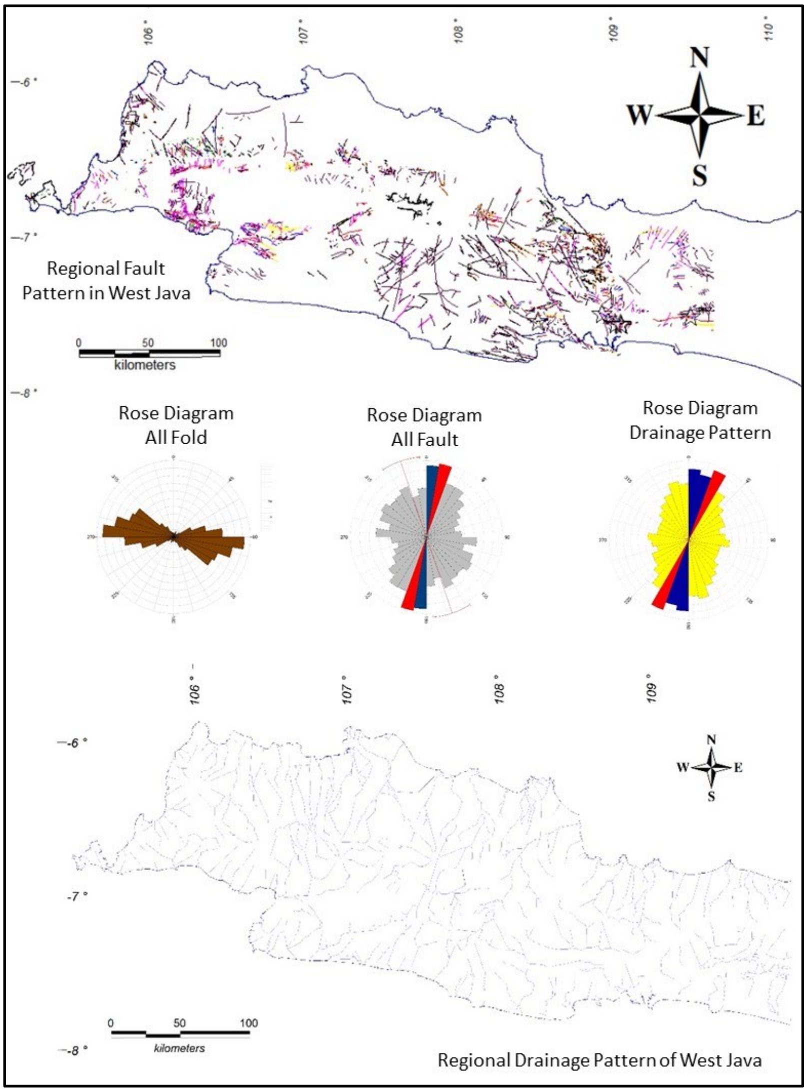

Figure 5. The characteristic of surface structure as indicated by regional structure geology and regional drainage pattern of West Java

The visual delineation of lineaments from a high gradient shaded zone of Bouger anomaly gridding (Figure 7), that is assumed to be a sudden density change due to the structure or faulting, has been applied to determine the structure style and characteristics. The visual lineament delineation was using on screen digitalization at scale 1 cm: 30 km on a computer application (MapInfo). The delineation of all visual lineaments can be divided into major and minor lineaments. Major lineaments are more distinctive and longer than minor structures. The visual identification of relief shaded Bouger anomaly map depicts a distinctive E-W; WNW-ESE trending of shaded lineaments in the middle part of West Java (Figure 7 and black thick dashed polyline in Figure 8). Even though the shaded lineaments are highly dissected by several cross-cut shaded zones, the lineament is still highly noticeable to be delineated. This major lineament or West Java Fault is cut by other major lineaments predominantly in NW trend, NE-SW trend and N-S trend.

All delineated lineaments from relief shaded Bouger anomaly are shown in the Figure 8. The rose diagram of all lineaments from regional Bouger anomaly indicates the maxima trend on N300^{o}E to N345^{o}E, where general trends of lineaments are ranging from N270^{o}E to N360^{o}E (Figure 8).

The other structure that occurs based on relief shaded Bouger anomaly identification is circular features. The most distinctive circular feature can be identified in the central part of West Java, indicated by low Bouger anomaly (cyan and green in color) or low anomaly Bouger value at less than 19 Mgal (Figure 7 and 8). This circular feature is situated at Garut area, called Garut Circular Feature or Garut Basin. The second circular feature is larger than Garut Circular Feature, but less clear for identification. Garut Circular Feature is likely situated at the southern part of this larger circular feature called West Java Circular Feature. The circular feature is crossed by West Java Fault in the middle. Furthermore, circular feature also occurs in the most western part of West Java, which is called Banten Circular Feature, however the identification of this circular feature was not clear.

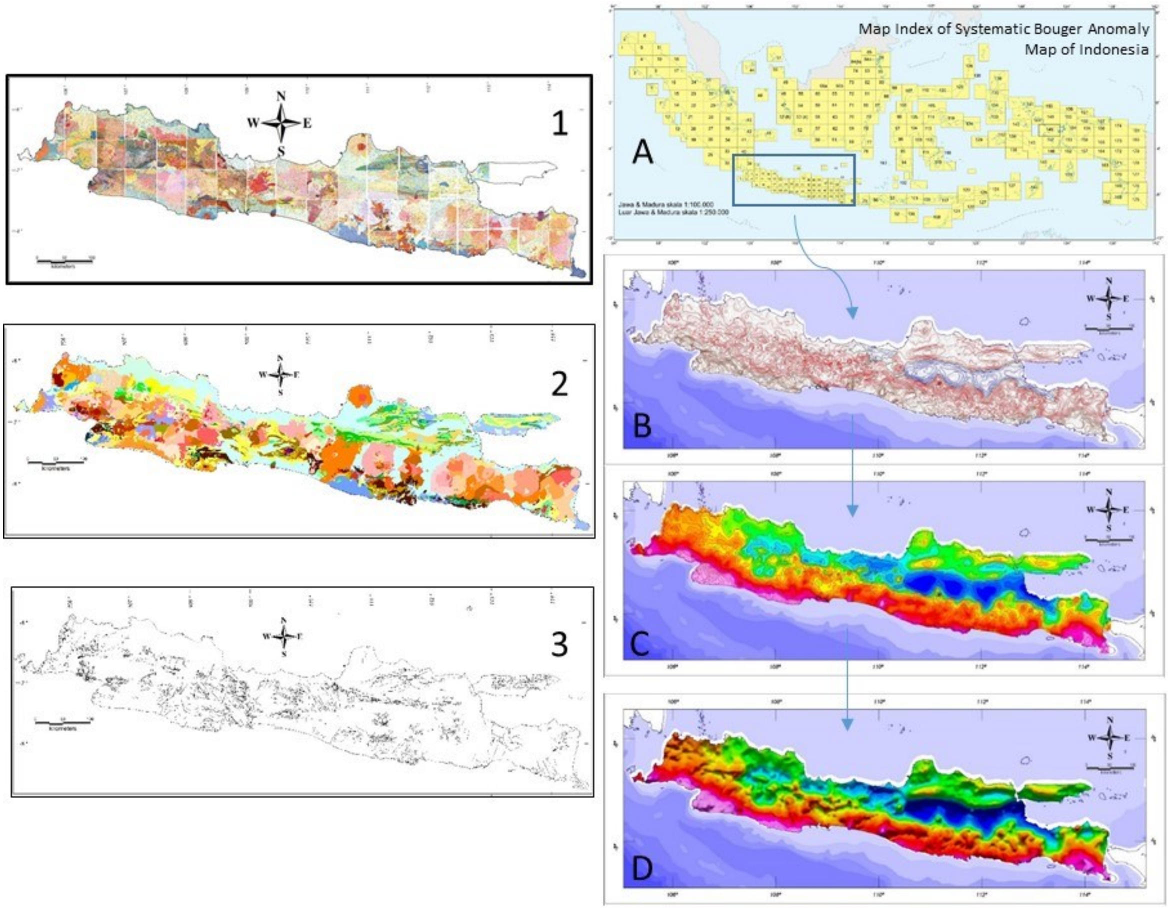

Figure 6. 1 shows the registered raster map of regional geology sheets map, published by Geological Survey of Indonesia where 2 is the digitized rock unit of regional geology in Java and 3 is digitized structure map in Java that will be used in this study. A is the index map of regional bouger map (Geological Survey of Indonesia) which has been digitized into contour. B to D show the steps of regional bouger anomaly processing since the contouring (B) and gridding (C) and finally the relief shading process (Ismayanto et.al, 2007).

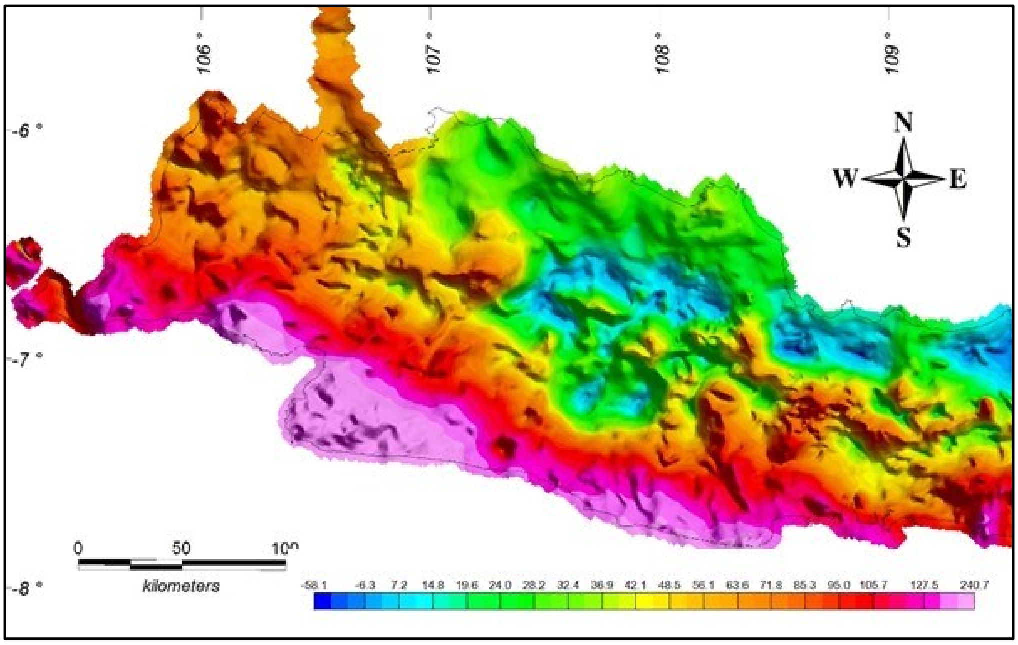

Figure 7. The relief shaded Bouger anomaly map of West Java

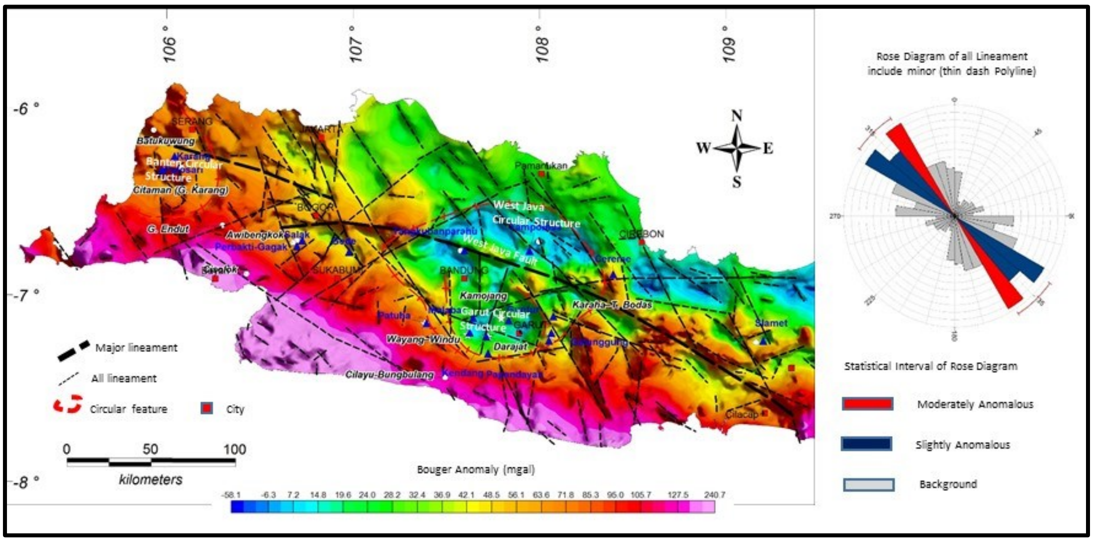

Figure 8. Delineation of lineaments from relief shaded bouger anomaly map of West Java

4.3 Regional Geological Structure Characteristic of West Java

According to each data set above, there are some differences in trending between surface structures from regional geology maps and subsurface structures from regional Bouger anomaly. While the surface structures are dominated by N-S and NNE-SSW trending faults and lineaments, the deep seated structure from regional Bouger anomaly depicts the major trend of NW-SE and WNW-ESE. The Riedel clay experiment is used as a model to explain and synthesize the difference. The difference of trend is actually showing the different crustal, according to the following explanation. If the dextral fault from rigid body in Riedel's clay experiment is adjusted or rotated to the West Java Fault trend (NW-SE; WNW-ESE), then structure on the clay (synthetic R and antithetic R') will show the N-S to NNE-SSW trending (Figure 9). Coincidently, the adjusted clay surface pattern as shown on its rose diagram, is similar to the surface structure geology pattern in West Java (Figure 9). Therefore the N-S to NNE-SSW tending surface structure is the surface manifestation of NW-SE to WNW-ESE deep structures. By applying the Riedel's clay experiment model, the differences between the two data sets that represent sub surface and surface structures are understood. Based on the model, West Java is highly dominated by NW-SE strike slip tectonic regime and the major fault related to the regime is West Java Fault with major trend at NW-SE (approximately at N300^{o}E in azimuth). The other trend of lineament, from relief shaded Bouger anomaly, can be divided into NW-SE trend, NE-SW trend, and N-S trend. The NW-SE and NE-SW trending lineaments show the conjugate characteristic. However, according to frequency data as shown by the rose diagram, the predominant trend is NW-SE trending. It can be assumed that the deep seated structure in West Java is dominated by NW-SE trend and represented by West Java Fault as a Major Structure in West Java.

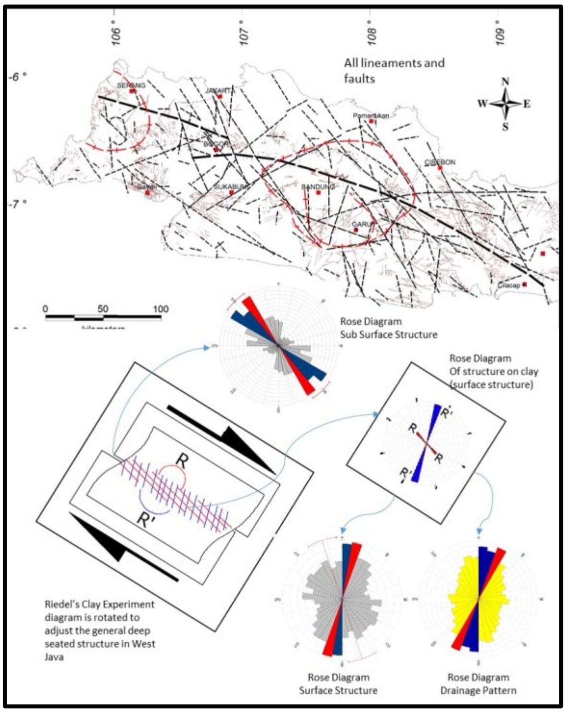

Figure 9. Model analysis of regional structure pattern (sub surface and surface) based on Riedel's clay experiment (adapted from Tchalenko 1970 in Corbett and Leach, 1998)

After the general characteristics of regional structure in West Java can be synthesized using the Riedel's clays experiment, the kinematic parameters of the structure can be identified by applying the complete Riedel Shear Model. The most important kinematic parameter to be identified is the extensional setting or dilational condition. By rotating the Riedel Shear Model as the same as the rotation of Riedel's clay experiment model to be fit with the West Java structure pattern, it can be discerned that the general extensional system in West Java is N-S (Figure 10). However, according to a dynamic approach of dilational condition adapted from vein development models (Corbett and Leach 1998), the extensional setting in West Java may vary at NNW–N-NNE trend, depend on degree of shearing process (Figure 10). Other than extensional setting, the applied Riedel shear model is also consistent to the fold direction in West Java that is approximately E-W trending.

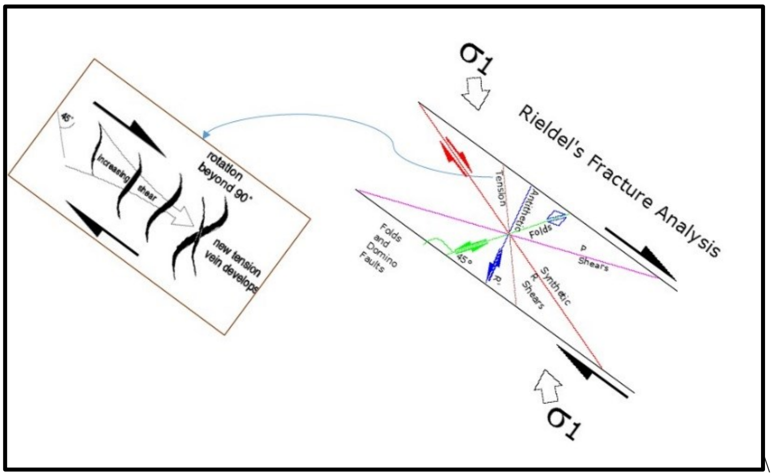

Figure 10. The extension and dilational condition in West Java is NNW-N-NNE according to rotated Riedel Shear Model in the general direction of deep seated fault in West Java and the extension is correspond to degree of shearing variations (Modified after Corbett and Leach, 1998)

The delineation of WNW-ESE of West Java Fault crosses at the middle part of West Java; along Cilacap – Bandung-Bogor-Banten, is a new concept of regional fault in West Java that is different from all previous studes on Java's structure (Figure 11) (c.f. Situmorang, 1976; Satyana, 2007; Hall and Clement, 2007 and 2009; and Untung and Sato, 1978). Situmorang (1976) applied the Moddy n Hill model to explain the regional structure in West Java and suggested major conjugate fault of NW-SE and NE-SW Fault in Java, where in West Java there was only an E-W trend third order /minor fault (Figure 11.A). The model has been developed by Satyana (2007), which included some geological data e.g. disappearance of Old Andesite Formation in the central Java due to the high compression and the indentation of Java coastline. The applied stress-strain ellipsoid model delineated conjugate major faults to accommodate the frontal-orthogonal subduction, namely NW trending of Pamanukan-Cilacap Fault and NE trending of Kebumen-Muria Fault in Java (Figure 11.B). The different approach and proposed model was developed by Hall et al. (2007) and Clements et al. (2009). This latest study preferred to apply thrusts to accommodate the N-S frontal subduction in Java. There are two main thrust faults parallel to the island, namely Southern Mountain Thrust and Barbaris-Kendeng Thrust (Figure 11.C). Previous study of regional gravity by Untung and Sato (1978) delineated the conjugate faults as major faults in Java. The study was the first to propose the Sumatra trend in Java's structure, especially in West Java. It was shown by NNW-SSE faults in West Java (Figure 11.D). However, the West Java Fault, which is located in central part of West Java was not delineated. Probably due to the difference in data or contour density, the fault could not be identified, especially when the fault is highly dissected as shown in the figure 7 and 8. Untung and Sato (1978) study was based on 10 to 20 mgal contour interval of Bouger anomaly, while this study is based on 2 to 5 mgal contour interval of Bouger anomaly.

The West Java fault is an arc parallel fault according to regional fault model in the subduction setting (Corbett and Leach, 1998). Arc parallel fault can occur in both oblique and frontal or orthogonal subduction setting (Figure 12). If West Java is dominated by Strike-Slip structure regime and represented by an arc parallel major strike slip, then the tectonic setting of the structure is more fit with oblique subduction setting rather than with frontal subduction setting (Figure 12). However, present tectonic regime of West Java is an orthogonal subduction (Hall, 2012). It can be argued here that West Java Fault probably the remnant of previous structure style when West Java was in oblique subduction. Probably, West Java started to change in the subduction setting because of the northwardly collision of East Java Micro Plate at Late Cretaceous to Early Eocene (Sri Budiyani, 2003). The plate convergence changed at 10 Ma in Sumatra in oblique subduction and Java in orthogonal subduction (Hall, 2102). By this mechanism, West Java was rotated counter clock wisely as indicated by paleo-magnetic evidence (Ngkoimani, 2007).

Major strike slip tectonic can develop favorable condition for magmatic activity. The negative flower structure in wrench fault is one of many conditions that has been proven to be favorable in localizing magmatic product and late stage hydrothermal products in different crustal level (Figure 13) (Corbett and Leach, 1998). The upper part of negative flower structure is a pull-apart basin which is bounded by faults. This setting is similar to the West Java Fault and Garut Circular Feature or Garut Basin. Garut Circular Features also consisted of abundant heat and mass transfer's product that indicate the occurrence of magmatic intrusion from deeper source as indicate by the model (Figure 13).

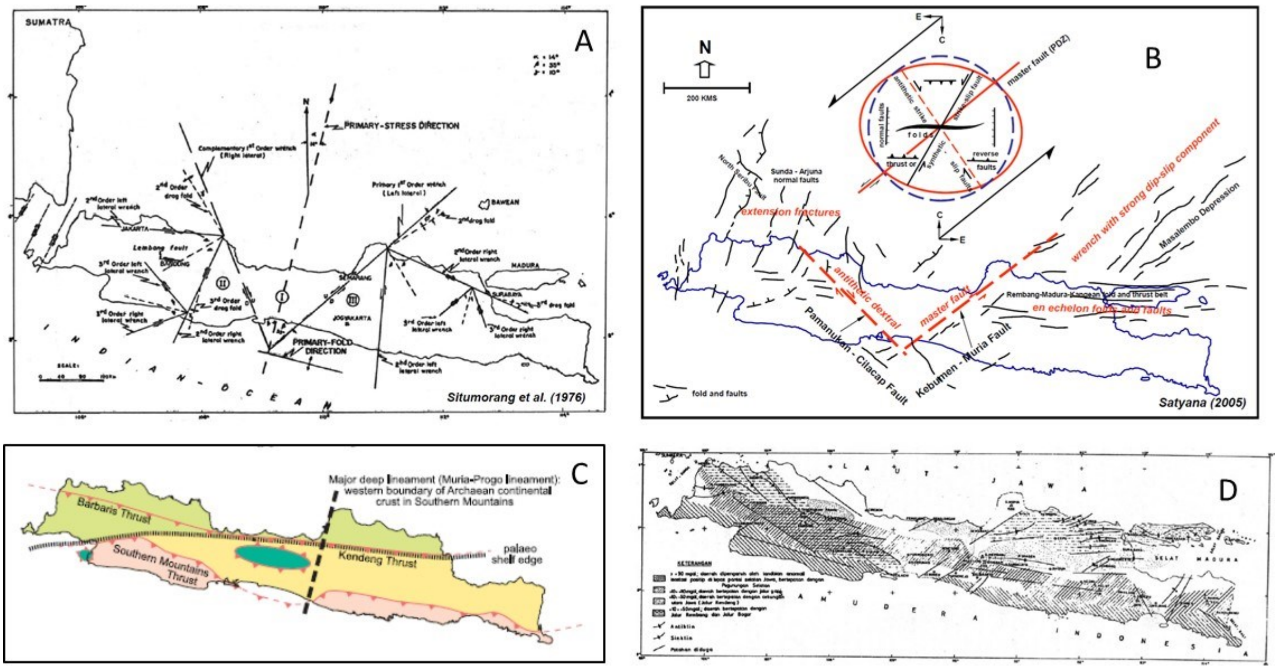

Figure 11. Various interpretation of Java's structure from previous study as discussed in the text A. Java's structure from Situmorang (1976); B. Java's structure from Satyana (2007); C. Java's structure from Clement and Hall (2009) and D. Java's structure from Untung and Sato (1978)

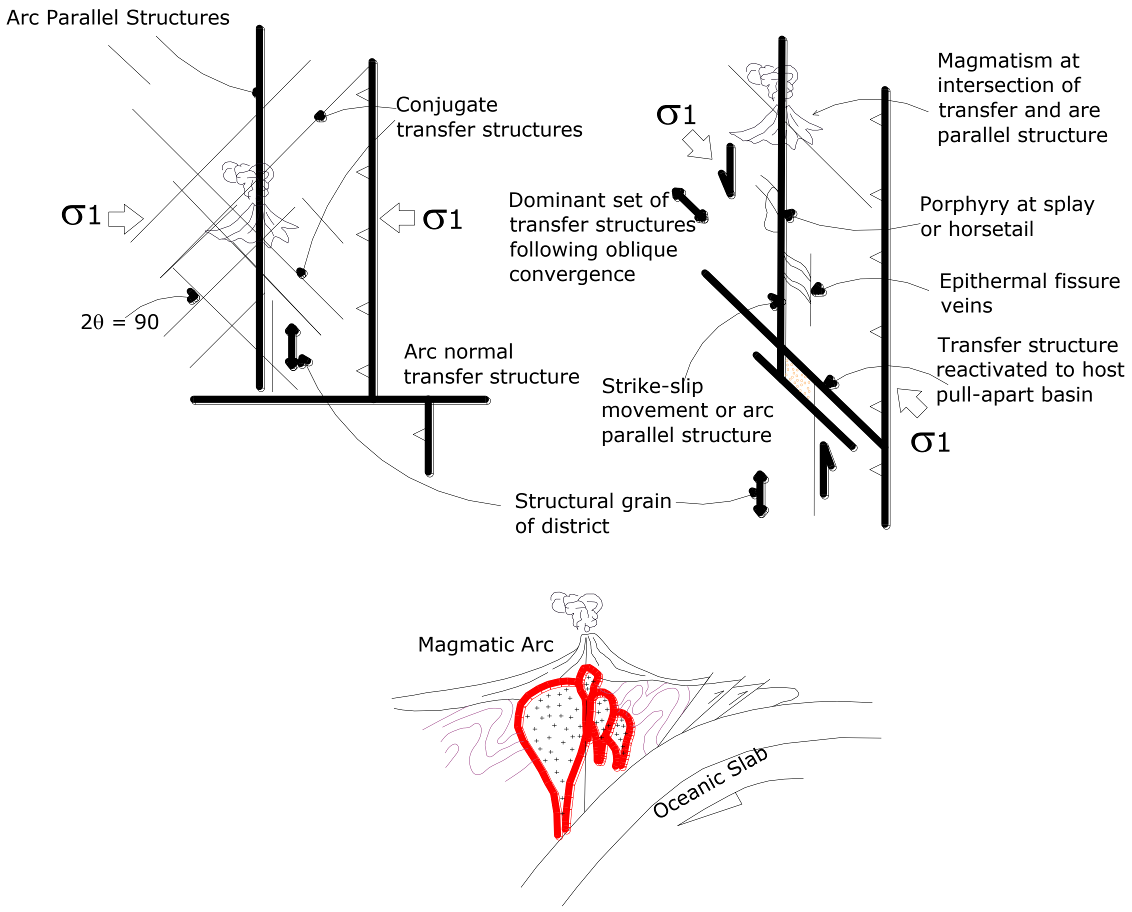

Figure 12. Arc parallel structures in orthogonal and oblique subduction setting, as a deep seated structure to provide pathways for magmatic intrusion (Corbett and Leach, 1998)

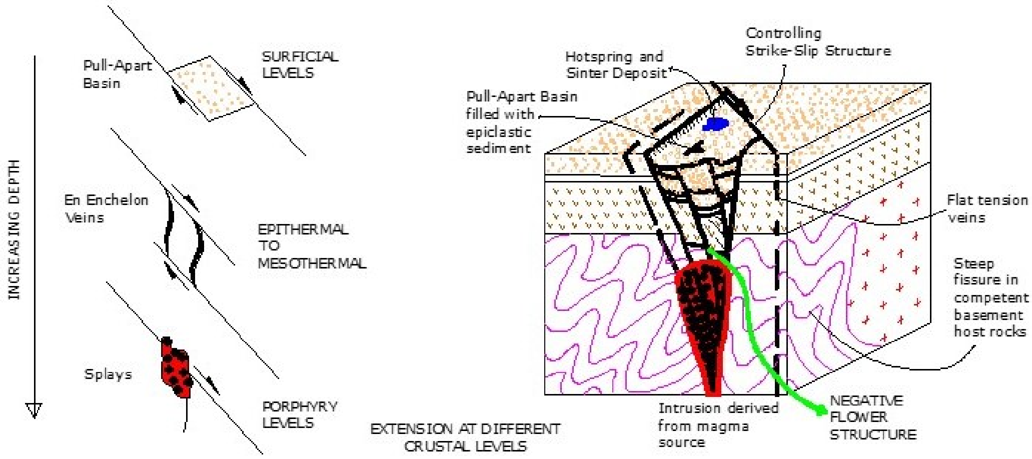

Figure 13. The extension setting at different crustal levels on negative flower structure in a wrench fault system. The model has been applied to explain the role in localizing porphyry intrusion, and lower to upper of hydrothermal mineralization (modified after Corbett and Leach, 1998). The role of controlling strike slip structure is similar to West Java Fault's role and the resulted basin from pull apart mechanism can be associated with Garut circular feature or Garut Basin

4.3 Regional Structure Control on Geothermal System

Structure control in geothermal system is divided into two major roles. Firstly, 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 favorable condition for secondary permeability in fluids interaction and accumulation (Corbett and Leach, 1998). West Java Fault plays an important role in localizing magmatic activity in West Java, as shown by the positive spatial correlation where volcano-magmatic products is located along the fault. The localities are (Figure 14 and 15) : (from east to west) : Pantai Ayah (HM); Cimanggu and Majenang (HM); Cireme and Tampomas (AV and GF); Tangkuban Parahu (AV, GF); Subang Hill (HM), Cariu and Parang Hill (HM), Gede-Pangrango (AV), Gn. Salak - Awibengkok (AV and GF) and Pongkor (HM). Circular features are also associated with volcano magmatic product, especially Garut Circular Feature. In Garut Circular Feature, the clustered magmatic product is located along the rim structure and within the circular structure which are: Karaha – Talaga Bodas (GF); Galunggung (AV); Cikuray (volcano); Papandayan (AV and GF) and Patuha (GF); and proven geothermal fields within the structure namely: Kamojang, Darajat, Wayang Windu, and Guntur-Masigit (AV and GF). The positive spatial correlation of volcano-magmatic localities is also shown in West Java Circular Feature. The localities associated with the structure are: Patuha (AV and GF); Gede-Pangrango (AV) at the western rim; Ciremai (AV) at the eastern rim and Tangkuban Parahu (AV) in the central part of the circular feature. Some localities can be associated with both West Java Circular Structure and West Java Fault. The third circular feature, Banten circular feature also consisted of volcanic rocks and there are some thermal features within the structure e.g. geothermal fields: Batukuwung, Citaman and Gunung Karang (GF and AV).

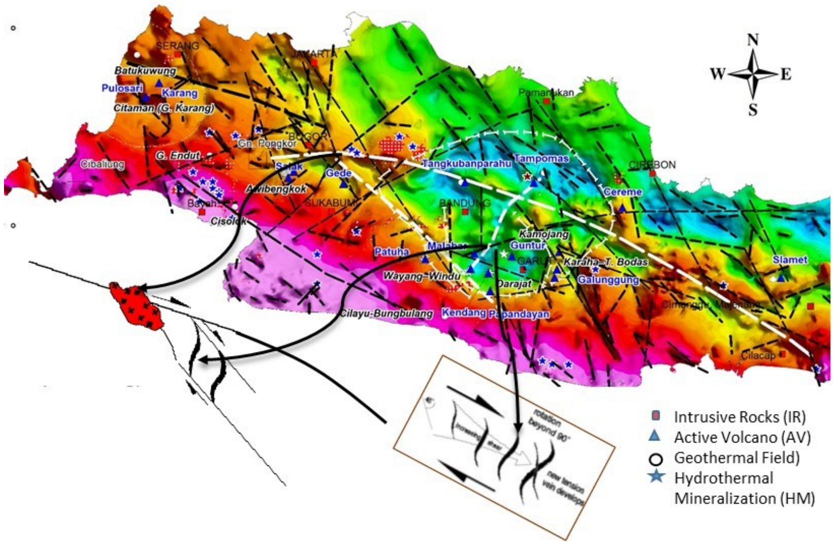

Figure 14. The overlaid map of volcano magmatic products and structure map of in West Java. The structure control is explained based on splay and echelon like structure (adapted from Corbett and Leach 1998). The volcano-magmatic products are active volcano (AV) from Smithsonian institute, intrusive rock (IR) from regional geology map, proven geothermal fields (GF) from Hochstein and Sudarman (2008) and hydrothermal mineralization localities (HM) from Sukirno (1997) and various sources.

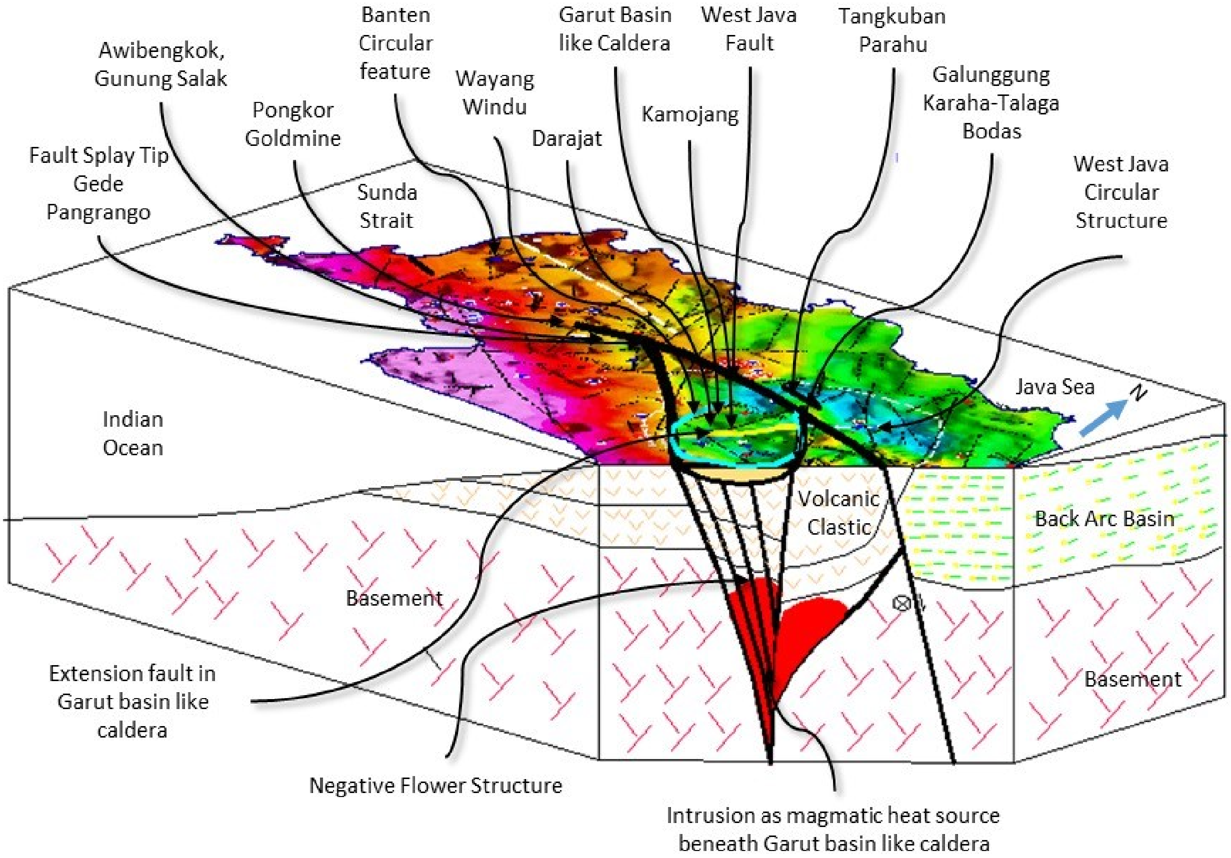

Figure 15. 3D block diagram of proposed model of controlling role of Regional Structure using a negative flower structure model on geothermal system in West Java (adapted from Corbett and Leach, 1997)

West Java Fault and Garut Circular Feature are different structures, but genetically the structures are related. 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. The fault splays are Salak-Gede-Patuha-Malabar-Papandayan fault and Tangkuban Parahu – Karaha – Galunggung fault. These two main splay faults formed a basin by pull apart mechanism, which is a regional extension where in the middle part of the basin is the main conduits for magmatic intrusion (Figure 15). It can be hypothesized that high potent magmatic activity in the central part is associated with unusual cluster of Vapor dominated System in the center part of Garut Circular Feature (Kamojang, Darajat and Wayang Windu).

While the first role is represented the role of structure in regional extension for magmatic conduits, the second role of regional structure control in geothermal system is providing an extensional condition in a local or prospect scale for fluids accumulation in geothermal reservoir. Based on Riedel Shear Model, the extensional setting in West Java is N-S in general and varies at NNW-N-NNE trending depend on degree of shearing. This extensional trend is shown in Kamojang Geothermal field where fault trends at N60^{o}E is controlled the heat source locality and faults trend at N140^{o}E is tensional faults for drilling targets (Robert et.al, 1983; Suryadarma et.al, 2010). The consistency of extensional setting is also found in Darajat geothermal field where N60^{o}E trending of Gagak Fault has been proven to be a favorable fault in providing permeability zone (Hadi, 2001; Pramono B, 2001; Herdianita, 2012). In Wayang Windu, which is located at the west of Kamojang-Darajat complex, the similar extensional setting also occurs. The major trend for fluid is at N40^{o}E which has been proven to be a permeable trend by drilling program in Wayang Windu (Boogie et. al, 2008).

The extensional pattern is also found in geothermal fields out of Garut circular feature's cluster. In Awibengkok, which is associated with West Java Fault, the E-W fault is responsible in locating deep intrusions, while shallow N-NE trend faults are responsible to the up flow zone (Stimac et al., 2008). The local structure characteristic is aligned with regional pattern in the area, where E-W fault associated with West Java Fault and the N-NE trending is the general pattern of extensional setting in West Java. In Karaha Bodas, the general pattern of NS extension pattern is also found in fracture scale within the geothermal reservoir (Nemcock et al., 2001).

Interestingly, the NW-N-NE extension trends, which resulted from major structure control, are also shown in the fossilized geothermal system indicate by vein trends. The mineralization in West Java is dominated by epithermal low sulfidation type characterized by vein system e.g. Pongkor (Basuki et.al, 1994, Syafrizal et.al 2005), Cikidang (Rosana and Matsueda, 2002), Gunung Subang (Ismayanto et.al, 2009), Ciarinem (Yuningsih and Matsueda, 2014) and Cibaliung (Agung H et.al, 2007). Vein is a dilational condition when opening fracture filled by minerals. The vein trends of hydrothermal mineralization are N-S in Pongkor. In Ciarinem veins striking is or N20^{o}W to N10^{o}E (Yuningsih, 2014). Northwest from Ciarinem, there is a vein system in Gunung Subang striking at N10^{o}E (Ismayanto, 2007). Cikidang prospect also has a veins trend in N-S direction (Rosana and Matsueda, 2002). Similar trend of N-S dilational setting is also found in Cirotan and Cibaliung where the vein system striking is at N10^{o}E. (Agung H. et.al 2007).

The hydrothermal mineralization ages in West Java varying at 11.18 – 10.65 Ma for Cibaliung; 2.4 to 1.5 Ma for Pongkor, Cikidang and Cirotan and 9.4 to 8.8 Ma for Ciarinem (Agung H et al., 2007; Marcoux & Milesi, 1994; Milesi et al. 1999; Rosana and Matsueda, 2002 and Yuningsih and Matsueda 2012). The age of mineralization shows that the tectonic stress regime provides similar extensional setting of fossil geothermal systems and active geothermal systems, and is stable for at least 11 ma according to the oldest mineralization in West Java. The suggestion is similar to the geochemical characteristic of magmatic products in West Java that show the stable condition for the last 10 Ma (Sendjaja, 2012).

5. CONCLUDING REMARKS

In West Java, there are different trends between surface structure from regional geology map and deep-seated structure from regional Bouger anomalies. The difference is a representation of different crustal levels, where N-S and NNE-SSW surface structures are surface manifestations of deep NW-SE and WNW-ESE structure according Riedel's clay experiment. The applied model suggested the regional structure of West Java is highly affected by NW-SE Strike Slip, and West Java Fault is the arc parallel - major regional fault in West Java. The structure style suggests that West Java is highly affected by oblique tectonic setting, even though present tectonic configuration of Java in general in its orthogonal setting. The kinematic analysis using Riedel shear model suggests that the extensional trending in West Java is N-S in general and may varies in NNW-N-NNE trending.

The most important regional structure control on geothermal systems in West Java is to provide the extensional condition. The control on extensional setting can be divided into two roles: 1) to provide extensional setting in regional scale to localize magmatic intrusion at depth and 2) to provide extensional setting in prospect scale of geothermal systems. The extensional setting in prospect scale controls the permeability in the systems. In regional scale, West Java Fault is associated with the Arc volcanism in West Java, suggested by spatial distribution of many volcano-magmatic products along the fault line including Awibengkok and Karaha-Talaga geothermal field. The fault and its splay, namely Salak-Gede-Papandayan Fault and Tangkuban Parahu-Galunggung Fault, is responsible to the formation of Garut Circular Structure by regional extension of pull apart basin mechanisms. The volcano magmatic activity is very intense in Garut Circular Structure, where numbers of volcano-magmatic products (volcanoes and its associated geothermal fields) occur in rim structure: Gede, Patuha, Papandayan, Cikuray, Galunggung, Karaha, Tangkuban Parahu; while in middle part of the circle are: Wayang Windu, Kamojang, Darajat and Guntur. On a smaller scale, the consistent extension setting found in active and fossilized geothermal system suggests the regional pattern that is driven by regional structure of West Java Fault.

This synthesis is a preliminary result. It has to be followed with more comprehensive study to develop the conceptual model of structure control on Heat and Mass transfer, especially on the Geothermal System in West Java. The tectonic implication also has to be considered in the development of conceptual models, by taking into account other geological parameters in West Java.

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