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SUBVOLCANIC HYDROCARBON PROSPECTIVITY OF JAVA: OPPORTUNITIES AND CHALLENGES

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ABSTRACT

Occupying the position of the active southern margin of the Eurasian Plate since the Cretaceous, Java Island has thick volcanic covers from Paleogene to Recent times.

Numerous oil and gas seeps occur on Java Island where Paleogene to Recent volcaniclastic sediments are at the surface concealing prospective basin sediments. Before good geologic science was applied, people believed that oil was derived from magmatism and volcanism (inorganic theory). Now we understand that the hydrocarbons were organically derived from maturation of organic matters within source rocks in sedimentary basins. The volcaniclastic sediments buried the source rocks, burying the source rocks to depths of oil and gas windows.

Oil and gas seeps in volcanic areas of Java show the presence of active petroleum systems underneath the volcanic cover. This indicates hydrocarbon prospectivity on Java Island (subvolcanic play) that is so far unexplored. The areas that show this prospectivity are: Banten Block, Majalengka-Banyumas Area, and North Serayu Area.

However, volcaniclastic covers are notorious for causing poor seismic data quality, making subsurface imaging difficult. This will challenge the methods and techniques of seismic and nonseismic data acquisition and processing. Once these challenges are resolved, the subvolcanic play of Java may be revealed.

INTRODUCTION

Java Island, located at the southern part of the Sunda Craton, was formed by rock assemblages associated with an active margin of plate convergence. The island has recorded plate convergence between the Meso-Tethys, Neo-Tethys and Indian oceanic crust with the southern part of Sundaland continent since the Early Cretaceous. Therefore, the island is made up mainly by complexes of plutonic-volcanic arcs from many ages and shelf or trough sedimentary rocks.

Oil and gas seeps are common on Java Island and can be grouped into three areas: Banten Block, Majalengka-Banyumas Area, and North Serayu Area (Figure 1). These areas are also covered by volcanic cover ranging in ages from Miocene to Recent. The presence of oil and gas seeps in these areas show the presence of active petroleum system in the subsurface although later volcanism covered the area.

Limited geological and geochemical work conducted on exposed rocks and seeps indicate that the elements (source, reservoir, seal) and processes (generation, migration, trapping, preservation) of petroleum system may exist beneath volcanism. Volcanic deposits played a role as overburden rocks to mature the source rocks. This will give opportunities for further exploration with the exploration concept called the subvolcanic play type. The first exploration well in Indonesia, Maja-1, was drilled in 1871 at the volcanic area of Majalengka and discovered oil.

However, thick volcanic covers notoriously cause poor seismic imaging on objectives beneath volcanics due to the rocks absorbing most of the seismic wave energy generated during the acquisition hence decreasing seismic signals significantly.

The paper is an impetus to call for fit geophysical technology in data acquisition and processing to improve seismic imaging in volcanic area. Once we have this technology, the petroleum opportunities in subvolcanic areas of Java or in other regions, will be viable to chase. Their active petroleum systems are proven by the presence of numerous oil seeps, but we need good geophysical technology to explore the prospectivity.

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DATA AND METHODS

Published literature and unpublished data were used during the study, including geological, geophysical and geochemical data. All of the literature and data were studied and analyzed and compiled, synthesized and summarized as this paper.

RESULTS AND DISCUSSION

Three basic geologic provinces trending east-west parallel with the long axis of the island can be outlined in Java: (1) Northern province: uplifted nonmarine to shallow marine sediments composing the prolific Northwest Java and Northeast Java petroleum basins, (2) central province: subsided presently uplifted volcaniclastic sediments in the middle, (3) southern province: uplifted volcanic and carbonate sediments. This paper deals with central and southern provinces, so far unexplored intensively for petroleum.

Tectonic & Volcanic Setting of Java Island

The island of Java is formed predominantly by Cenozoic volcanic rocks which rise mostly above the Neogene marine strata. The basement rocks comprise Cretaceous rocks exposed in a few scattered areas as mélange deposits (in Ciletuh-West Java and Luk Ulo-Central Java) or continental metamorphics (in Jiwo Hill/Bayat-Central Java) (Satyana, 2014a, b).

In a broad tectonic setting, Java occupies the southernmost margin of the present Asian Plate. Before the Cretaceous, Java formed the southern active margin of Sundaland, a continental terrane of the Asian Plate. Since the Cretaceous, the island has become the site for plate convergence between the Indian oceanic plate and Sundaland (Katili, 1975; Hamilton, 1979, Hutchison, 1989).

Tectonic elements resulting from oceanic-continental plate convergence include subduction zones, magmatic arcs, accretionary prisms, and sedimentary basins from Lower Cretaceous to Quaternary periods overlapping each other on Java Island.

In studying the evolution of the Bogor Basin in West Java, Martodjojo (1984) stated that from Late Cretaceous to Early Eocene a magmatic arc was located in the north of Jakarta extending northeastward to the Java Sea. In the meantime Java was interpreted as a fore-arc basin. Whereas, during Early Miocene time the arc moved to the south of Java Island, and West Java had become a back-arc basin. Volcanic rocks there were considered as turbidites coming from outside of the basins. This opinion implies that there was no magmatic (volcanic) arc in Java from Cretaceous to Early Miocene. Tertiary Java volcanism began in Early Miocene and has continued to Quaternary and recent time.

Later study based on geochemistry and geochronology of 35 selected magmatic rocks distributed across Java, Soeria-Atmadja et al. (1994) argued that the Tertiary magmatic activity in Java took place in two distinct periods: Late Eocene-Early Miocene (40-18 Ma) and Late Miocene-Late Pliocene (12-2 Ma) and was succeeded by Quaternary volcanism (Figure 2). The first magmatic belt is located along the southern part of Java and is related to Paleogene subduction. The second magmatic belt is located in the north of the first magmatic belt and is related to Neogene subduction. Generally, the Quaternary volcanoes are distributed within the Neogene magmatic belt. This study shows a northward movement of magmatism (and possibly the related subduction) from Paleogene to Neogene one. Consequently, volcanic arc that is located above the magmatic arc also moved from south to the north.

Regional further study on volcanic setting of Java was conducted by Bronto et al. (2006) based on published geological maps of Java and published as well as new radiometric datings. Bronto et al. (2006) concluded that volcanisms in Java have occurred since Paleogene, or even Late Cretaceous. Stratigraphically, older volcanic rocks were covered by the younger ones. Bronto et al. (2006) proposed "superimposed volcanism" to explain this. Superimposed volcanisms have occurred in Java since Early Cretaceous, through Paleogene and Neogene until Quaternary and recent time. In the eastern part of Java the superimposed volcanism is rather obscured, particularly with the appearance of Quaternary volcanoes that are located further to the north than exposures of Tertiary volcanic rocks. This may be controlled mostly by north-south trending faults and previous subvolcanic intrusive bodies beneath the surface. Further studies are required to clarify this problem.

Bronto et al. (2006) also observed the formation of sedimentary basin (volcanic basin) in volcanic arc (intra-arc basin). Some basins are formed among composite cones in the volcanic arcs. Some Quaternary intra-arc basins in West Java are Cianjur Basin, Bandung Basin, Garut Basin and Tasikmalaya Basin, while in Central Java is Yogyakarta Basin. It is believed that Tertiary intra-arc basins were also formed. Generally, those basins are many although smaller compared with back arc and fore arc basins; tectonics and sedimentations are much more intensive due to highly magmatic and volcanic activities relating to subduction zones. Those characteristics may have implications to the presence of hydrocarbon, such as gas, oil and coal. Jatibarang Formation that is a large oil reservoir (e.g. discussed by Gresko et al., 1995) consists of alternating basaltic lava flows and tuffs (e.g. Martodjojo, 1984). Those compositions indicate that oil can be located in a proximal facies of a Paleogene volcano there. An oil exploration in the Lapindo Brantas Block (e.g. Darmoyo et al., 2001) has found a hydrocarbon prospect in Pleistocene volcaniclastic deposits. These imply that oil exploration should pay attention to the presence of voluminous and widely distributed volcanic rocks having Cenozoic ages in Indonesia.

The above discussions show that magmatism and volcanism are voluminous in Java since the beginning of the Tertiary. Some oil seeps occurring in volcanic area have been geochemically analyzed and reveal a source older than the volcanic deposits. The reservoirs that store the migrated petroleum can be older or contemporaneous with the volcanic deposits. Trap formation can also be prior to or coeval with volcanism. Source maturation always occurs after volcanism since the volcanic deposits become the overburden rocks to bury and mature the petroleum sources.

The discussions on subvolcanic hydrocarbon prospectivity will be discussed for each of the three regional areas where oil seeps occur in volcanic overburden: (1) Banten Block, (2) Majalengka-Banyumas Area, (3) North Serayu Area.

Subvolcanic Hydrocarbon Prospectivity of Banten Block

In Banten Block, the geologic setting is similar with the South Sumatra Basin where the tectonostratigraphy during the Paleogene is similar, but in the Neogene, the Banten Block was different with the South Sumatra Basin when volcanic arc existed in the area, causing the Banten Block to include backarc and intraarc settings (northern area) and forearc settings (southern area). The oil seeps are concentrated in volcanic area (intraarc setting). Based on limited geological, geochemical, and geophysical work, and some exploration wells drilled in this area, the petroleum system of the Banten Blocks is as follows.

The primary sources are Eocene-Oligocene Bayah shales and coals (Figure 3). The secondary sources may be early-Late Miocene Bojongmanik shales and coals. Paleogene local deeps/half grabens act as kitchen areas within the block. The presence of oil seeps within the block may indicate that the source has been mature generating petroleum. Field data on vitrinite reflectance shows that the Bayah Formation has entered into the oil window with Ro of 0.6-1.5 % and the Miocene Sareweh Formation is in early oil window of Ro 0.4-0.8 %. Migration has been taking place both laterally through carrier beds and vertically through faults. The primary reservoir is probably the Eocene Bayah fluviodeltaic sandstones with porosity up to 20 % and permeability reported to be almost 900 mD. Other potential reservoirs are from Miocene Sareweh and Bojongmanik limestones, and Cijengkol sandstones with porosities 15 to above 25 %. Structural traps may relate to Pliocene inversion or stratigraphic traps related to Eocene and Oligocene pinchout sands as well as carbonate build ups. Seals are provided by intraformational shales within the Paleogene section and regional seals of Bojongmanik shales.

The challenge here is to image the structures due to poor quality of seismic data related to Mio-Pliocene and Pliocene to Recent volcanism covering the area. Recent volcanic cones in this area for example are Karang, Pulasari, Endut, and Halimun volcanoes.

Subvolcanic Hydrocarbon Prospectivity of Majalengka-Banyumas Area

In Majalengka-Banyumas area, the presence of oil seeps is very prolific (Figure 4). This area was discussed in detail for its petroleum prospectivity by Armandita et al. (2009). Intra-arc region of Java from Majalengka to Banyumas area straddles the West-Central Java border. The area has been the least-explored area in Java. This contrasts with the facts that numerous oil and gas seeps exist here and the first exploration well of Indonesia (Maja-1 well, drilled in 1871, oil discovery) are located in this area. The Maja oil was geochemically analyzed and correlated to a source from Early Miocene shale equivalent to Talang Akar Formation (Figure 5).

Major NW-SE trending dextral fault called the Pamanukan-Cilacap Fault Zone (Satyana and Purwaningsih, 2002) crossed this area possibly since the early Neogene or could be slightly older. Around the Majalengka-Kuningan- Majenang areas, the fault zone formed duplex system causing pull-apart opening of trough or trans-tension duplexes. The opening controlled the occurrences of pre-Late Miocene back-arc volcanism sourcing the Late Miocene-aged turbiditic Halang volcanoclastic deposits. The Majalengka-Banyumas trough was then inverted in the Mio-Pliocene forming a structural high. The Pemali sediments were deposited afterward in low areas flanking the structural high.

Trough and trans-tension duplexes of the Majalengka-Banyumas area and their inversion had controlled the petroleum system of this intra-arc region. High heat flow and geothermal gradients due to pull-apart opening and volcanism, thrust loading within inverted Halang deposits and thick Pemali burial sediments had matured the Paleogene and/or Neogene source rocks existing in this area. Petroleum was generated and migrated updip to the Majalengka-Banyumas structural high and trapped in various structures, mostly sub-thrust traps (Figure 6). Numerous oil and gas seeps reveal that petroleum system is working in this area.

Reservoir quality, trap integration and poor structural imaging due to volcanic cover may risk exploration. However, based on its active petroleum system, the area merits further exploration endeavor.

Subvolcanic Hydrocarbon Prospectivity of North Serayu Area

In the North Serayu area, northern Central Java, oil seeps occur among volcanic cover (Figures 7, 8). Satyana and Armandita (2004) and Satyana (2007, 2013) detailed the petroleum prospectivity in this area. The uplift of southern Central Java in the Middle-Late Miocene was volumetrically compensated by an increase of subsidence of the floor of the North Serayu Basin. This caused gravitational sliding (gravity tectonics, gliding tectonics) movements from south to north (Figure 9), but also caused portions of the northern flank of the basin to slide down under gravity toward the deepest part. In the Mio-Pliocene, a basal limestone of the Bodas Series was deposited transgressively and unconformably upon the older Miocene series. Then again strong basin subsidence began, which volumetrically compensated strong Mio-Pliocene uplift of the South Serayu Range at the southern part of Central Java. Structures related to gravity tectonics, such as toe thrusting, developed verging to the north. Eocene to Late Miocene rock beds of Worowari, Lutut, and Sigugur nonmarine to shallow marine formations (van Bemmelen, 1970), and Merawu and Lower Penyatan turbidites were deformed as toe thrust anticlines and fault-propagation folds.

All elements and processes of the petroleum system can be formed in this system (Figure 10). Hydrocarbon sources can be provided by the nonmarine to shallow marine Worowari shales and marly clays of the Merawu Beds. Based on an integration of the data of crude oils and the geochemical model, the most probable source rock of the North Central Java Basin is the source rocks which are age-equivalent to the East Java Ngimbang Formation, therefore Eocene Worowari shales have potential to be the source rock in this area. Most of the organic matter contained in the sediments indicate a Type III kerogen, primarily vitrinite and some of them oxidized amorphous materials. Reservoirs could be formed by the quartzitic sandstones and tuffaceous sandstones of the Lutut and Merawu Beds, and reef limestones of the Sigugur Beds. Potential seals are intraformational shales within the Merawu and Penyatan Beds. Maturation of the source rocks could be attained as the basin subsided and burial sediments of post Late-Miocene volcanics were deposited. Generated hydrocarbons could enter the traps of the toe thrust anticlines formed in the Lutut and Merawu Beds or reefs of the Sigugur Beds via faults of the toe thrust system.

A number of seepages in the surface indicate the presence of a viable petroleum system in the region. Van Bemmelen (1970) reported a number of oil seepages and one oil field located in the North Serayu Zone. The seepages occur in the areas of Karangkobar, Bawang and Subah, Klantung and Sodjomerto, Kaliwaru, West of Mt. Ungaran (many seepages), and East of Mt. Ungaran (Figure 7). Exploratory drillings carried out by Dutch oil companies since the early 1900s near the seepages had no success. Drilling in Klantung and Sodjomerto was successful and the Cipluk Field was discovered. During the 35 years of production, the average yearly production was a few hundreds of tons. Cipluk Field (now abandoned) is formed by a faulted anticline of Late Miocene Banyak volcaniclastic sandstones. Oil seeps in this area have been geochemically analyzed and sourced by sediments equivalent in age and facies with Talang Akar Formation in West Java Basin.

It appears that volcanic cover in this area plays multiple roles: reservoir, overburden rocks, but also to mask deeper objectives. The Paleogene objectives in this area like in the West and East Java Basins could be prospective but we need good seismic imaging.

Seismic Imaging beneath Volcanic Rocks: Case Study

The main challenge to explore petroleum beneath volcanic covers is poor subsurface seismic imaging due to absorption and/or distortion of seismic waves by volcanic deposits (Figure 11).

To date there has been only minor exploration for hydrocarbons in Java Island conducted in areas with volcanic cover. Some exploration has occurred in areas of Pertamina EP, Pan Orient Citarum, Equator Energy Kuningan, Lundin Banyumas (Figure 11), Bina Insani Alas Jati, ExxonMobil Gunting, and Lapindo Brantas. Some of the blocks have been totally relinquished. Pertamina EP, Lundin Banyumas, and Lapindo Brantas were or are still actively exploring the area. The seismic data in their volcanic areas are usually poor, contributing more or less to the failure of exploration wells.

The special seismic acquisition method that has been developed for volcanic areas should be applied. The method of seismic acquisition in volcanic areas was published by Calvert and Hayward (2009) for seismic acquisition in the Nechako Basin, which underlies much of the Cariboo-Chilcotin plateau of central British Columbia, Canada. A major impediment to exploration of the basin is the extensive surface cover of Tertiary to Recent volcanic rocks, which can reach thicknesses as great as 600 m. The most recent exploration effort, which ended in 1986, was undertaken by Canadian Hunter, and provided highly variable seismic imaging of the stratigraphy and basin architecture, in part due to the effects of the surface volcanics.

This fundamental question on the nature of the Nechako basin was not resolved by the seismic data acquired by Canadian Hunter, because the quality of the images was often poor, likely due to the combined effects of the volcanic cover and the seismic acquisition technology available at the time. There is therefore a strong argument for acquiring extensive regional geophysical data across the basin. In summer 2008, Geoscience BC acquired 330 km of seismic data near Nazko along and across the NNW-oriented surface trend of Early Cretaceous rocks in the central Nechako basin. The primary objectives of the survey were: 1) To evaluate the effectiveness of modern seismic acquisition technology in this volcanic-covered basin and 2) to map the extension into the subsurface of the outcropping Cretaceous rocks, and to identify the primary structural controls on their distribution in the central part of the basin.

The quality of the Canadian Hunter vibroseis seismic data, is quite variable. In some volcanic areas, very few first arrivals can be observed, suggesting that source coupling can be a significant problem. In other areas where volcanic rocks lie at the surface, first arrivals were well recorded to the maximum offset, but no laterally continuous underlying reflections are present on the stack sections. In areas with no volcanic surface rocks, the data quality is usually reasonable given the technology of the time. Therefore much of the new survey design was directed towards maximizing the signal to noise ratio, and the main characteristics of the survey were:

1) Large array of vibrators and long sweeps to maximize source effort;

2) High stack fold through the use of a short source interval and large number of recording channels;

3) Restriction of the sweep to lower frequencies to improve transmission through near-surface volcanic rocks;

4) Long offsets to record deeper, sub-volcanic reflections and first arrivals that can constrain the thickness of the volcanic layer, and perhaps the depth to the igneous basement;

5) Extended correlation of long sweeps to record mid-lower crustal reflections that will constrain the evolution of any sub-basins and provide data QC in areas where shallower reflections may not be present.

Calvert and Hayward (2009) applied the field seismic parameters that they changed from previous parameters (Table 1). They mentioned that the parameters were effective for imaging the basin structures under the volcanic cover.

Seismic parameters reported by Calvert and Hayward (2009) can be referred to as a pilot project to improve seismic data quality in working areas in Java. However, dense population in volcanic areas in Java will become another problem to do seismic acquisition with long offsets or bigger explosives that were not an issue in British Columbia.

Non-Seismic Imaging beneath Volcanic Rocks

It should be also considered to build the methods of imaging subvolcanic structures using nonseismic methods such as gravimetric, magnetotelluric, electrical and electromagnetic. Regionally, gravity method using SVD (second vertical derivative) can locate sedimentary basins beneath volcanic cover as shown by Widianto (2008) for Java Island (Figure 12).

CONCLUSIONS

Oil and gas seeps are numerous in volcanic areas of Java, showing the presence of active petroleum systems. The oils were sourced by source rocks older than and buried by volcanic deposits. Reservoirs also exist beneath volcanic deposits or within the deposits. Traps may be formed contemporaneously with volcanism or earlier. Volcanic deposits buried the source rocks into the oil window and started oil generation. Generated oils migrated into the traps beneath or within the volcanic deposits. However, imaging subvolcanic structures is difficult since seismic quality in volcanic areas is poor. Breakthroughs in methods of seismic acquisition and processing or nonseismic methods are required. Once we have the proven technology, the subvolcanic play of Java will be disclosed.

ACKNOWLEDGEMENTS

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TABLE 1

COMPARISON OF KEY PARAMETERS BETWEEN THE 1981 CANADIAN HUNTER SEISMIC SURVEY AND THOSE USED IN THE 2008 GEOSCIENCE BC SURVEY IN VOLCANIC AREA OF BRITISH COLUMBIA, CANADA. NEW 2008'S PARAMETERS RESULT IN BETTER SEISMIC QUALITY (AFTER CALVERT & HAYWARD, 2009)

	GBC 2008	CH 1981
Source interval (m)	40	100
Receiver interval (m)	20	50
No. channels	960	96
Max. Offset (m)	14390	2550
Nominal fold	240	24
Fold at 0.5 s (est.)	50	20
No. vibrators x weight (kg)	4 x 24,000	5 x 7467
No. sweeps per VP	4	16
Peak force (%)	80	60-75
Sweep duration (s)	28	15
Sweep bandwidth (Hz)	8-64	10-70

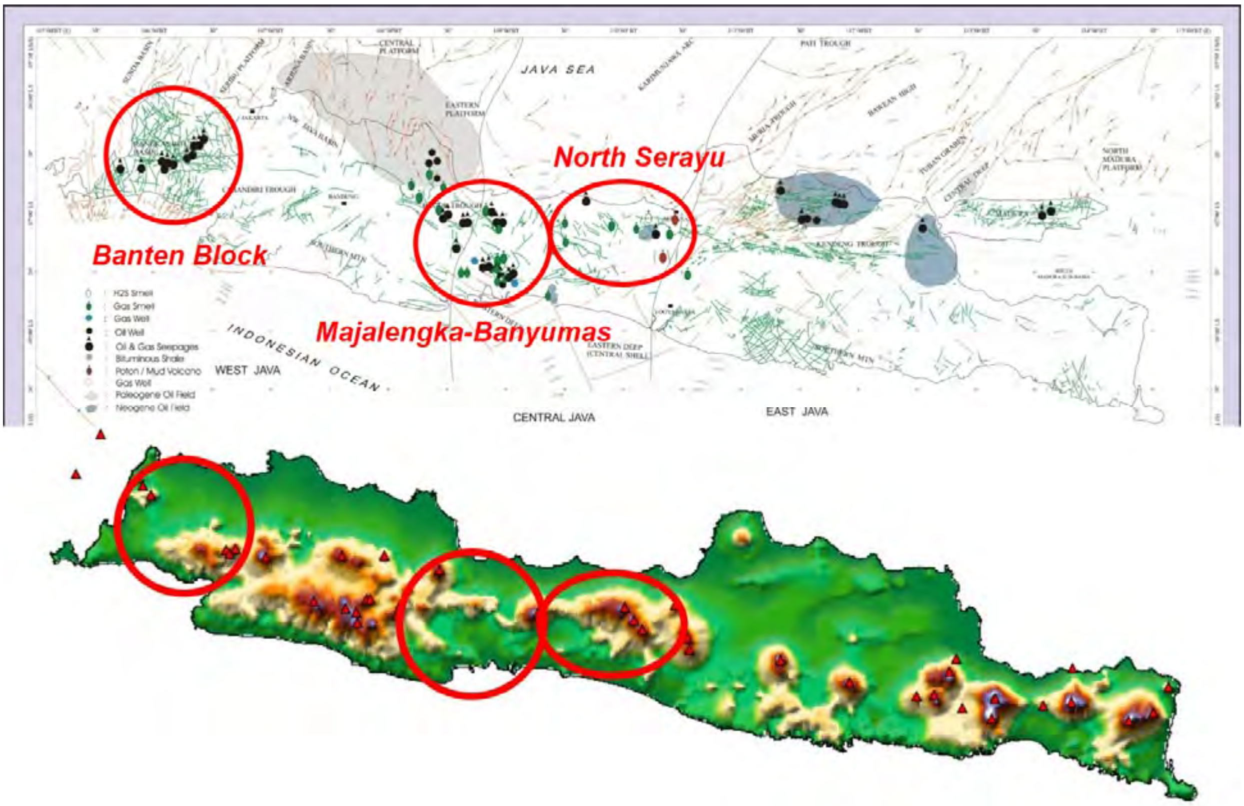

Figure 1 - Above. Map of Java Island showing structural trends and presence of oil and gas seeps. The seeps can be grouped into three areas: Banten Block, Majalengka-Banyumas Area, and North Serayu Area. Below. Topographic map of Java Island, all high areas are volcanic which share the same locations with three areas of seepages.

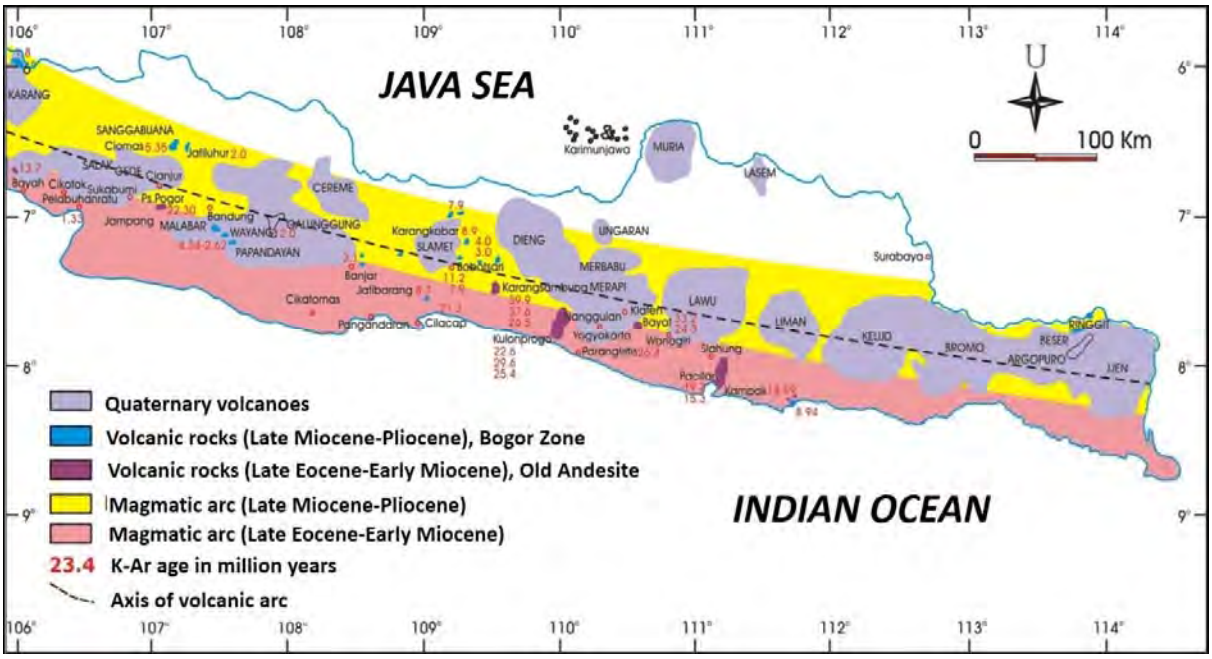

Figure 2 - Tertiary magmatic activity in Java took place in two distinct periods: Late Eocene-Early Miocene (40-18 Ma) and Late Miocene-Late Pliocene (12-2 Ma) and was succeeded by Quaternary volcanism. The first magmatic belt is located along the southern part of Java and is related to Paleogene subduction. The second magmatic belt is located in the north of the first magmatic belt and is related to Neogene subduction (Soeria-Atmadja et al., 1994)

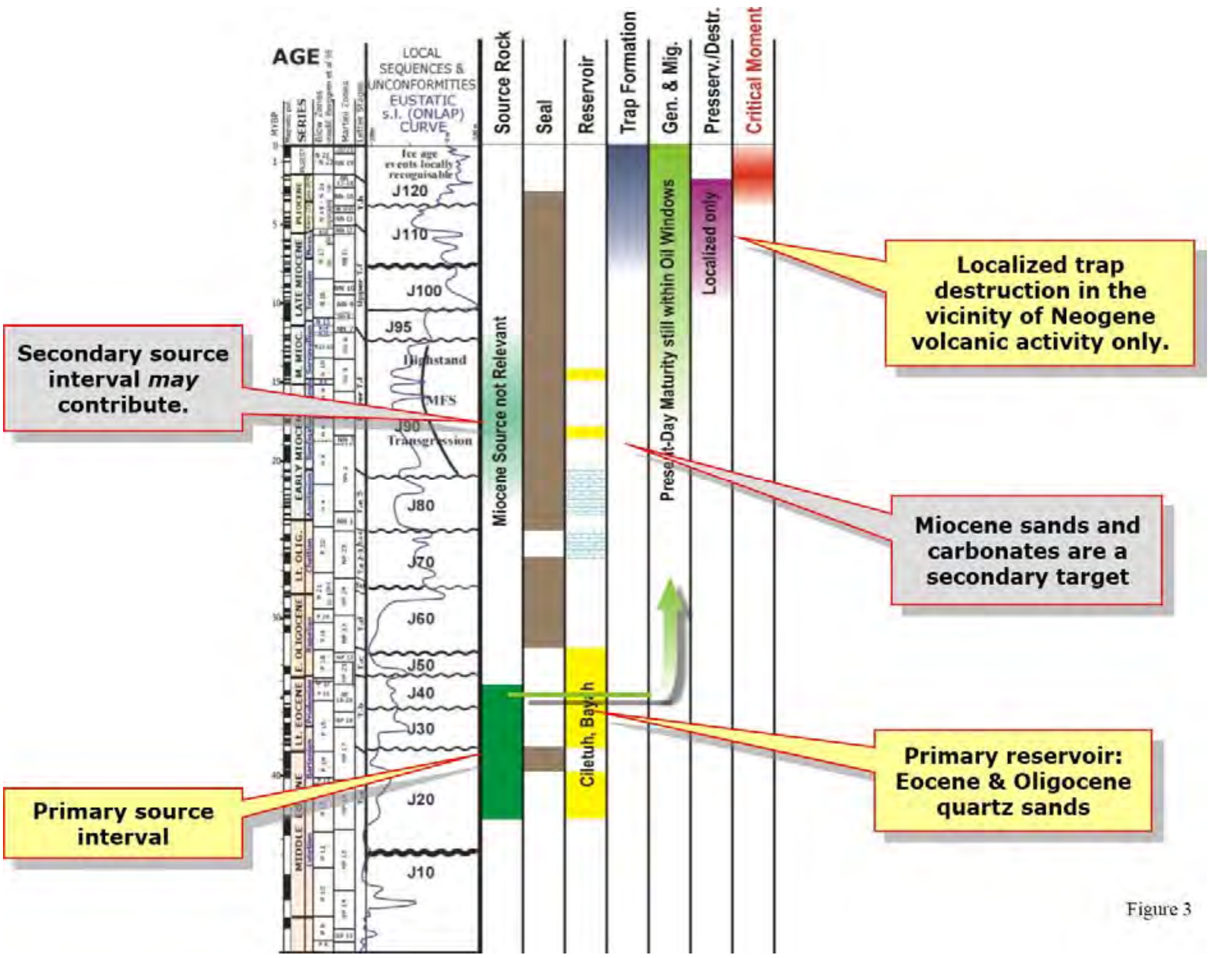

Figure 3 - Petroleum system chart of Banten Block. Most of the petroleum system elements are within Paleogene section, which later were covered by Neogene volcanics.

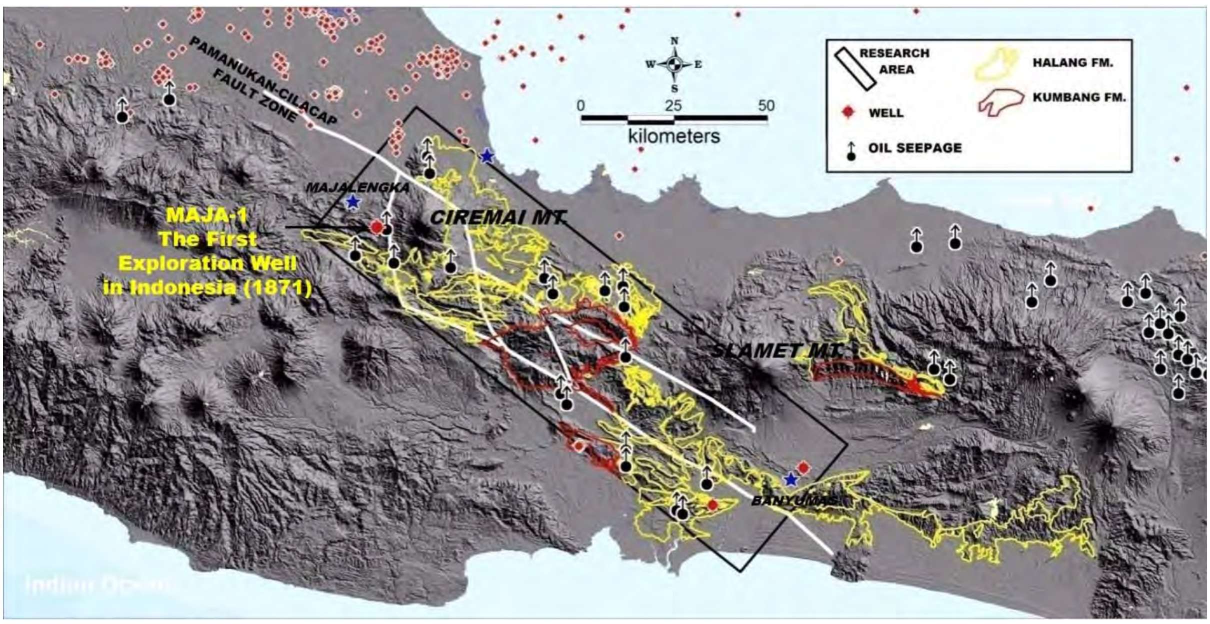

Figure 4 - Majalengka-Banyumas area with oil seeps that are distributed parallel with Late Miocene Halang volcanics (yellow) and Pliocene Kumbang volcanics (red). The duplex major strike-slip faults of Pamanukan-Cilacap may control this distribution. The first exploration well of Indonesia, Maja-1 (1871), was drilled in the volcanic area of Majalengka and discovered oil. The right side map shows numerous oil seeps in North Serayu area (after Armandita et al., 2009).

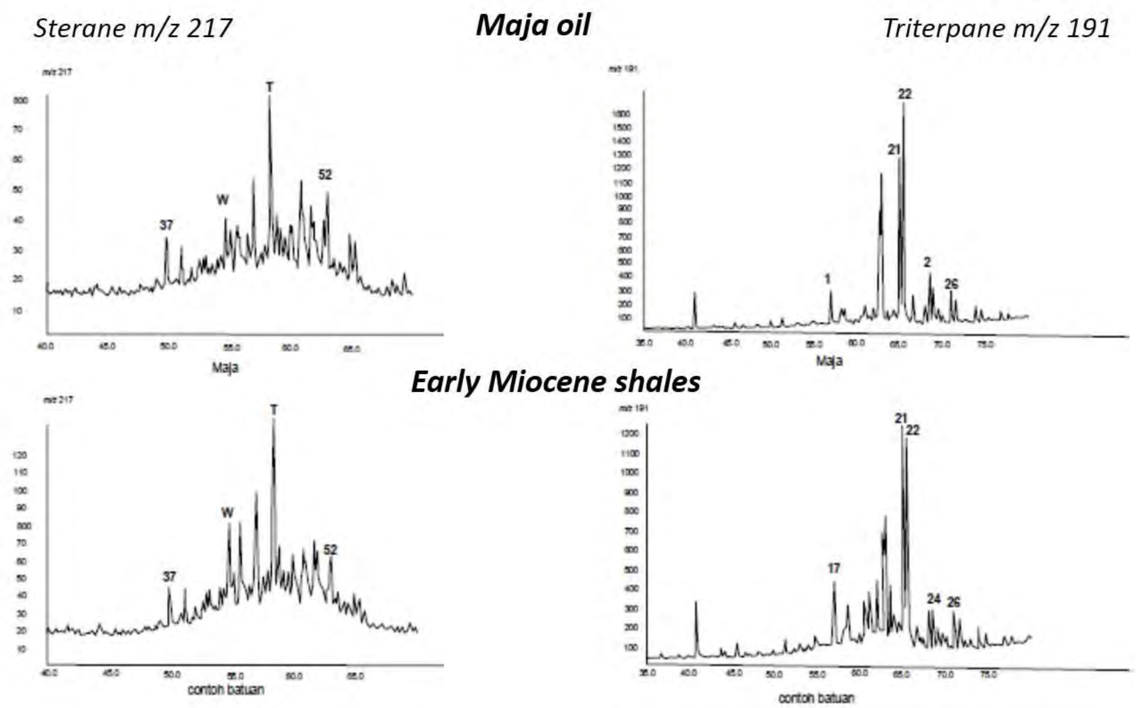

Figure 5 - Sterane and triterpane biomarker distribution of Maja oil, well correlated with Early Miocene shales equivalent to Talang Akar shales, showing that the source rocks are older or underneath the Neogene volcanic cover (data contributed by Totong Usman, Pertamina EP).

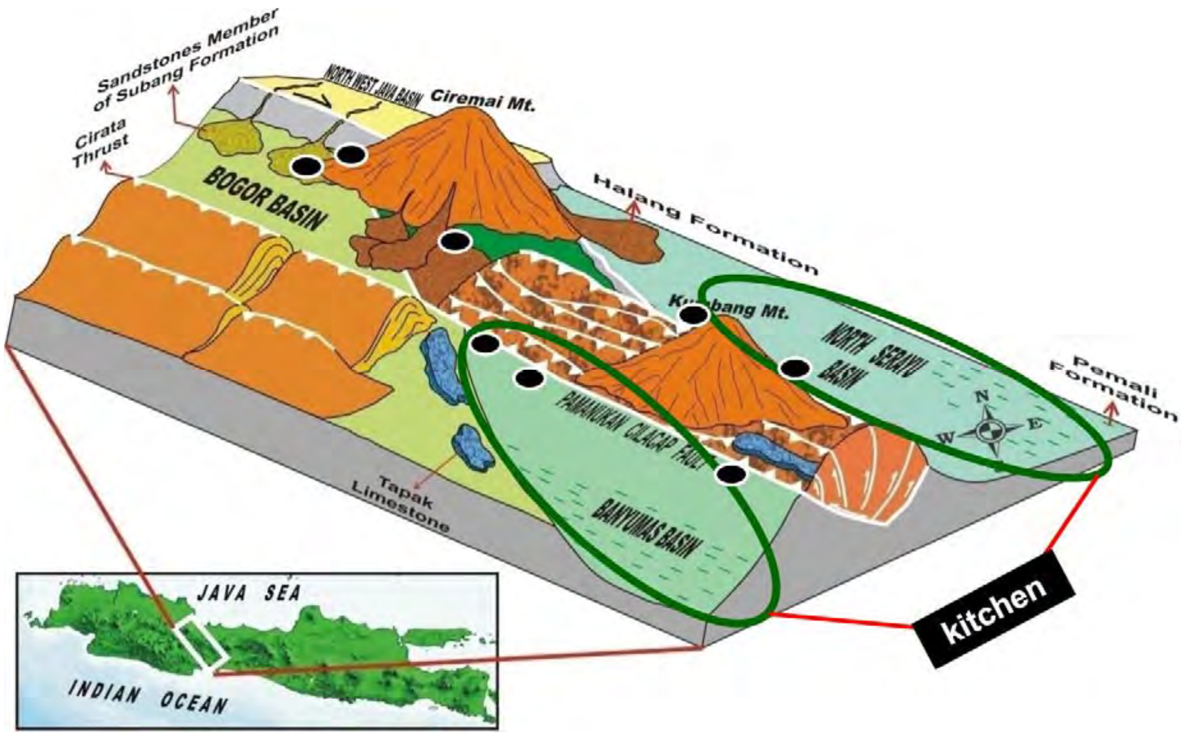

Figure 6 - Schematic diagram showing the uplift of Majalengka-Banyumas, which is isostatically compensated by subsidence in adjacent areas forming Banyumas/Citanduy and North Serayu Basins. The basins also subsided by burial Pemali sediments eroded from the uplift areas. Oil seeps are distributed along the border of the uplift area and in its subsurface trapped within sub-thrust structures (after Armandita et al., 2009)

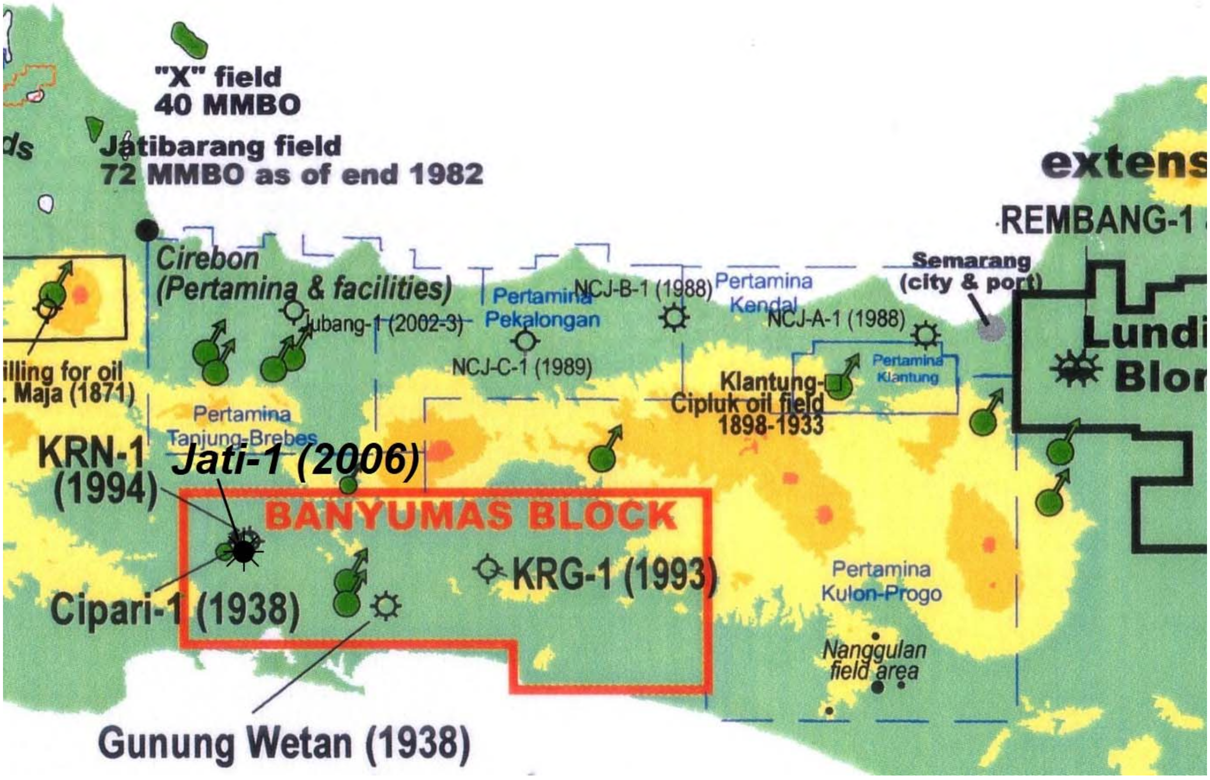

Figure 7 - Map showing the oil seep distribution in Banyumas and North Serayu areas. The oil seeps mostly are located in the volcanic area. Some exploration wells are indicated.

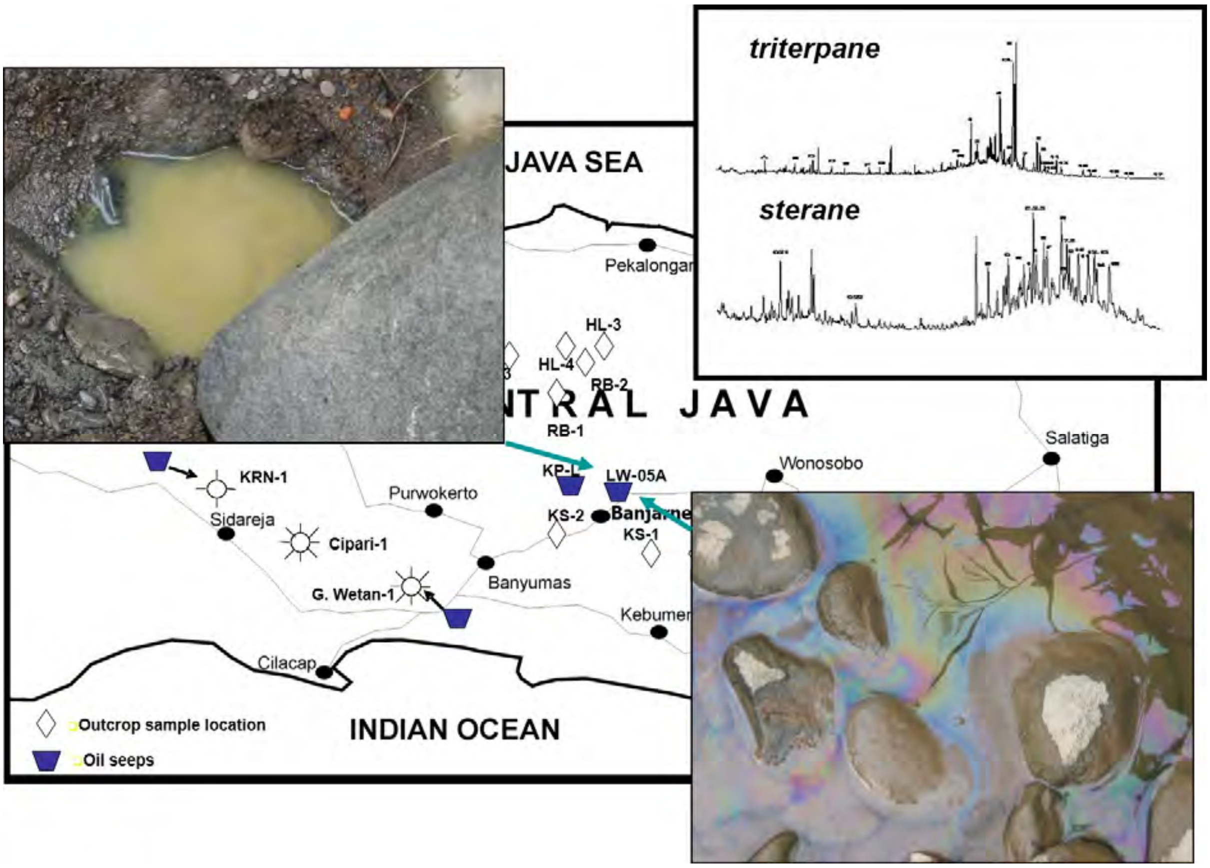

Figure 8 - Oil seeps of Banyumas and North Serayu areas showing terrestrial facies based on triterpane and sterane (data contributed by Eddy Subroto, ITB).

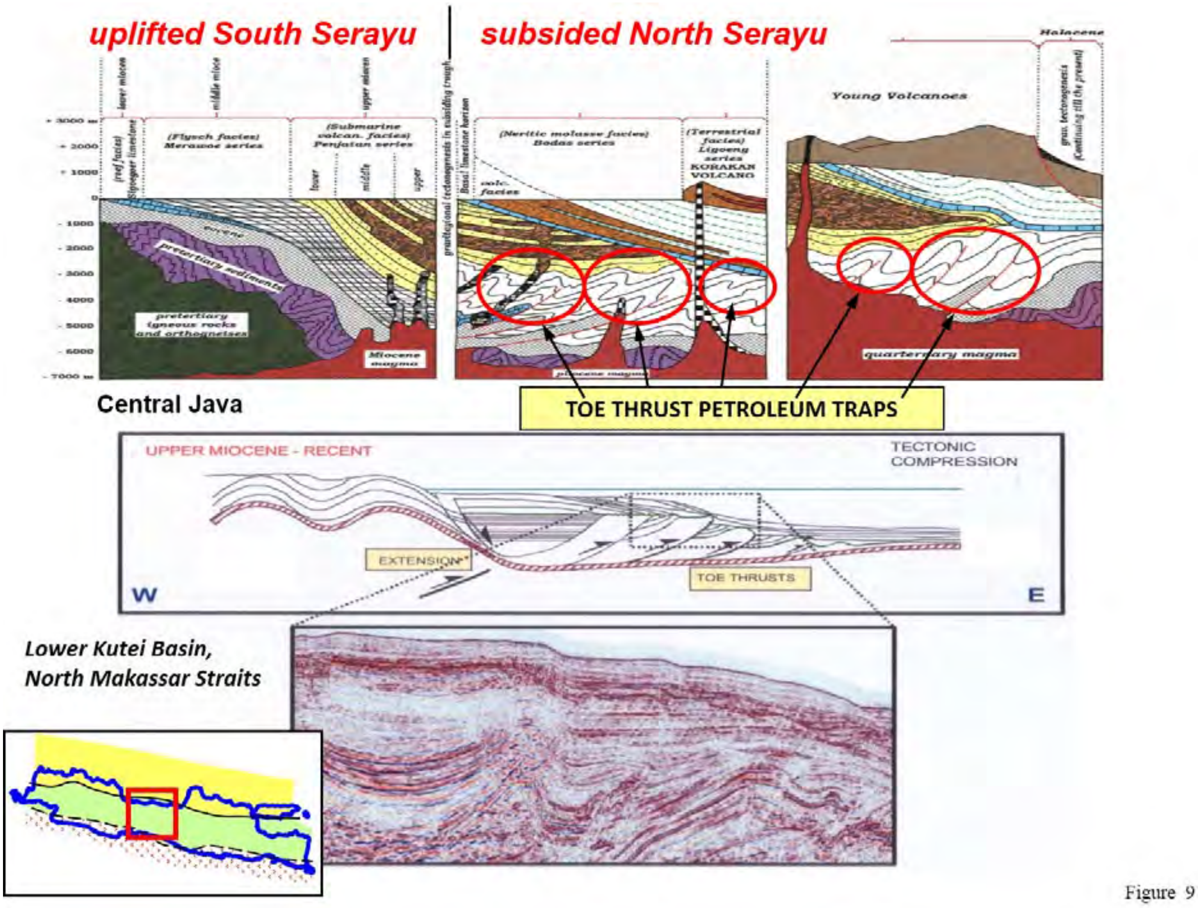

Figure 9 - Gravity tectonics of South to North Serayu with volcanic cover. Below the volcanic cover are structures related to gravity/gliding tectonics (toe-thrust) (modified after van Bemmelen, 1970), similar to those occurring in the deepwater of the North Makassar Straits due to gravity sliding but with no tectonics (modified after Guritno et al, 2003).

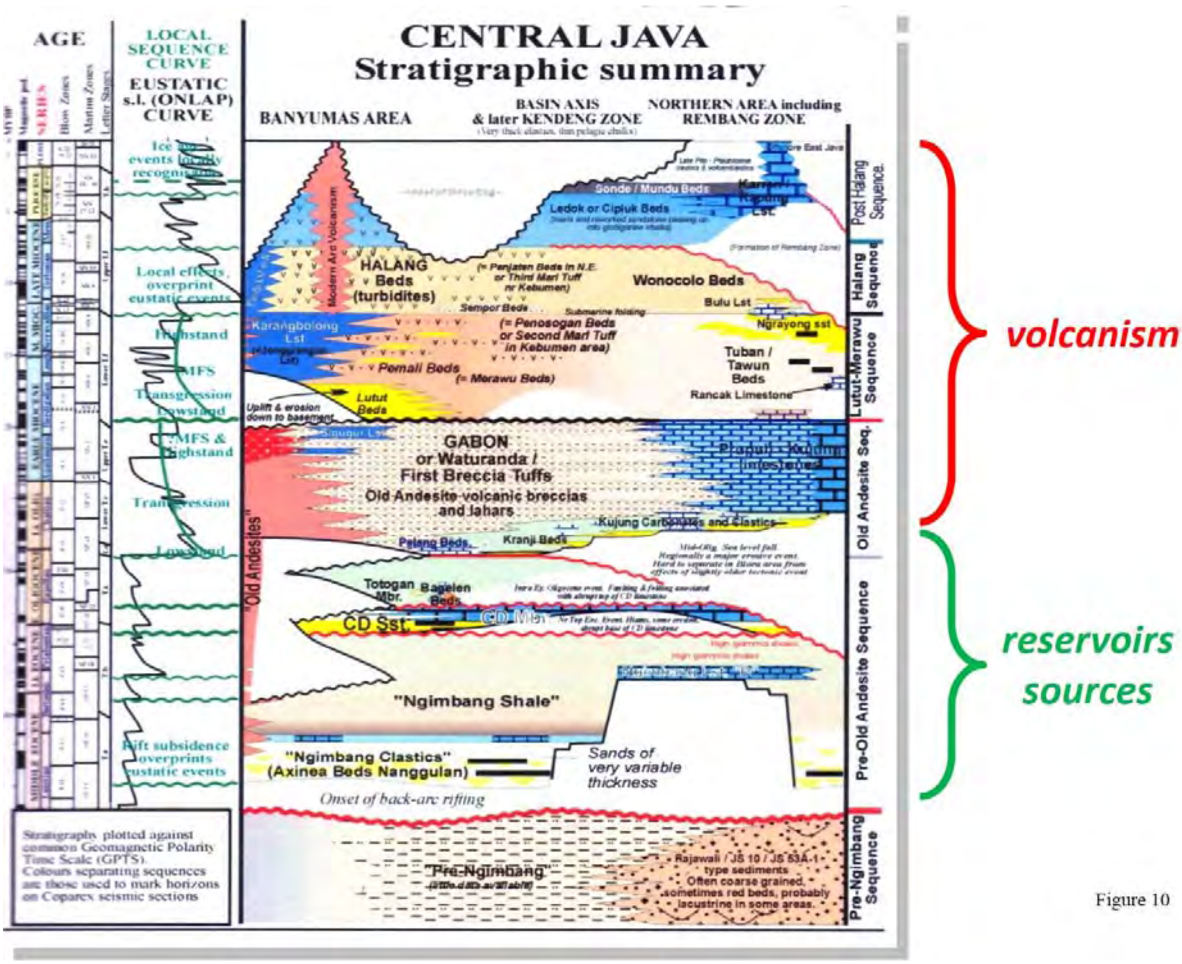

Figure 10 - Stratigraphy of Central Java showing petroleum system elements of source and reservoirs in Paleogene which are covered by Neogene volcanics.

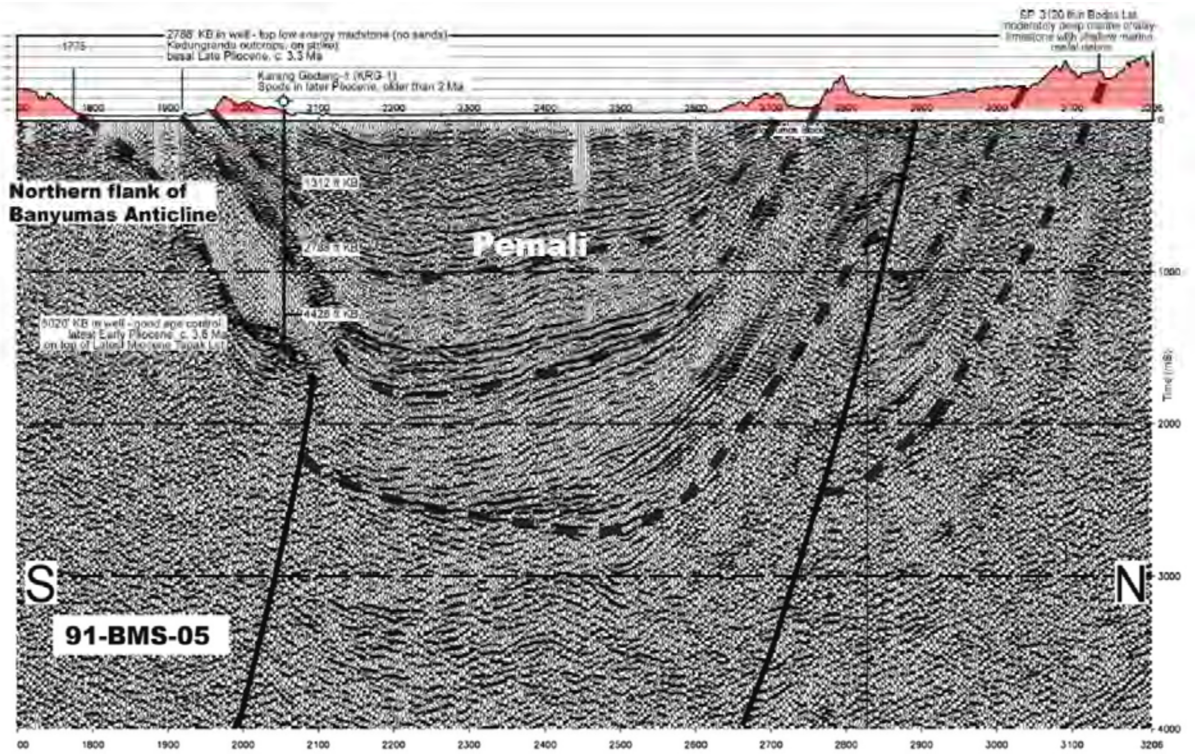

Figure 11 - Seismic section across Banyumas-Serayu showing good resolution in areas with no volcanic cover but poor seismic quality in area with volcanic cover (red) at surface (Lunt et al., 2008).

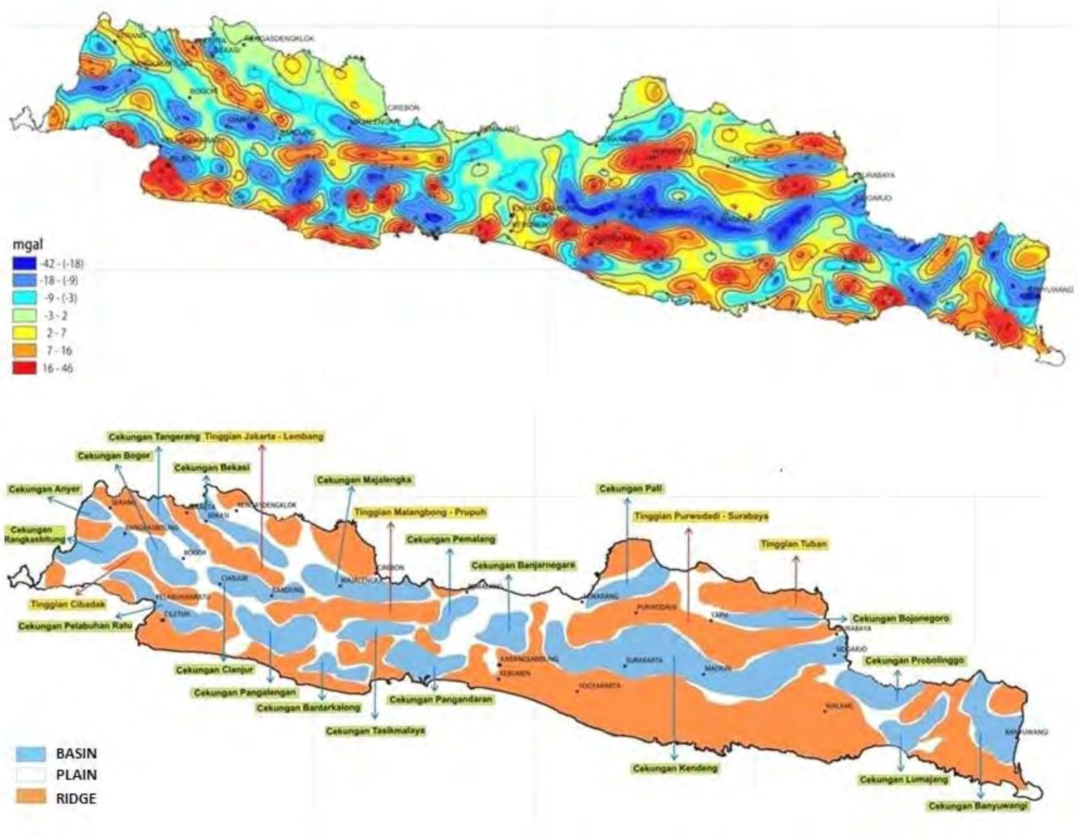

Figure 12 - Regional map of Java, above showing horizontal gradient gravity anomaly map of Java using SVD – second vertical derivative, to result in the map below, showing basin configuration map, effect of volcanic covers can be cut out (Widianto, 2008).