PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Thirtieth Annual Convention & Exhibition, August 2005

OLIGO-MIOCENE CARBONATES OF JAVA, INDONESIA: TECTONIC-VOLCANIC SETTING AND PETROLEUM IMPLICATIONS

Awang Harun Satyana*

ABSTRACT

On Java, carbonates of Oligo-Miocene age are widely distributed. This time period is also noted for its volcanism which is commonly referred to as the period of the "Old-Andesite" volcanism and is distributed across southern Java. This interesting contemporaneity has been evaluated to understand the inter-relationships between the tectonic-volcanic setting of the carbonates and their petroleum implications.

Two trends of Oligo-Miocene carbonates can be recognized: (1) A Northern Trend, including the Cepu-Surabaya-Madura, North Central Java, and Ciputat-Jatibarang areas, comprising the carbonates of the Kujung, Tuban, Baturaja and Middle Cibulakan formations and(2)A Southern Trend, including the Gunung Kidul – Banyumas – Jampang – Bayah – Sukabumi – Rajamandala areas. The Northern Trend carbonates developed in a back-arc setting, 75-150 kms away from a contemporaneous volcanic arc located in present-day southern Java. The Southern Trend developed within an intra-arc setting where contemporaneous volcanism took place. No reefal carbonates are found to be developed contemporaneously with the volcanism in the Gunung Kidul-Banyumas-Jampang areas of the Southern Trend. The Oligo-Miocene reefs which were growing on ridges in the Bayah-Sukabumi-Padalarang areas were not deposited contemporaneously with the volcanism.

A window of volcanic quiescence occurred across Java from 18 – 12 Ma (uppermost Early Miocene - Middle Miocene). During the same period, the sea significantly transgressed many areas in SE Asia. This condition caused deposition of abundant reefal carbonates along the Southern Trend and included the following formations: Wonosari/Punung Formation in the Gunung Kidul area, the Jonggrangan Formation in the Kulon Progo area, the Karangbolong/Kalipucang Formation in the Banyumas region, and the Bojonglopang Formation in the Jampang area.

The Northern Trend carbonates are very prolific petroleum reservoirs. Volcanic impurities are absent to very minor and are diagenetically insignificant. The geological setting of the carbonates is very supportive for the existence of a viable petroleum system. The Southern Trend carbonates in part show good-excellent porosities such as the Wonosari Formation carbonates, while others show severe neomorphism such as the Rajamandala Formation carbonates. There is no hydrocarbon discovery along the Southern Trend but the area has been inadequately explored. Nevertheless, the presence of a viable petroleum system is considered of higher risk than that of the Northern Trend.

INTRODUCTION

The relationship between tectonic setting, volcanism, and carbonate sedimentation in Indonesia is best described on Java Island during the Oligo-Miocene. During this period, the tectonic setting of Java was varied comprising volcanic island-arc, back-arc basins, intra-arc basins, and fore-arc basins (Figure 1). One of the most important events of the island's volcanism took place in the Oligo-Miocene with the formation of a volcanic belt which presently occupies the Southern Mountains of Java (Figure 2). Meanwhile, Java's Cenozoic equatorial position has provided an ideal environment for extensive and prolonged carbonate production. A generally rising eustatic sea-level during this period (Haq et al., 1987) allowed the accumulation of thick reefal units (Figures 3, 4, 5). Carbonate sedimentation developed during the Oligo-Miocene in many parts of Java and

* BPMIGAS

copious amounts of volcaniclastic material strongly influenced the carbonate development.

The traditional view of volcaniclastic derived material being generally prohibitive to carbonate development is over-simplified as recent studies have shown (Lokier, 1999; Wilson, 2000). Reefs fringe many active and recent volcanic islands in Indonesia, such as Krakatau, Banda, and Sangihe islands (Tomascik et al., 1997). Misconceptions that carbonates are unlikely to accumulate and/or be preserved near active volcanic areas have been dispelled by a number of studies of carbonates in ancient arc settings. In more distal areas, shielded from volcaniclastic debris, or during periods of volcanic quiescence, the flanks of volcanoes or nearby areas within the photic zone often become the sites of carbonate production.

A regional review of tectonic and volcanic influences on the development and termination of the Oligo-Miocene carbonates in Java and their petroleum implications are addressed in this paper. There is no previous publication on this theme. The paper is based on a number of published and unpublished data/studies and then synthesized into a regional review.

REGIONAL TECTONO-VOLCANIC AND SEDIMENTARY FRAMEWORK

Java Island is the best known area in Indonesia from the geological point of view. The first geological description of Java Island was given by Junghuhn (1853) and was followed by the more complete geological treatise by Verbeek and Fennema (1896). Van Bemmelen (1970) in his excellent book on the geology of Indonesia described the geology of this island in detail. A modern geological study of Java Island was given by Hamilton (1979) as a part of his broad tectonic compilation of Indonesia. These works remain as important references today.

The island of Java is formed predominantly by Cenozoic volcanic rocks which rise mostly above the Neogene marine strata (Figure 1). The basement rocks comprise Late Cretaceous or earliest Tertiary melange deposits exposed in a few scattered areas (Hutchison, 1989). In a broad tectonic setting, Java occupies the southern-most margin of the present Asian Plate. Java forms the southern active margin of Sundaland, a continental terrane of the Asian Plate. Since the Late Cretaceous, the island has become the site for plate convergence between the Indian oceanic plate and Sundaland (Katili, 1975; Hamilton, 1979). Tectonic elements resulting from oceanic-continental plate convergence include the subduction zone, magmatic arc, accretionary prism, and sedimentary basins from Late Cretaceous to Quaternary periods overlap each other on Java Island.

A Late Cretaceous subduction zone trends east-west in the southern part of the island, in West and Central Java, and curves northeastward across East Java to SE Kalimantan-SW Sulawesi. A contemporaneous Late Cretaceous magmatic arc was situated to the north of the island in the present-day Java Sea. Later, during the Oligo-Miocene a magmatic arc (called the "Old Andesite" by van Bemmelen, 1970) (Figure 2) occupied the site of the Late Cretaceous subduction zone in West and Central Java, trending east-west along the southern part of the island through southern East Java towards the Nusatenggara islands and Banda Arc (Katili, 1975). This indicates the southward shift in the position of the arc and subduction zone from the Late Cretaceous to the Oligo-Miocene. During the Neogene, Java's magmatic arc shifted northward and this continued into the Quaternary (Katili, 1975). This indicates a gentler-dipping Benioff Zone during the Neogene relative to that of the Paleogene.

The plate interactions are believed to have influenced basin formation and configuration which is due to the existence of block faulting in the basements. A regional review of the Tertiary depositional patterns of Java was made by Sujanto and Sumantri (1977). They stated that depositional patterns on Java Island show various phenomena such as growth-faulting, regional platforming, turbiditic flysch-like deposition within troughs, and reef growth on ancient volcanoes.

OLIGO-MIOCENE PLUTONIC-VOLCANIC ARC

Based on geochemistry and geochronology of 35 selected magmatic rocks distributed across Java, Soeria-Atmadja et al. (1994) concluded 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 (Figures 2, 7). The Oligo-Miocene arc is included into the former period. The presence of this belt indicates active subduction from Late Oligocene time onwards (Hamilton, 1979).

The products of the earlier event had built up the "Old Andesite" Formation (the Oligo-Miocene magmatic-volcanic arc) presently distributed along the southern part of Java. This arc related to the Paleogene subduction located to the south offshore Java Island in the Indian Ocean. The distribution of volcanic rocks of the Old Andesite Formation can be followed along the south coast of Java from the Pacitan area in East Java as far as the Pelabuhanratu-Bayah region in the west via Bayat, Parangtritis, Kulon Progo, Luk Ulo, Pangandaran and Cikatomas (Soeria-Atmadja *et al*., 1994) (Figure 2). These rocks are also distributed in the offshore area south of Java Island as penetrated by the Alveolina-1 and Borealis-1 wells (Shell, 1972-1973). Katili (1975) suggested this belt extended from Sumatra through Java to the Banda Arc region. The petrological characteristics of this belt are dominantly calc-alkaline (Hamilton, 1979). Lava flows in this belt are of island-arc tholeiites (Soeria-Atmadja et al., 1994).

The rocks in the Pacitan area consist of basaltic pillow lavas with cross-cutting dykes. In the Bayat area, numerous dykes and other intrusive bodies of mostly basaltic composition are exposed. At Parangtritis, the rocks consist of agglomerate, volcanic breccia, and dykes of andesitic and basaltic composition. In the Kulon Progo area, numerous necks, lava domes, pyroclastic and laharic breccias, and finer volcanic sediments are exposed. In the Luk Ulo area, the rocks consist of several andesitic to basaltic dykes and sills and plugs intruded into the sedimentary cover of Late Eocene to Early Miocene. Many lava flows and laharic breccia of calc-alkaline composition are exposed in the Pangandaran – Cikatomas area (southeastern West Java). In the Pelabuhanratu-Bayah area, the rocks consist of andesitic to basaltic lava flows, volcanic breccia, and tuffs.

Van Bemmelen (1970) stated that the Oligo-Miocene magmatic arc partly formed submarine volcanoes and was contemporaneous with the deposition of *Lepidocyclina*-bearing limestones of Early to Middle Miocene age. Therefore, an arc of Eocene and Oligocene volcanic islands is widely assumed to have been present in medial or southern Java. The presence of submarine volcanoes affected their association with marine sedimentation, mainly carbonates. Hamilton (1979) doubted this association. He stated that it was difficult to visualize the existence of a chain of active volcanoes within a terrain undergoing deposition firstly of a sheet of quartzose clastic sediments and then of another sheet of shelf carbonates. Previous age assignments for the volcanic materials may be erroneous (Hamilton, 1979). However, further studies confirm this association as will be discussed below.

TECTONO-VOLCANIC INFLUENCES ON CARBONATE SEDIMENTATION

Recent and ancient volcanic arcs have commonly provided sites for extensive shallow-water carbonate production, yet studies of carbonate sedimentation contemporaneous with volcanic activity are rare. It has traditionally been held that clastic sediments, particularly fine-grained volcanic particles, have a strongly detrimental effect on carbonate production. However, recent studies indicate that this is not always necessarily the case (Lokier, 1999; Wilson, 2000).

Fulthorpe and Schlanger (1989) provided review on paleo-oceanographic and tectonic settings of Late Oligocene to early Middle Miocene reefs and associated carbonates of offshore Southeast Asia (Figure 6). They did not discuss the carbonates which become the objective of this paper, but their general conclusions on carbonates developing at convergent plate boundaries in the island-arc of the Philippines, can be used here. In an island-arc system, the primary site for shallow-water carbonate deposition is the arc massif of volcaniclastics, extrusive, and plutonic rocks, which forms a thickened crustal block. Reef development near islands in an active volcanic arc is hindered not only by the effects of volcanism but also by rapid erosion of the growing volcanic edifice. Shielding from pyroclastic and erosional debris is essential. Reefs are not developed on young, rapidly-eroding pyroclastic shores. Reef development depends on the frequency of eruptions. Deposition of thick carbonate sections can occur during periods of volcanic quiescence. Periods of volcanic activity, characterized by eruption, edifice building, and rapid erosion, are unfavorable for the development and preservation of thick, continuous, reef and associated carbonates. A second depositional setting for reef growth in convergent plate boundaries is the back-arc basin. A third potential setting for reef development in an island-arc system is the crest of an accretionary prism.

Fulthorpe and Schlanger (1989) showed four potential sites of reef and associated carbonate sediments within an island-arc system (Figure 5), including : (1) uplifted, normal-faulted blocks of the arc massif, (2) deeply subsided, normal-faulted blocks, pelagic drape or volcaniclastic cap buildups of the arc massif and remnant arc behind the back-arc basin, (3) volcanic islands of the arc massif, and (4) uplifted, thrust-faulted blocks of the accretionary prism.

Wilson (2000) investigated tectonic and volcanic influences on the development and termination of the Middle Eocene to Early Miocene carbonates of the Tonasa Formation in South Sulawesi. Here, it was observed that the volcanic activity had limited the lateral extent of the platform, inhibited carbonate production, and terminated it. However, carbonate production contemporaneous with volcanism occurred in more distal, or localized, areas shielded from volcaniclastic input. It was also noted the role of normal-faulted blocks for carbonate drowning, exposure and erosion, re-development, and re-deposition. Wilson (2000) concluded that the evolution and demise of the Tonasa Carbonate Platform is similar in many ways to other carbonates developed in back-arc, intra-arc, or other tectonically active settings with some clastic or volcaniclastic input.

REGIONAL DISTRIBUTION OF THE OLIGO-MIOCENE CARBONATES

There are two trends of carbonate deposition recognised onshore present-day Java during the Oligo-Miocene (Figure 8), namely : (1) A Northern Trend, including the carbonates of the Cepu-Surabaya-Madura areas, North Central Java, and Ciputat-Jatibarang areas (2) A Southern Trend, including the carbonates of the Gunung Kidul – Banyumas – Jampang – Bayah – Sukabumi – Padalarang areas. Briefly, it can be stated that from their tectonic setting and volcanic influence point of view, the two trends are different. The northern trend developed mainly in the subsurface of the back-arc setting and was located far from the contemporaneous volcanic arc, whereas the southern trend developed in the intra-arc setting and shared the same location with or close to the volcanic arc. Each trend will be treated in detail showing the origin and nature of the carbonate sedimentation, the regional geology, and volcanic influence.

NORTHERN TREND: CEPU-SURABAYA-MADURA, NORTH CENTRAL JAVA, AND CIPUTAT-JATIBARANG AREAS

Cepu-Surabaya-Madura Areas

The Oligo-Miocene carbonates of the Cepu-Surabaya-Madura (Figure 8) areas have been discussed recently by Satyana and Darwis (2001), Satyana (2002), Purwaningsih *et al*., (2002), and Satyana and Djumlati (2003). These carbonates are important hydrocarbon producers in the East Java Basin as proven by significant hydrocarbon discoveries made in these carbonates in the last five years.

The carbonates in the onshore Java area are concentrated along basement ridges forming parallel belts trending WSW-ENE in the Cepu, Surabaya, and Madura areas (Figure 9). Four ridges are recognized: the West Cepu High, the East Cepu High, the Kemandung Ridge, and the "BD" Ridge (Ardhana, 1993). These ridges are Early Tertiary elements which resulted from segmentation of the basement during the rifting of the East Java back-arc basin. These ridges continue northeastward into the present-day East Java Sea forming similar but broader basement ridges such as the "JS-1" Ridge and the North Madura Platform.

During the Oligo-Miocene, the Cepu-Surabaya-Madura areas were located in the open sea to the south of the shelf edge which was situated along the present-day northern coast of East Java from Rembang to north of Madura Island. The shelf area was located to the north of the shelf edge which is now the East Java Sea. Therefore, the West Cepu to "BD" ridges were high areas in the open sea.

Reefal carbonate deposition took place on these high areas and mostly as pinnacle reefs. In intervening low areas, deep marine marls, chalks, and shales were deposited as proved by the section encountered by several wells. Ngimbang-1, located to the south of the East Cepu High, penetrated 200 ft of thick, chalky facies and the Jatirogo-1 well, to the east of the West Cepu High, penetrated 150 ft of thick chalky facies.
The carbonates of this group are called the Kujung, Prupuh, and Tuban carbonates in the Cepu and

Surabaya areas or the Poleng and Prupuh carbonates on Madura Island (Figures 4, 5, 11). The group is Late Oligocene to Early Miocene in age. The Kujung Formation consists of three units from the base upwards: Kujung III, II, and I. The basal Kujung III unit is a clastic-rich regressive sequence. The Kujung II unit is a transgressive sequence of shallow-water carbonates and calcareous shales with localized carbonate build-ups over high areas. The Kujung I (Prupuh Member) unit carbonates are high-energy, clean limestones with common pinnacle reefal build-ups. The Rembang reef was developed on the West Cepu High. The Kedung Tuban, Banyu Urip, Sukowati, Mudi, and Kembang Baru reefs were developed on the East Cepu High. The Gondang, Grigis, and Telaga reefs developed on the Kemandung Ridge. The Banjarsari, Porong, KE 11-C, KE-11 E and "BD" reefs were developed on the "BD" Ridge. Generally, the ridges tilt to the southwest due to tectonic uplift which occurred to the northeast along the Rembang-Madura-Kangean (RMK) Zone. Accordingly, on each high, western reefs usually drowned and stopped growing, whereas eastern reefs continued to grow.

The upper carbonates of this group, called the Prupuh carbonates, are exposed to the east of Tuban (Burgon, 2002). The Prupuh limestone in the outcrop is a slope facies of mixed chalky sediments and allochthonous reefal debris. It is about 105 to 175 meters thick. In the type area near Prupuh village there are many calcarenite beds rich in larger foraminifera. The bedded calcarenites must be considered transported. The interbedded marls are abundantly rich in planktonic foraminifera indicative of basal Early Miocene, Zone N4 age, and benthonic assemblages are indicative of a moderately deep marine setting (approximately deep outer shelf, possibly upper bathyal equivalent). The underlying Oligocene beds also have rare, thin limestone beds containing transported larger forams. On Madura Island, marine Oligo-Miocene sediments (Rembang Beds) (van Bemmelen, 1970) form the core of the island. These deposits were folded in the Middle Miocene.

A submarine volcanic arc developed to the south of these ridges and is called the Old Andesite rock unit. The arc represents the island-arc formed by partial melting of both subducted Indian oceanic crust to the south, and overlying, accreted continental crust. Therefore, the basement ridges where the Oligo-Miocene reefs developed, were situated within the back-arc basin since they were formed relatively behind the volcanic arc. Well and outcrop data of the Oligo-Miocene carbonates show no volcanic materials in interbeds within the Kujung/Poleng/ Prupuh/Tuban carbonates and indicate that contemporaneous volcanism to the south did not affect the carbonate sedimentation.

Based on field study in South Sulawesi, Wilson (2000) suggested that carbonate sedimentation was localized in areas near to volcanic activity. In areas within 5-15 kms from the volcanic centers, volcanogenic input commonly hindered shallow-water carbonate production. The Tonasa Carbonate Platform developed up to 40-50 kms to the west of the main inferred volcanic arc. Except for limiting eastward lateral extent of the platform and the interdigitation and minor volcaniclastic input to the east, volcanic activity had little overall tangible effect on the development of the carbonate platform in western South Sulawesi. On Java, the carbonates of Cepu-Surabaya-Madura areas are 75-125 kms from the Old Andesite volcanic arc. This distance is considered sufficient to shield the carbonates from the volcanism.

North Central Java Areas

Sigugur Formation limestones (van Bemmelen, 1949) of Aquitanian (earliest Miocene) age, located in the central part of the North Serayu Range physiographic zone, may represent the Oligo-Miocene carbonates of this area (Figure 9). This formation transgressively covers Eocene rocks. In the South Serayu Range (southern trend), Sigugur Formation limestones are found as fragments within Gabon Old Andesite. No further published work has been found for the Sigugur Formation limestones in Central Java.

The presence of Oligo-Miocene carbonates of the North Central Java Trend (Figure 8) is based on subsurface data. However, the carbonates have not been studied in detail. Three wells were drilled in the area between Pemalang and Semarang in northern Central Java during 1987-1988 by a joint operation of Pertamina and Jolco. Two wells (NCJ A-1 west of Semarang and NCJ B-1 east of Pekalongan) found Oligo-Miocene carbonates interbedded with shales and some intercalations of sands and coals. The third of the wells (NCJ C-1 south of Pemalang) was drilled more to the south than the other wells but did not find any carbonates in the Oligo-Miocene section, only shales. The carbonate of the NCJ A-1 well overlies diorite porphyry with a K-Ar age of 14.65 Ma (Middle Miocene). This igneous rock is considered not as basement but an intrusive body or ramifications of a plutono-volcanic body south of Semarang (old Ungaran complex). The carbonate penetrated by the NCJ B-1 well overlies un-dated volcanic breccia considered to be a volcanic product of the Gabon Old Andesite which protruded more to the north in Central Java. However, no volcanic impurities were reported within the carbonates.

The carbonates penetrated by the NCJ A-1 and NCJ B-1 wells are considered to be developed within a shelfal environment area. Based on biostratigraphic data, it is known that carbonate sedimentation took place in inner to middle sublittoral conditions in clear, warm water with open marine influences. Age-equivalent shelf areas are more developed in West and East Java. The NCJ C-1 well is considered to have penetrated an off-shelf Oligo-Miocene section. The Oligo-Miocene shelf edge of north Central Java therefore still exhibits a continuing trend from those of West and East Java.

Ciputat-Jatibarang Areas

Early Miocene carbonates, including reefs developed on the land-attached platform of the present northern West Java area in the sub-basins of Ciputat, Pasirputih, and Jatibarang (Figure 8); and the intervening highs of Rengasdengklok, Pamanukan, and Gantar-Kandanghaur (Patmosukismo and Yahya, 1974; Adnan *et al*., 1991). The carbonates resulted from sea transgression over the shelf during this period. The carbonates are part of the Middle Cibulakan Formation which is age-equivalent with the Baturaja Formation in the South Sumatra and offshore West Java areas (Figures 4, 5, 12). The formation consists of foraminiferal/algal shelfal limestones with coral reef buildups and bank limestones on top of the platform, deposited on the tops and flanks of ancient highs, possibly also on the crest of active growth faults. With a progressive shaling out of the formation basinwards, particularly towards the southern margin of the Bogor Trough, reservoir distribution is clearly dependent on the basin's structural configuration.

The carbonates cover Late Oligocene basal sands of the Lower Cibulakan Formation (equivalent to the Talang Akar Formation). The formation was formed by sediments eroded from pre-Tertiary basement or Eocene to Oligocene Jatibarang volcaniclastics. In offshore West Java, some carbonates directly onlap old highs such as the Seribu Platform and the Krisna High.

The Jatibarang Formation volcanics were deposited during rifting in the latest Eocene(?) and Oligocene and its thickness increased with the progressive subsidence of the basin (Pertamina and Beicip, 1985). The formation is found mainly in the Jatibarang sub-basin. Lavas and breccias are distributed in the southern part of the basin while tuffs are found more to the north. In a vertical section, the Jatibarang Formation volcanics are composed of pyroclastics with minor fracturing in the lower part. In the middle interval, andesitic lavas interbedded with tuffs with vugs and cavities dominate. Interbedded pyroclastics occur, together with conglomerates, shales, thin limestone and sandstone layers, deposited in a marine to paralic environment.

The origin of the Jatibarang Formation volcanics has not been fully understood. Age dating of the basement (monzonite and diorite) underlying the volcanics resulted in ages of 65-58 Ma (Late Cretaceous to Paleocene time) but also 213 Ma (Triassic) for a silty argillite (Patmosukismo and Yahya, 1974). The present author considers that the Triassic-aged basement is a part of the southern-most rim of Sundaland. The Late Cretaceous-aged basement is part of the Late Cretaceous-earliest Tertiary magmatic arc, and the Jatibarang Formation volcanics represent a later magmatic arc (Eo-Oligocene volcanic arc) which was migrating southwards before occupying the present-day southern coast of Java in Oligo-Miocene times. However, the distribution of the Jatibarang arc should be further detailed. No influence from the Jatibarang volcanism on the Middle Cibulakan carbonates has been noted since the volcanism had ended before the carbonates were deposited.

The Ciputat-Jatibarang area was in a back-arc setting during the Early Miocene relative to the Oligo-Miocene volcanic arc which was developed along southern Java. Jampang-aged volcanism in the Southern Mountains of West Java reached its maximum activity during this period. However, no volcanic material is found within the Middle Cibulakan Formation carbonates, meaning that contemporaneous volcanism did not affect the carbonate sedimentation. The Ciputat-Jatibarang area was 100-150 kms away from the volcanic arc. This distance is considered too far for volcanism to affect the carbonate sedimentation in any significant manner.

SOUTHERN TREND: GUNUNG KIDUL-BANYUMAS-JAMPANG-BAYAH-SUKABUMI-PADALARANG AREAS

Eastern Spur of Java

In the eastern spur of Java (Figure 8), the Southern Mountains consist of volcanic deposits of the "Old Andesite" Formation with intercalations of *Lepidocyclina*-bearing limestones of Lower to Middle Miocene age (van Bemmelen, 1970). Moreover, there are extensive formations of reef-limestones to the south of Malang, Nusa Barung, the area surrounding Puger, and the Blambangan Peninsula. However, the reefs are younger than the Merawan granite intrusions (post-Middle Miocene). These limestones are probably the equivalent of the Wonosari Formation limestones in the Gunung Kidul area, which are considered as being in the upper part of the Middle Miocene.

Jiwo Hills and Southern Surroundings

The Southern Mountains of East Java are best studied in the area south of Surakarta and Klaten (van Bemmelen, 1970) referred to as the complex of the Jiwo Hills and their southern surrounding areas (Figure 8). The first geologic description of the area was given by Verbeek and Fennema (1896). Detailed stratigraphy was provided by Bothé (1929, 1934), van Bemmelen (1970), Sumosusastro (1957), Sumarso and Ismoyowati (1975) and later by geologists from UPN and UGM in Yogyakarta (Jurusan Teknik Geologi UGM, 1994).

The Oligo-Miocene volcanic products of the western part of this area are represented by turbiditic gravity flows of the Kebo-Butak, Semilir, Nglanggran formations (Late Oligocene to early Middle Miocene) which are correlatable with the Besole Formation in the eastern part, and by the Sambipitu and Oyo formations at the end of Early Miocene to early Middle Miocene (Figures 10, 11). The Kebo-Butak Formation is made up of andesitic to dacitic, tuffaceous shales, fine-bedded silts, sandstones, conglomerates and tuffites. Basaltic andesite sills intrude the sequence. Andesitic to basaltic lava is found in the middle part, whereas andesitic breccia occurs in the upper part. Based on fossil assemblages, the Kebo-Butak Formation is of Late Oligocene to early-most Miocene in age and was deposited in an open marine environment (Sumarso and Ismoyowati, 1975). Conformably overlying the Kebo-Butak Formation is the Semilir Formation consisting of white, tuffaceous material alternating with bright tuffites, clayey glass tuffs and pumice-tuff breccias. The Semilir Formation is N5-N9 in age (Early Miocene). Interfingering with the Semilir Formation is the Nglanggran Formation comprising volcanic breccia, agglomerate, poorly bedded tuff, and andesitic to basaltic pillow lava, and 'autoclastic' and 'hyaloclastic' breccia. The equivalent Besole Formation consists of andesitic-dacitic pillow lava, dacitic tuff, and local dioritic intrusions.

No interbedded or intercalated platform or reefal carbonate is found within the Kebo-Butak, Semilir, or Nglanggran formations. Fragments of foraminifera-bearing limestone were found in the Kebo-Butak Formation (Suyoto-UPN-personal communication). The fragments are possibly from limestone from the upper part of the Late Eocene Wungkal-Gamping Formation. Intensive volcanism during the Oligo-Miocene is manifested by rock assemblages of the Kebo-Butak to Nglanggran Formations and is considered to hinder coeval carbonate deposition and reef development in the area.

During the Middle Miocene, sea-level reached maximum transgression and carbonate deposition and development replaced the volcaniclastic dominance. This was contemporaneous with the end of Paleogene volcanism in Java at 18 Ma (uppermost Early Miocene) which resumed at 12 Ma (Soeria-Atmadja et al., 1994). The dormant volcanism and maximum transgression during the Middle Miocene provided a good environment for the development of carbonate sedimentation. Carbonate strata interbedded with early Middle Miocene Sambipitu Formation turbidites were followed by the Oyo Formation which is the first sequence in the area to demonstrate the contemporaneous sedimentation between carbonate and volcanism as expressed by well-bedded tuffaceous limestones, tuffaceous marls, and andesitic tuffs. The dominance of carbonate sedimentation over volcanism is shown by thick, (more than 800 meters) Middle-Late Miocene carbonates of the Wonosari (Punung) Formation which consists of bedded and reefal carbonates with interbeds of tuffaceous sandstones, tuffaceous and marly limestones and siltstones. Siregar (1996) discussed that Wonosari Formation carbonate sedimentation occurred until the Pliocene. Paleogene volcanics are considered to provide sites for deposition of shallow-water Wonosari Formation reefs. The Wonosari Formation is widely exposed to the south of Bayat, from Parangtritis in the west to the Pacitan area in the east (Surono et al., 1988). The formation is a reefal complex comprising four facies (Siregar, 1996; Praptisih and Siregar, 2002) consisting of : (1) tidal-algal packstone which dominates the distribution in the southern area, (2) reef crest-reef front of a coral boundstone facies, (3) upper slope, orbitoid-algal packstone, and (4) lower-slope packstone-wackestone. The last three facies are distributed to the north. Siregar (1996) concluded that the facies of the Wonosari Formation represent a deepening towards the north.

Wonosari Carbonate-Volcaniclastic Sedimentation

Volcaniclastic controls on carbonate sedimentation have been published recently by Lokier (1999). This reference was based on the study centred around the Miocene Wonosari/Punung Formation situated in the Gunung Sewu area to the southeast of Yogyakarta (Figure 10). Lokier (1999) concluded that the effects of volcaniclastic input on biotic development can be assigned to at least three distinct categories. Where the input of volcanic-derived material was low, a wide variety of epifaunal and infaunal organisms occurred including: forams, algae, corals, molluscs, and echinoids. During short periods of elevated volcanic sediment input, there was a rapid increase in the number of individuals and the number of species. Sustained volcanic input resulted in a decrease in the number of species present but with elevated numbers of individuals. Energy levels and volcaniclastic sediment grain size appear to have been the main factors controlling the prevalent biota. High energy levels and coarse volcaniclastic material appear to have resulted in a dominance by laminar, concentric rhodoliths. Lower energy conditions together with finer volcaniclastics are associated with abundant larger benthic foraminifera.

Kulon Progo-Banyumas-Cilacap Area (South Central Java)

The Oligo-Miocene "Old Andesite" in this area (Figure 8) is known as the Gabon or Waturanda Volcanics (Figure 10). They comprise breccia tuffs, volcanic breccias and lahars. Contemporaneous structures developed in this area resulted in the formation of high and low areas. Significant physiographic-tectonic features include: Gabon High, Citanduy Low, Besuki-Majenang High, Kroya Low, Karang Bolong High, Kebumen Low, Kebumen High, and Kulon Progo High (Sujanto and Sumantri, 1977). Volcanism during the Oligo-Miocene had deposited volcano-turbidites of the Waturanda Formation in the low areas. No carbonate sedimentation occurred during the dominance of the volcanism. In the upper part of the Gabon Volcanics, limestone fragments referred to as the Sigugur Formation limestones are found locally. However, they are transported from some areas outside of the Cilacap area (Hening Sugiatno, Lundin Banyumas, personal communication).

Carbonate sedimentation initially occurred in the upper part of the Early Miocene and took place in high areas such as on the Kulon Progo High and Karang Bolong High resulting in Early-Middle Miocene-aged reefs of the Sentolo, Jonggrangan and Karang Bolong/Kalipucang formations. The reefs built up on former volcanic highs. Van Bemmelen (1970) stated that on the northern side of the Karangbolong High, a tuffaceous layer is intercalated between the Sentolo Formation limestones and the "Old Andesite" breccias and that the oldest post-volcanic formation consists of the Early Miocene Jonggrangan Formation marls and limestones. However, recent paleontological analysis on samples from Gunung Kucir and West Gunung Dlanggung (Kulon Progo) (Pambudi and Budiadi, 1999) showed that the Sentolo Formation is older than the Jonggrangan Formation. The Sontolo Formation is Early Miocene and the Jonggrangan Formation is Middle to Late Miocene in age; both were deposited unconformably above the "Old Andesite" as transgressive shallow marine sediments.

In South Central Java, as the axis of volcanic activity progressively shifted to the north, in Early and Middle Miocene times, the remnant volcanic highs formed potential areas for carbonate development (Clarke, 1976). These volcanic highs were of varying sizes and patterns. Some were sub-aerial, and thus contributed erosional volcaniclastics to the carbonates; others remained submerged in shallow-water allowing reef carbonates to develop, while some were deeper, permitting only skeletal, biostromal carbonates to accumulate. The latter type of carbonate was drilled by Java Shell in 1972-1973 (Alveolina-1, Borealis-1) and revealed that the carbonates which are in contact with the volcanics at the base of the sequence are completely dolomitized and it is argued empirically that dolomitisation is due to the proximity of the volcaniclastic sediments.

Karangnunggal-Pangalengan-Jampang

The Southern Mountains of West Java begin at Nusa Kambangan, increasing westwards in width to 50 km in the Southern Mountains of the southern West Java and ending at Pelabuhan Ratu Bay (Figure 8). The Oligo-Miocene volcaniclastic deposits in the Southern Mountains of West Java are represented by the Jampang Series (van Bemmelen, 1970) (Figure 12).

The eastern part of the Southern Mountains in West Java is referred to here as the Karangnunggal area. The deepest exposures of the Jampang Series consist of pyroxene-andesitic breccias with rare intercalations of marly tuff-sandstones and limestones with *Lepidocyclina* and *Trillina howchini* (Early Miocene). In this deepest part of the section, basalto-andesitic dikes occur, and it is also intruded by the granodiorites of Tenjolaut, causing hydrothermal (propylitization) of this Old Andesite Formation. The middle part of the Jampang Series is formed by about 800 meters of well-stratified tuff-sandstones and ash-tuffs. The top part of the section consists of well-stratified dacitic ash-tuffs and pumice-tuffs with intercalated silicified dacitic lava or tuff flow of Genteng dacite, which is Middle Miocene in age. Carbonate sedimentation dominated the area in the Late Miocene with the deposition of the Bentang Formation which consists of tuff-marls, tuff-sandstones and conglomerates, with lignitic beds and resin nodules and massive, reefal limestones formed farther offshore.

The central part of the Southern Mountains of West Java (Pangalengan area) is elevated somewhat higher than the western and eastern parts, and is more deeply dissected by rejuvenated erosion. The narrow ridges of pyroxene-andesites and breccias are residual hard-rock ridges of the Old Andesite formation. There is no significant carbonate sedimentation until the Late Miocene when fossil-bearing, marly tuff-sandstones of a littoral-neritic facies of the Koleberes Formation (Cigugur) were deposited. These deposits are equivalent to the Bentang Formation.

The western part of the Southern Mountains of West Java is called the Jampang area and has become the reference for the Oligo-Miocene volcaniclastic deposits in West Java (Figure 12). The Jampang Series begins with tuffaceous *Globigerina*-marls, tuffaceous-sandstones, and beds of calcareous tuff-breccias of andesitic and dacitic composition, intercalated with thick lenses of limestone with larger foraminifera (*Spiroclypeus,Eulepidina,Nephrolepidina, Lepidocyclina, Miogypsina, Cycloclypeus, Trillina howchini*) indicating an Oligo-Miocene age.The upper part of the Jampang Series consists of dacitic tuff-sandstones and pumice tuffs, alternating with breccias and tuffs of an andesitic composition. Intercalated limestone lenses sometimes contain *Spiroclypeus* indicating an Early Miocene age. The area between Lengkong and Jampangkulon was one of the eruption centres of this Jampang Series volcanism. Here, coarse breccias alternate with massive andesitic and basaltic lava flows. Moreover, great intrusive bodies of andesite and dacite are found.

Significant carbonate sedimentation started when the Jampang Series volcanism was already more-or-less extinct in the Late Miocene. The formations include the Lengkong Formation and Bojonglopang Formation reef limestones. The Lengkong Formation consists of marls, mudstones, and calcareous sandstones with hard, platy limestones and minor tuffaceous materials. The Bojonglopang Formation reef limestones comprise a complex 250-300 meters thick of unstratified, hard coral-limestones and soft, porous *Globigerina* limestones, passing eastwards into platy limestones.

The limestones in the Southern Mountains of West Java can be considered as being deposited on off-shelf platforms, presumably base-leveled submarine volcanoes, or, folded uplifted and subsequently abraded volcanic debris sediments of the Jampang Formation. This uplift and subsequent erosion took place during the mid-Tertiary orogeny (Koesoemadinata et al., 2000).

Bayah Mountains

The Bayah, Sukabumi, and Padalarang (Figure 8) areas form mountains and ridges made up of Tertiary formations which rise above the axial depression of West Java referred to as the Bandung Zone by van Bemmelen (1970). Significant Paleogene carbonate sedimentation took place within these ridges with more-or-less volcanic influence from the Old Andesite formation.

The Bayah Mountains in the South Banten area form the western extension of the Bandung Zone. The Old Andesite volcanism commenced as early as the Early Eocene as tuff intercalations within the Bayah Layers. The Late Eocene Cicarucup Layers cover the Old Andesite and contain Old Andesite detritus. This proves that the Old Andesite volcanism began in this area in the lower part of the Paleogene, that is earlier than in the rest of Java. The fauna of the Cicarucup Layers contains larger foraminifera and strikingly resembles that of the Nanggulan Formation in Central Java.

A marine transgression occurred during the Oligocene, the Bayah area subsided and sediments of the Cijengkol Formation were deposited (Figures 13, 14). This is in accordance with the concept that at that time the southern belt of Java was elevated above sea-level, while basin subsidence continued in the adjacent northern tract. The Lower Cijengkol Formation consists of coarse andesitic conglomerates and andesitic tuffs with occasional coal seams. Reefal carbonates, marls, clay-shales, and sandstones occur in the Upper Cijengkol Formation. In the Oligo-Miocene, sediments of the Citarate Formation were deposited mainly in the southern area, consisting of reef limestones in the lower part and the “tuffite zone” in the upper part. The limestones contain terrigeneous detritus. The tuffite zone comprises tuffaceous limestone-gravels, conglomerates, breccias, sandstones, marls, and limestones, always with detritus from the Old Andesite formation. The Citarate Formation can be correlated with the lower part of the Jampang Series.

The reef limestones which alternate with volcaniclastic deposits are still found in the Early Miocene Cimapag, Sareweh, and Badui formations (Figure 13). The Cimapag Formation extends transgressively over all older formations, mainly in the central area. The basal strata are polymict breccias and conglomerates, and are succeeded by a very variable complex of andesitic and dacitic volcanic products, which alternate with conglomerates, sandstones, clays, and occasional reef limestones. The Cimapag Formation is disconformably overlain by the Sareweh Formation in the northwestern area and consists of reefal limestones, marls, sandstones, and tuffites. The Badui Formation is distributed disconformably above the Sareweh Formation in the northern area and consists of andesitic conglomerates and sandstones passing upward into limestones, mudstones, and marls. The Cimapag-Sareweh-Badui Series form a group of sediments deposited around the central Bayah High during the Early to Middle Miocene, especially in the adjacent Bogor Basin.

Sukabumi - Padalarang Highs

Significant Oligo-Miocene reef carbonates of West Java are called collectively the Rajamandala Reefs/Formation and crop-out on the highs of Sukabumi and Padalarang which are ridges emerging from the central depression and are considered as the eastward continuation of the Bayah Mountains (van Bemmelen, 1970) (Figure 8). The ridges, trending WSW-ENE are part of a complicated steep anticlinorium of Tertiary sediments associated with northward thrusting. South of the ridges, there is a transition between the central depression of the Bandung Zone and the Southern Mountains. In the core of the Rajamandala anticline a number of andesitic intrusions are found, which were intruded contemporaneously with and after deformation. Detailed reef studies covering the Sukabumi High were provided by Adinegoro (1973) and Carnell (2000) and on the Padalarang High by Koesoemadinata and Siregar (1984), Premonowati and Satyawan (1998), and Koesoemadinata *et al*. (2000). The regional geology of the area was described by Baumann et al. (1973).

Reefal limestones developed on the Sukabumi High platform (Figure 12) during the Late Oligocene to Early Miocene, corresponding to N3-N4 or late Te, (Adinegoro, 1973), and is equivalent to the development of the Kujung Reefs in East Java. The reef building organisms are primarily calcareous algae. Coral colonies are only locally important as reef builders. *Bryozoans* are rare. Accumulations of larger foraminifera, mostly *Lepidocyclina*, are able to build up platy limestones and they also contribute as reef-building materials. Several reef limestones facies can be distinguished: reef limestones with growing reef and detrital limestones with reef debris. The reef limestones developed on the substratum of Early Oligocene quartzitic sandstones of the Gunung Walat Formation and on Late Oligocene sandy clay and sandy marls of the Batuasih Formation. Carnell

(2000), based on his field investigation in the area south of Cibadak, concluded that the Rajamandala carbonates are dominated by a shallow algal/foraminiferal carbonate shelf containing numerous reefal build-ups dominated by a fore reef debris facies and an algal/foraminiferal shelf facies.

No volcanic material was found within the Rajamandala carbonates of the Sukabumi High, indicating that the contemporaneous Old Andesite volcanism to the south in the Jampang area of the Southern Mountains did not affect the carbonate sedimentation. It is considered that the Jampang volcanism had just begun and did not have influence on the earlier carbonate sedimentation of the Sukabumi High. To the south, the Sukabumi High was separated by the Cibadak-Pelabuhanratu Low from the Jampang area. During the Early Miocene, a deepening of the depositional environment due to subsidence of the Bogor Basin ended the Rajamandala reef development and was contemporaneous with increasing Jampang volcanism (Figure 12). Volcaniclastic turbidites of the Citarum Formation consisting of mudstones, siltstones, and volcaniclastics with occasional sandstones and detrital limestone lenses covered the Rajamandala carbonates.

To the northeast, after the interruptions in the Cianjur area due to facies change, or presence of a channel or Quaternary volcanic cover, the Oligo-Miocene Rajamandala reefs re-appear in the Padalarang High to the west of Bandung. These limestones have a minimum thickness of 600 meters and dip to the south. They are involved in asymmetric folding and thrusting to the north. Koesoemadinata et al. (2000) provided the general stratigraphy of the carbonates. Correlation of measured sections demonstrates that the limestones become more massive and less stratified from NE to SW while the insoluble residue decreases. Corals increase in abundance towards the southwest, while planktonic forams increase toward the northeast. The major constituents of the limestones are red algae and large foraminifera, while corals form a very significant constituent, especially in the massive thick beds. Koesoemadinata and Siregar (1984) detailed the facies of these carbonates. Along its WSW-ENE trend, the limestones exhibit shallower facies to the south including: (1) a graded granular limestone representing turbidites at the toe of the basin-slope facies, (2) a foraminiferal algae with rudstone representing a fore-reef facies, (3) a coral-algal bafflestone to boundstone representing a reef crest to reef flat facies and (4) a possible milliolid limestone with isolated patch reefs representing a lagoonal back-reef facies. The milliolid facies is also observed to erode the massive coral limestone (Permonowati and Satyawan, 1998).

The facies of the Rajamandala limestone is similar with the facies of the Middle Miocene Wonosari Formation reefs and carbonates in the Gunung Kidul area which also deepen to the north facing a central depression of the Solo Zone. The sub-stratum of the Rajamandala reefs in this area is the Batuasih Formation which is Early Oligocene in age and it is covered by a thick turbiditic sequence of the Early Miocene Citarum Formation.

The Rajamandala reefs sequence is interpreted by Koesoemadinata and Siregar (1984) as a barrier or fringing reef, extending WSW-ENE with reef spurs protruding towards the Bogor Basin in the north, into which reef debris was deposited forming slope and toe-of slope deposits. The relationship to the Southern Mountains is that the reefs formed the northern edge of the Southern Mountains which was positioned as an off-shelf platform (isolated platform) relatively to the land-attached shelf area in northwest Java. The off-shelf platform of the Southern Mountains was separated by a regional normal fault trending WSW-ENE with the southern block being upthrown and tilted to the south towards the Indian Ocean. No volcanic materials are discovered within the Rajamandala carbonates. The development of the Rajamandala reefs ended in the mid-Early Miocene when the Southern Mountains were uplifted and volcanic activity was intensified. This occurred contemporaneously with the subsidence of the Bogor Basin to the north. Influx of volcaniclastic turbidites buried the reefs.

PETROLEUM IMPLICATIONS

Northern Trend

The prospectivity of the Oligo-Miocene carbonates of the Northern Trend as oil producers, especially in the East Java Basin, has been proven since the early 1970s. Recently, the carbonates have become the main target of exploration in this area. Significant hydrocarbon discoveries have been made in these carbonate reservoirs. Satyana and Darwis (2001), Satyana (2002), and Satyana and Djumlati (2003) discussed these discoveries.

Two modes of Kujung carbonate deposition can be distinguished in this area: (1) deposition on a land-attached platform, and (2) deposition on offshore isolated platforms. A continuous southwest-northeast to west-east trending Oligo-Miocene shelf-edge separated these two domains of carbonate deposition. To the north of the shelf-edge barrier, the deposition of the Oligo-Miocene carbonates/reefs was controlled by the segmented basement of the land-attached platform. The segmented basement formed a number of horsts and grabens trending roughly southwest-northeast facilitating the deposition of the carbonates on the highs. Three carbonate reef facies are recognized within this area: (1) fringing reef at the edge of basement, (2) basinal lime mud mound, and (3) patch-reef over platform. Along the shelf-edge area, one type of carbonate facies is recognized namely the shelf-edge barrier reef.

To the south of the Paleogene shelf-edge barrier, the deposition of the Oligo-Miocene carbonates and reefs was controlled by segmented basement forming the offshore isolated platforms (Figure 9). The isolated platforms represent a number of horsts and grabens trending roughly WSW-ENE. Reefs grew above these highs forming pinnacle reefs over offshore isolated platforms.

The Kujung III/II carbonates have moderate matrix porosity that has been enhanced locally by fracturing. The average porosity is 23 – 25 %. Average permeability is excellent (160 mD in the Camar field). The Kujung I reefs exhibit good to excellent reservoir characteristics (porosity 20 – 30 % and permeabilities up to 194 mD). In some places, such as the Madura Platform, porosity is expected from repeated exposure on the crest of the old Madura Platform (Figure 16).

The western part of the Northern Trend comprises the Early Miocene Baturaja Formation (Middle Cibulakan) carbonates. The carbonates are prolific oil and gas reservoirs both onshore and offshore. The reservoir quality of the Baturaja limestone offshore is better than that of the onshore area. The carbonates consist of reefal build-ups growing on paleo-basement highs or on a carbonate platform during the Early Miocene. In the Bima field, on the Seribu Platform offshore Northwest Java, the Upper Baturaja Formation was reported as being a carbonate build-up deposited during 26-21 Ma (Late Oligocene-Early Miocene) (Wooding et al., 1990 in Pertamina BPPKA, 1996). The porosity is associated with leaching of skeletal grains and is facies dependent. Good reservoir is normally associated with reefal carbonates surrounding basement paleo-highs. In the Bima field, porosity ranges from 24-36 % and permeability ranges from 100 to 1000 mD and porosities range from 19-30 % in the Rama field (Tonkin, 1991 in Pertamina BPPKA, 1996). Several episodes of sea-level lowering occurred during the deposition of the Baturaja Formation. This caused the Baturaja Formation reefs to become karstified during emergence above sea level and meteoric water percolated down into the reservoir and formed moldic and vuggy porosities. Reef-related facies constituting good reservoir occur mainly from skeletal wackestone, coral/skeletal packstone and coral boundstone.

Based on petrographic review (Figure 15), there are no impurities derived from volcanic materials contained in the matrix of either of the Kujung and Baturaja formation carbonates. This means that volcanic ejecta from contemporaneous volcanic activity in southern Java did not affect the carbonate sedimentation which was taking place in northern Java. The long distance (100 to more than 150 kms) between the southern volcanic arc and sites of carbonate deposition in northern Java may have prevented the overlapping sedimentation between carbonate and volcanic deposition (Figure 9). The absence of volcanic materials within the Northern Trend carbonates gives positive points for the quality of carbonate reservoirs since the porosity-reducing diagenetic changes due to volcanic-related clay deposition do not occur.

Recent hydrocarbon discoveries within the Oligo-Miocene carbonates of the East Java Basin reflect the effectiveness of the related petroleum system involving mature source rocks (kitchen area), migration pathways, good carbonate reservoirs, resilient seals, and good stratigraphic traps. This is supported with favorable related timing of generation-migration-trapping and good preservation of the hydrocarbon accumulation. The proven kitchen areas generating hydrocarbons are low areas where Ngimbang and Talang Akar sources were deposited. The source rocks are of marginal marine, deltaic, and lacustrine origins. Maturation started in the lows during the Middle Miocene by reactivation and renewed subsidence of many depression areas causing further burial. Hydrocarbons migrated through carrier beds and/or faults from kitchen areas into high areas where Kujung and Baturaja reefal carbonates were developed. Intraformational shales of the Kujung Formation or shales of the Tuban Formation and Upper Cibulakan Formation provide the top-seal

Southern Trend

Southern Java has experienced a relative lack of petroleum exploration. Exploration in this area has only been concentrated in South Central Java or the Banyumas area both onshore and offshore. Geological and seismic surveys as well as exploration drilling have been conducted by the early Dutch operator, Pertamina, and several PSC contractors (Shell Java, Coparex Banyumas, and Lundin Banyumas). Lundin Banyumas is still operating. No discovery has been reported, but oil seepages are well known to occur in this area. Beyond this area, there is no petroleum exploration conducted in southern Java.

Shell Java was the only operator targeting the Oligo-Miocene carbonates as the objective. They operated the South Central Java offshore area from 1971-1974. Two wells were drilled in 1972-1973, Borealis-1 and Alveolina-1, both were dry wells. The geology and exploration of this area were reported by Bolliger and de Ruiter (1975) and Clarke (1976). Various facies of carbonates are developed: some carbonates were mixed with volcaniclastics derived from subaerial, mid-Oligocene volcanic highs, some were developed as reefal build-ups sitting on remnant volcanic highs, others developed as skeletal, biostromal carbonates related to deeply submerged volcanic highs. The Alveolina-1 well penetrated Early- Middle Miocene reefal carbonates. The carbonates proved to be of excellent reservoir quality, but contained no hydrocarbons. The carbonates in contact with the volcanics at the base of the sequence are completely dolomitized and it is argued empirically that dolomitisation is due to the proximity of volcaniclastic sediments. The cessation of carbonate sedimentation is shown to be due to drowning of the platform.

To the east of the Banyumas area, Miocene carbonates are represented by the Wonosari Formation carbonates which are Middle Miocene to Pliocene in age (Siregar, 1996). As discussed previously, the carbonates were deposited after the Oligo-Miocene volcanism diminished and can be subdivided into four facies of coral-algal reefs. There is no published study evaluating the potential of the Wonosari Formation carbonates as petroleum reservoirs. Some studies were conducted on these carbonates evaluating their potential as groundwater aquifers (Siregar et al., 1994a, b in Siregar, 1996). A recent field trip to examine these carbonates found that several reef facies of the Wonosari Formation carbonates could have good to excellent porosities such as in facies of coral boundstone which is rich in mouldic and vuggy porosities and facies of planktonic packstone-wackestone with excellent primary porosities.

There is no published study on the petroleum potential of the Oligo-Miocene carbonates of southern West Java (Rajamandala carbonates). Adinegoro (1973) and Koesoemadinata and Siregar (1984) studied the sedimentology and biostratigraphy of the carbonates at their outcrops in the Sukabumi and Padalarang areas, respectively. The Rajamandala outcrops in Sukabumi were re-examined by Carnell (2000) which resulted in facies analysis, interpretation of depositional setting, and diagenesis. In the Sukabumi area, the Rajamandala limestone shows an overall shallowing upwards from relatively deep, shelfal carbonates to shallow marine limestones. The sedimentary record is dominated by a shallow algal/foraminiferal carbonate shelf containing numerous reefal build-ups. Diagenesis has had a strong influence on the Rajamandala limestone with several phases of leaching and cementation apparent. The outcrops at Sukabumi show extensive development of karst features. In addition, fracturing and associated dolomitisation are locally important. Micritisation is locally developed but has not been extensive. Leaching of corals created mouldic pores which were subsequently cemented with calcite. This calcite has cemented all available primary porosity. Neomorphism resulted in much of the fabric being recrystallized to secondary spar. In the Padalarang area, pore spaces of coral boundstone facies are filled up by muds containing coral debris and large foraminifera often bound with encrusting red algae. The rocks are usually dense, massive, non-bedded to poorly bedded, with no primary porosity. Recrystallization is fairly common. This may indicate that reservoir potential of the Rajamandala carbonates is poor.

The carbonates of the Southern Trend of Java, as previously discussed, were deposited non-contemporaneously with the Oligo-Miocene volcanism. Deposition of carbonates in offshore South Central Java and the Wonosari Formation postdated the main episodes of the "Old Andesite" volcanism. In contrast deposition of the Rajamandala carbonates pre-dated the main episodes of "Old Andesite" volcanism of West Java. Therefore, volcanic impurities do not appear to significantly affect the diagenetic change in the carbonates.

The presence of a viable petroleum system is riskier to demonstrate in the Southern Trend as compared to that of the Northern Trend. Based on the regional stratigraphy, there is no identified stratigraphic sequence which may constitute potential petroleum source rocks. However, numerous oil and gas seepages in the onshore Banyumas area may indicate the presence of an active kitchen and migration in this area. Locally distributed black calcareous shales/marls of Early Oligocene Batuasih marls in the Sukabumi area may provide petroleum source rocks for the Oligo-Miocene Rajamandala reefs.

The southern Java area has been under-explored, therefore our knowledge of the presence of potential petroleum system is very poor.

CONCLUSIONS

1. On Java, during the Oligo-Miocene there was active development of platform and reefal carbonates and "Old Andesite" volcanism.

2. Based on their tectonic-volcanic setting, two trends of the Oligo-Miocene carbonates can be recognized: (1) A Northern Trend, including the Cepu-Surabaya-Madura, North Central Java, and Ciputat-Jatibarang areas, and (2) A Southern Trend, including the Gunung Kidul-Banyumas-Jampang-Bayah-Sukabumi-Padalarang areas.

3. The Northern Trend was developed in a back-arc setting, 75-150 kms away from the Oligo-Miocene volcanic arc of southern Java. There is no volcanic material found within the carbonates meaning that contemporaneous volcanism did not affect the carbonate sedimentation. The distal location from the volcanic arc is considered to be the reason.

4. The Southern Trend was within the intra-arc setting. No reefal carbonates are found to be developed contemporaneously with the volcanism in the Gunung Kidul-Banyumas-Jampang areas. Insignificant foraminiferal limestones developed as intercalations with the Jampang volcanics in West Java during the Early Miocene.

5. Significant reefs grew during the Oligo-Miocene on the ridges located in front of the present-day Southern Mountains including in the Bayah-Sukabumi-Padalarang areas. Platform and reefal limestones developed during the Paleogene in the Bayah area. The volcanism in this area started in the Early Eocene and had diminished when the Oligo-Miocene transgression resulted in deposition of reefal carbonates. In the Sukabumi-Padalarang areas, Rajamandala reefs developed preceding volcanism of the Early Miocene as recognized in the Jampang Formation . When this volcanism intensified, the growth of the Rajamandala reefs was terminated.

6. The quiescence of volcanism in Java from 18 – 12 Ma (Uppermost Early Miocene - Middle Miocene) was contemporaneous with the maximum extent of the sea transgression. Significant reefal carbonates developed during the period along the present-day Southern Mountains of Java such as those of the Wonosari/Punung Formation in the Gunung Kidul area, the Jonggrangan Formation in the Kulon Progo area, the Karangbolong/Kalipucang Formation in the Banyumas area, and the Bojonglopang Formation in the Jampang area. The substrate on which these reefs grew comprises base-leveled Oligo-Miocene submarine volcanoes.

7. The Northern Trend carbonates are very prolific reservoirs. Volcanic impurities are absent or are very minor constituents and insignificant diagenetically. The geological setting of the carbonates is very supportive for the existence of a viable petroleum system. The Southern Trend carbonates partly show good-excellent porosities such as the Wonosari Formation carbonates, while others show severe neomorphism such as the Rajamandala Formation carbonates. There is no hydrocarbon discovery along the Southern Trend but the area has been inadequately explored. The presence of a viable petroleum system is riskier than that of the Northern Trend.

ACKNOWLEDGMENTS

The paper (without an evaluation of the petroleum system) was firstly presented at the Joint Conference of IAGI (Indonesian Association of Geologists) and HAGI (Indonesian Association of Geophysicists) in Jakarta, December 2003. The paper has benefited from discussions with C. Prasetyadi and Suyoto (University of Pembangunan Nasional Veteran Yogyakarta), Sutikno Bronto (Geological Research and Development Centre Bandung), Hening Sugiatno and Peter Lunt (Lundin Blora and Banyumas). Margaretha Purwaningsih (ConocoPhillips) is thanked for providing summaries of some literatures, contributing data and drafting some figures. The paper is edited by John Bates (Santos). BPMIGAS is acknowledged for giving an opportunity to publish this paper.

REFERENCES

Adinegoro, U., 1973. Reef limestone in the Sukabumi area, Proceedings Indonesian Petroleum Association, the 2nd Annual Convention, p. 109-120.

Adnan, A., Sukowitono, Supriyanto, 1991. Jatibarang sub basin – a half graben model in the onshore of Northwest Java, Proceedings Indonesian Petroleum Association, the 20th Annual Convention, p. 279-298.

Baumann, P., de Genevraye, P., Samuel, L., Mudjito, Sajekti, S., 1973. Contribution to the geological knowledge of Southwest Java, Proceedings Indonesian Petroleum Association, the 2nd Annual Convention, p. 105-108.

Bothé, A. Ch. D., 1929. Djiwo Hills and Southern Range, Excursion Guide 4th Pacific Science Congress Java, Bandung, 14 ps.

Bothé, A. Ch. D., 1934. Geological Map of Java, Sheet Klaten, Geological Survey of Indonesia, Bandung, unpublished.

Burgon, G., Lunt, P., and Allan, T., 2002. Indonesian Petroleum Association Field Trip to Eastern Java, Indonesian Petroleum Association.

Carnell, A., 2000. The Rajamandala limestone at Sukabumi; can it be considered a field analogue for the Baturaja limestone, Proceedings American Assoc. of Petroleum Geologists, International Conference, Denpasar.

Clarke, M.H., 1976. Carbonate build-ups on volcanic highs south of Java, (Abstract), Proceedings of the Carbonate Seminar, Special Volume, Indonesian Petroleum Association, p. 120.

Fulthorpe, C.S. and Schlanger, S.O., 1989. Paleo-oceanographic and tectonic settings of early Miocene reefs and associated carbonates of offshore Southeast Asia, The American Association of Petroleum Geologists Bull., v. 73, No. 6, p. 729-756.

Hamilton, W., 1979. Tectonics of the Indonesian Region, USGS Professional Paper 1078, US Govt. Print. Off., Washington DC, 345 ps.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic, Science, v. 235, p. 1156-1167.

Hutchison, C.S., 1989. Geological Evolution of South-East Asia, Clarendon Press, Oxford, 368 ps.

Junghuhn, F., 1853. Java, Deszelfs Gedaante, Bekleeding en Inwendige Structuur, Amsterdam.

Jurusan Teknik Geologi UGM, 1994. Geologi Daerah Pegunungan Selatan : Suatu Kontribusi, Pertemuan Ilmiah Ulang Tahun ke-10, Stasiun Lapangan Geologi "Prof. R. Soeroso Notohadiprawiro, Bayat, Klaten.

Katili, J.A., 1975. Volcanism and plate tectonics in the Indonesian island arcs, Tectonophysics, 26, p. 165-188.

Koesoemadinata, R.P. and Siregar, S., 1984. Reef facies model of the Rajamandala Formation, West Java, Proceedings Indonesian Petroleum Association, the 13th Annual Convention, p. 1-18.

Koesoemadinata, R.P., Tabri, K.N., Premonowati, and Yuwono, B., 2000. Carbonate Fieldtrip to Tagog Apu - Rajamandala Area West Java, September 28-29, 2000 – Guide Book, Indonesian Associations of Geologists-Jakarta Chapter, 70 ps.

Lokier, S.W., 1999. Volcaniclastic controls on carbonate sedimentation within the Gunung Sewu area, south area, South Central Java, Indonesia, Abstract, Proceeding of the 1st FOSI-IAGI Regional

Seminar: Tectonics and Sedimentation of Indonesia and 50th Anniversary Memorial of R.W. van Bemmelen's Book – The Geology of Indonesia, p. 50.

Martodjojo, S., 1994. Data stratigrafi, pola tektonik dan perkembangan cekungan pada jalur anjakan-lipatan di P. Jawa, Kumpulan Makalah Seminar Geologi dan Geotektonik Pulau Jawa, sejak Akhir Mesozoik hingga Kuarter, Jurusan Teknik Geologi, Fakultas Teknik, Universitas Gadjah Mada, Yogyakarta, p. 15-26.

Pambudi, S. and Budiadi, E., 1999. Sedimentation model of Jonggrangan Fm-Sentolo Fm in Gunung Kucir-West Gunung Dlanggung area, Kulon Progo, Yogyakarta, Abstract, Proceeding of the 1st FOSI-IAGI Regional Seminar: Tectonics and Sedimentation of Indonesia and 50th Anniversary Memorial of R.W. van Bemmelen's Book - The Geology of Indonesia, p. 48-49.

Patmosukismo, S. and Yahya, I., 1974. The basement configuration of the Northwest Java area, Proceedings Indonesian Petroleum Association, the 3rd Annual Convention, p. 129-152.

Pertamina and Beicip, 1985. Hydrocarbon Potential of Western Indonesia, Pertamina and Beicip, Jakarta, 293 ps.

Pertamina BPPKA, 1996. Petroleum Geology of Indonesian Basins: Principles, Methods and Application, Volume III West Java Sea Basins, Pertamina BPPKA, Jakarta, 132 ps.

Praptisih and Siregar, M.S., Petrografi dan fasies batugamping Formasi Wonosari di daerah Bayat, Jawa Tengah, in Sumberdaya Geologi Daerah Istimewa Yogyakarta dan Jawa Tengah, Ikatan Ahli Geologi Indonesia, Pengda DIY-Jateng, p. 32-40.

Purwaningsih, M.E.M., Satyana, A.H., Budiyani, S., Noeradi, D., and Halik, N.M., 2002. Evolution of the late Oligocene Kujung reef complex in the Western East Cepu High, East Java Basin: seismic sequence stratigraphic study, Proceedings Indonesian Association of Geologists (IAGI), 31st Annual Convention, p. 655-671.

Satyana, A.H., 2002. Oligo-Miocene reefs: East Java's giant fields, Proceedings Giant Field and New Exploration Concepts Seminar, IAGI, Jakarta 17 October 2002.

Satyana, A.H. and Darwis, A., 2001. Recent significant discoveries within Oligo-Miocene carbonates of the East Java Basin: integrating the petroleum geology: Proceedings Indonesian Association of Geologists (IAGI) 30th Annual Convention and Geosea 10th Regional Congress, p. 42-46.

Satyana, A.H. and Djumlati, 2003. Oligo-Miocene carbonates of the East Java Basin : Facies definition leading to recent significant discoveries, American Assoc. of Petroleum Geologists, International Conference at Barcelona.

Siregar, M.S., 1996. Endapan pasang-surut dalam Formasi Wonosari, Proceedings Indonesian Association of Geologists, the 25th Annual Convention.

Smyth, H., Hall, R., Hamilton, J., and Kinny, P., 2003. Volcanic origin of quartz-rich sediments in East Java, Proceedings Indonesian Petroleum Association, the 29th Annual Convention, p. 541-559.

Soeria-Atmadja, R., Maury, R.C., Bellon, H., Pringgoprawiro, H., Polves, M., and Priadi, B., 1994. Tertiary magmatic belts in Java, Journal of Southeast Asian Earth Sciences, v. 9, No. ½, p. 13-27.

Soeria-Atmadja, R., Suparka, S., Abdullah, C.I., Noeradi, D., Sutanto, 1994. Magmatism in western Indonesia, the trapping of the Sumba block and the gateways to the east of Sundaland, Journal of Asian Earth Sciences, v. 16, No. 1, p. 1-12.

Sudarmono, Suherman, T., and Eza, B., 1997. Paleogene basin development in Sundaland and its role to the petroleum systems in western Indonesia, Indonesian Petroleum Association Proceedings of the Petroleum Systems of SE Asia and Australia Conference.

Sujanto, F.X. and Sumantri, Y.R., 1977. Preliminary study on the Tertiary depositional patterns of Java, Proceedings Indonesian Petroleum Association, the 6th Annual Convention., p. 183-213.

Sukarna, D., Noya, Y., Mangga, S.A., 1994. Petrology and geochemistry of the Tertiary plutonic and volcanic rocks in the Bayah area, Proceedings Indonesian Association of Geologists (IAGI), 23rd Annual Convention, p. 389-412.

Sumarso and Ismoyowati, T., 1975. Contribution to the stratigraphy of the Jiwo Hills and their southern surroundings (Central Java), Proceedings Indonesian Petroleum Association, the 4th Annual Convention, p. 19-26.

Sumosusastro, S., 1957. A contribution to the geology of eastern Djiwo Hills and the Southern Range in Central Java, Indonesian Journal for Natural Science, v. 112, p. 115-134.

Surono, Toha, B., Sudarno, I., 1992. Peta Geologi Lembar Surakarta-Giritontro, Jawa Tengah, Skala 1 : 100.000, Geological Research and Development Centre, Bandung.

Tomascik, T., Mah, A.J., Nontji, A., and Moosa, M.K., 1997. The Ecology of the Indonesian Seas, Part One, (The Ecology of Indonesia Series, Vol. VII), Periplus Editions (HK) Ltd., Singapore, 642 ps.

Van Bemmelen, R.W., 1970. The Geology of Indonesia, Govt. Printing Office, The Hague, v. 1A, 732 ps.

Verbeek, R.D.M. and Fennema, R., 1896. Geologische Beschrijving van Java en Madoera, Amsterdam.

Wilson, M.E.J., 2000. Tectonic and volcanic influences on the development and diachronous termination of a Tertiary tropical carbonate platform, Journal of Sedimentary Research, v. 70, No. 2, p. 310-324.

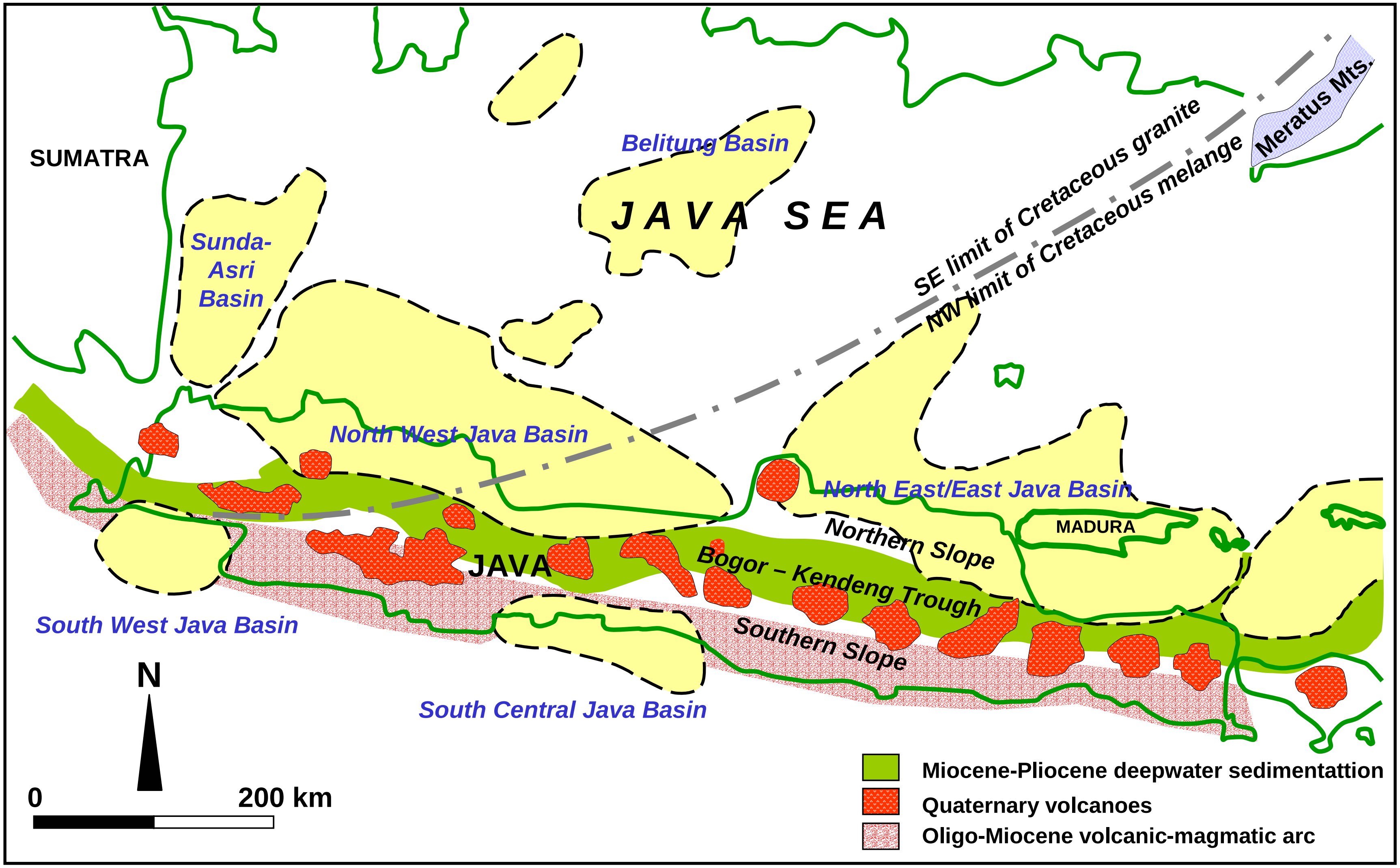

Figure 1 - Present-day tectonic setting of Java Island showing the tectonic provinces, Quaternary volcanoes and sedimentary basin outlines. Miocene-Pliocene deepwater sedimentation area and Oligo-Miocene volcanic-magmatic arcs are indicated for reference.

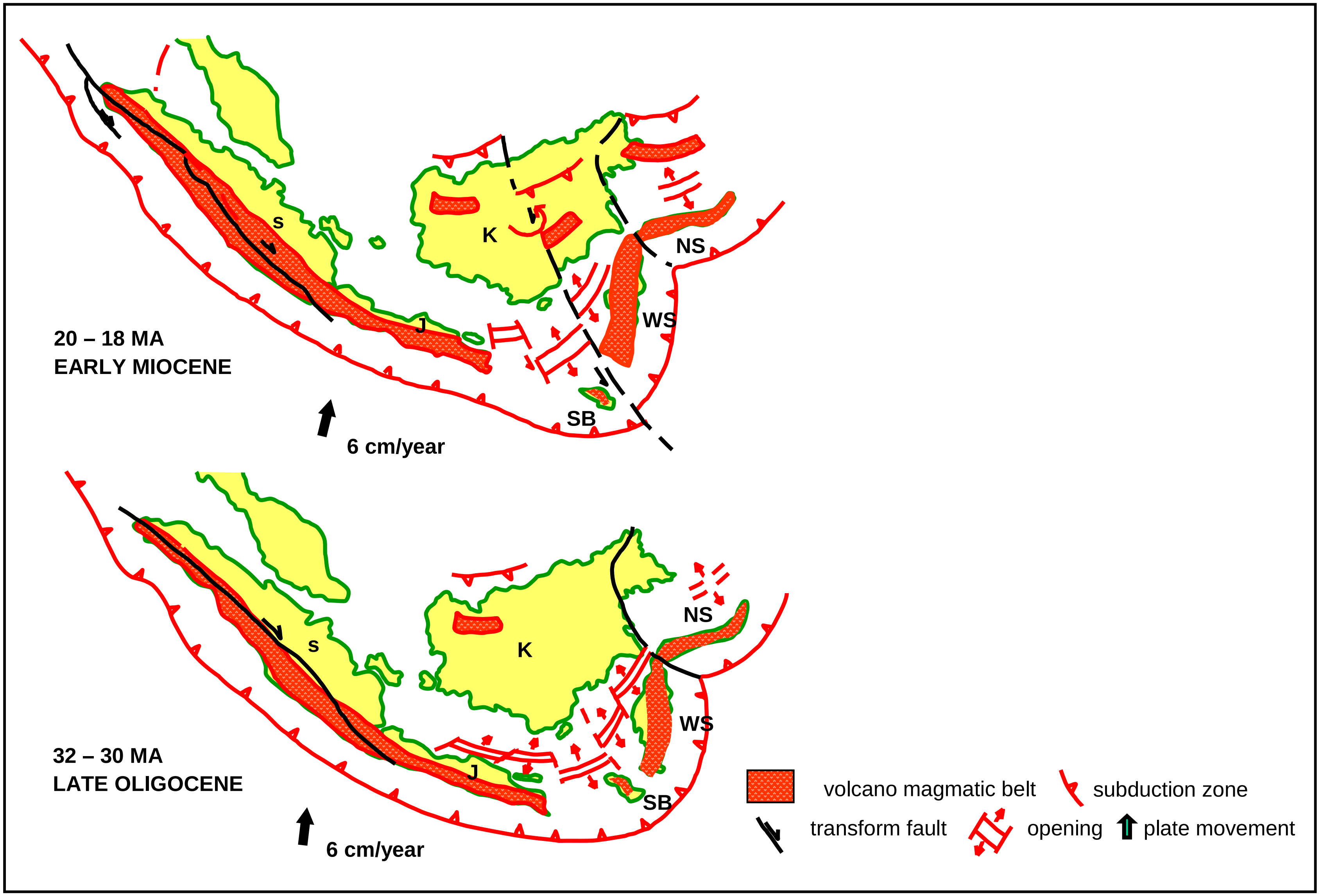

Figure 2 - Oligo-Miocene tectonic and volcanic-magmatic setting of Western Indonesia. Trace of the subduction zone is along present-day islands to the west of Sumatra and the submarine ridge to the south of Java. The volcanic-magmatic arc of Java is the present-day Southern Mountains of Java. In the Java area, back-arc basins developed behind the volcanic-magmatic arc due to back-arc rifting. To the north towards Kalimantan, was situated the landmass of Sundaland. S=Sumatra, K=Kalimantan, NS=North Sulawesi, WS=West Sulawesi, SB=Sumba, J=Java. (modified after Soeria-Atmadja *et al*. (1994).

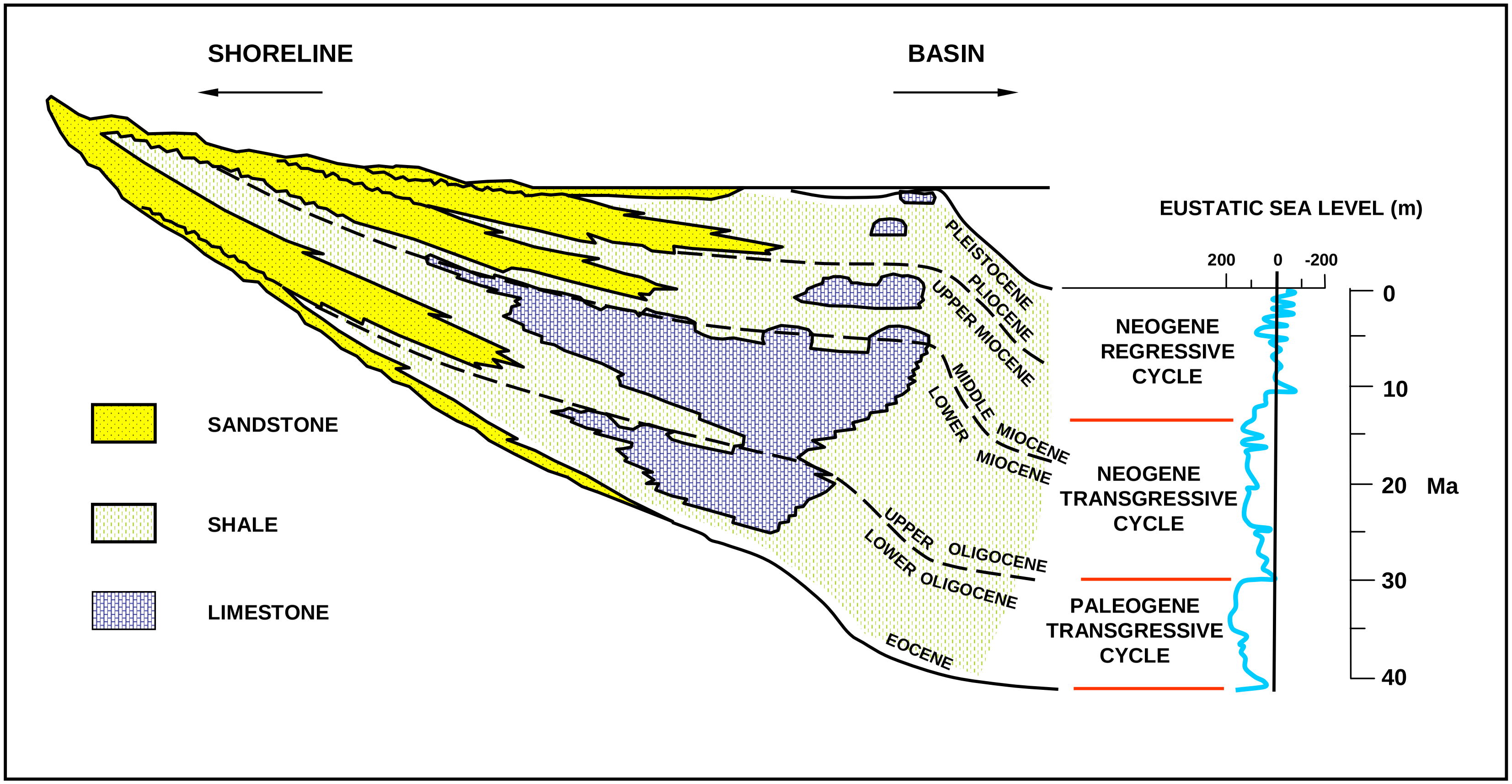

Figure 3 - Tertiary sedimentation cycles in SE Asia. Neogene Transgressive Cycle corresponds to period of rising eustatic sea level. Oligo-Miocene carbonates of SE Asia reached maximum extent during this period (after Fulthorpe and Schlanger, 1989).

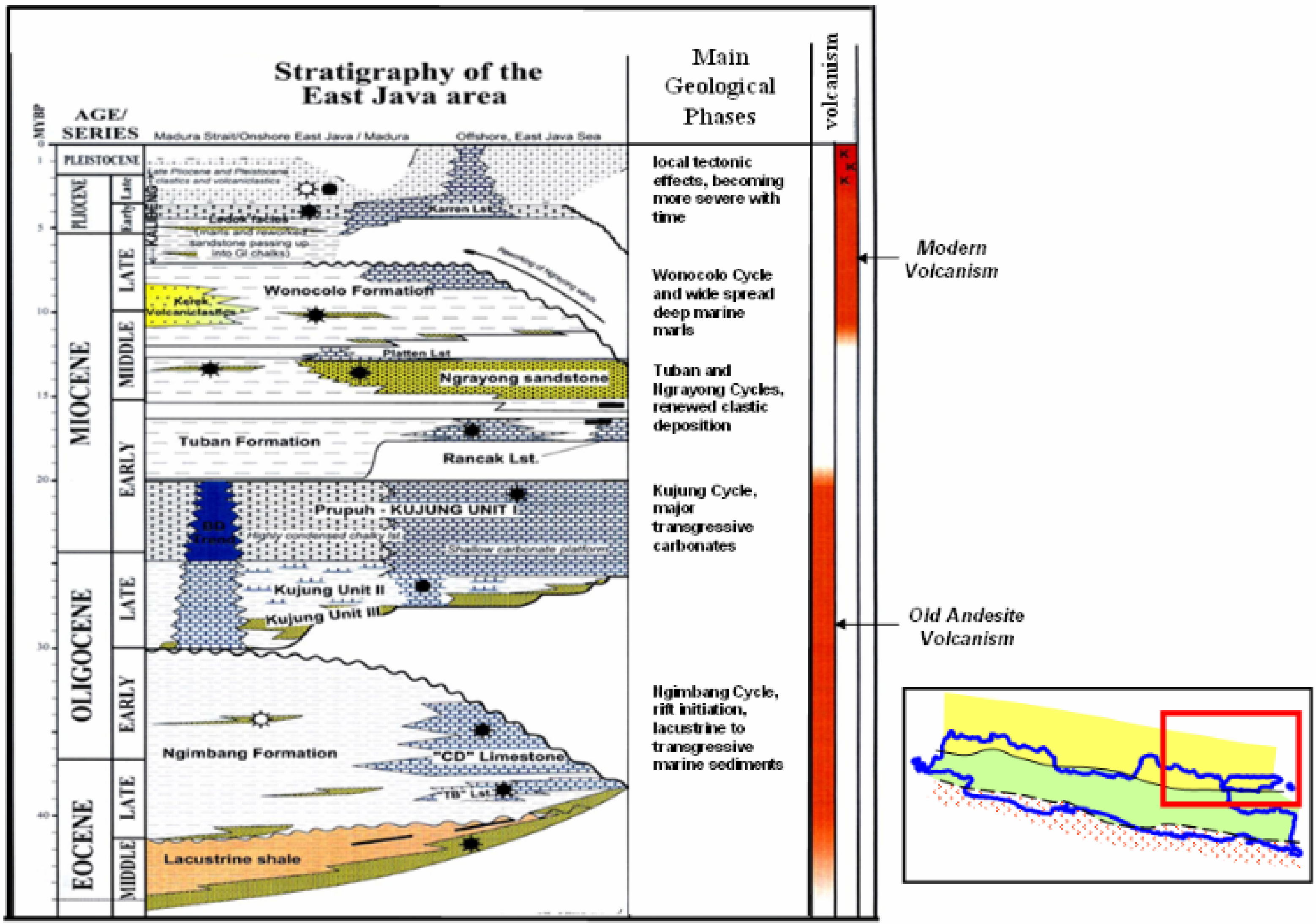

Figure 4 - Stratigraphy of the East Java Basin. Note the contemporaneity between the deposition of Kujung carbonates during Oligo-Miocene and Old Andesite volcanism (modified after Gulf Resources/ConocoPhillips Ketapang, 1998, unpublished).

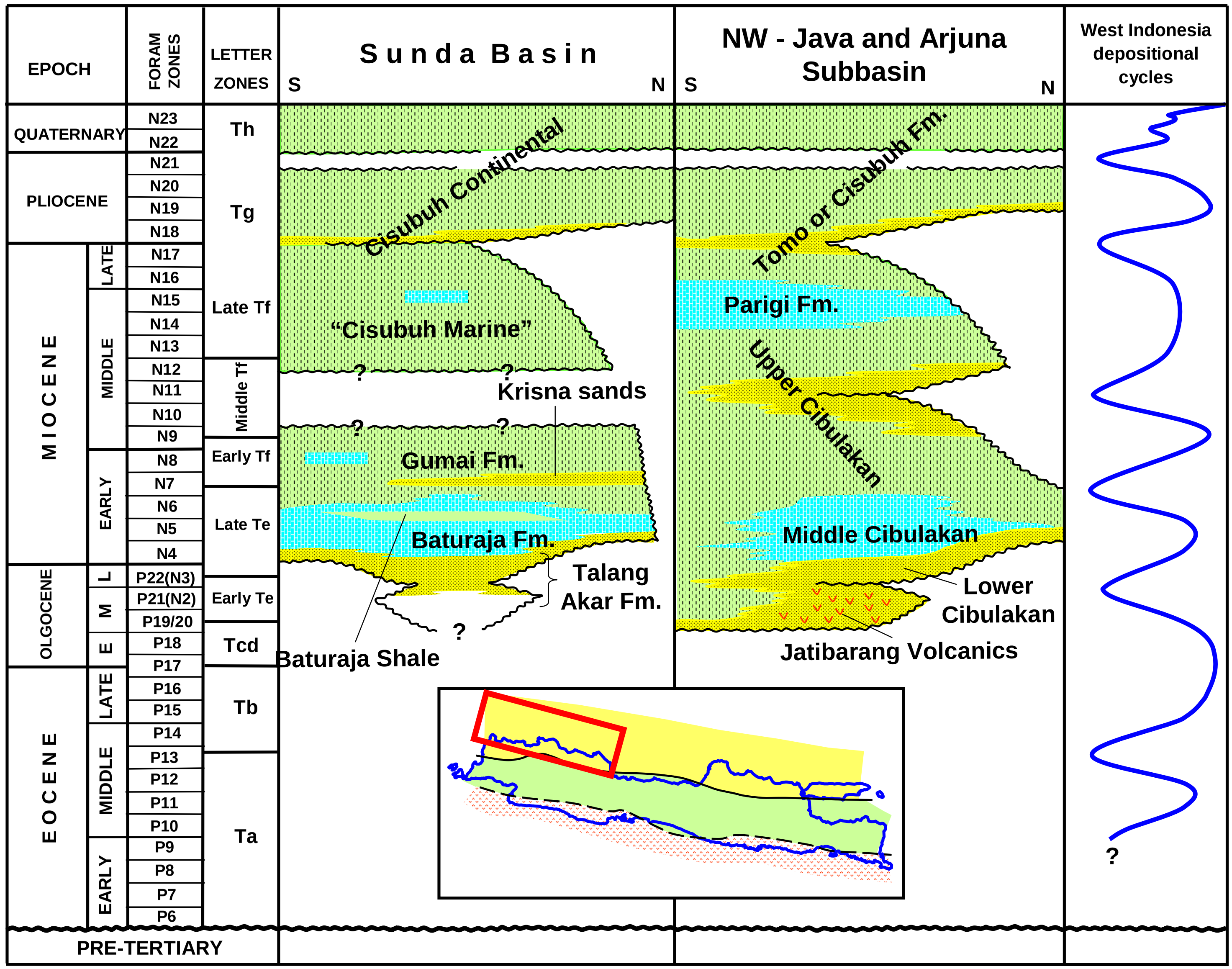

Figure 5 - Stratigraphy of the West Java basinal area showing the development and the deposition of Baturaja (Middle Cibulakan) carbonates during Early Miocene (modified after Pertamina and Beicip, 1985).

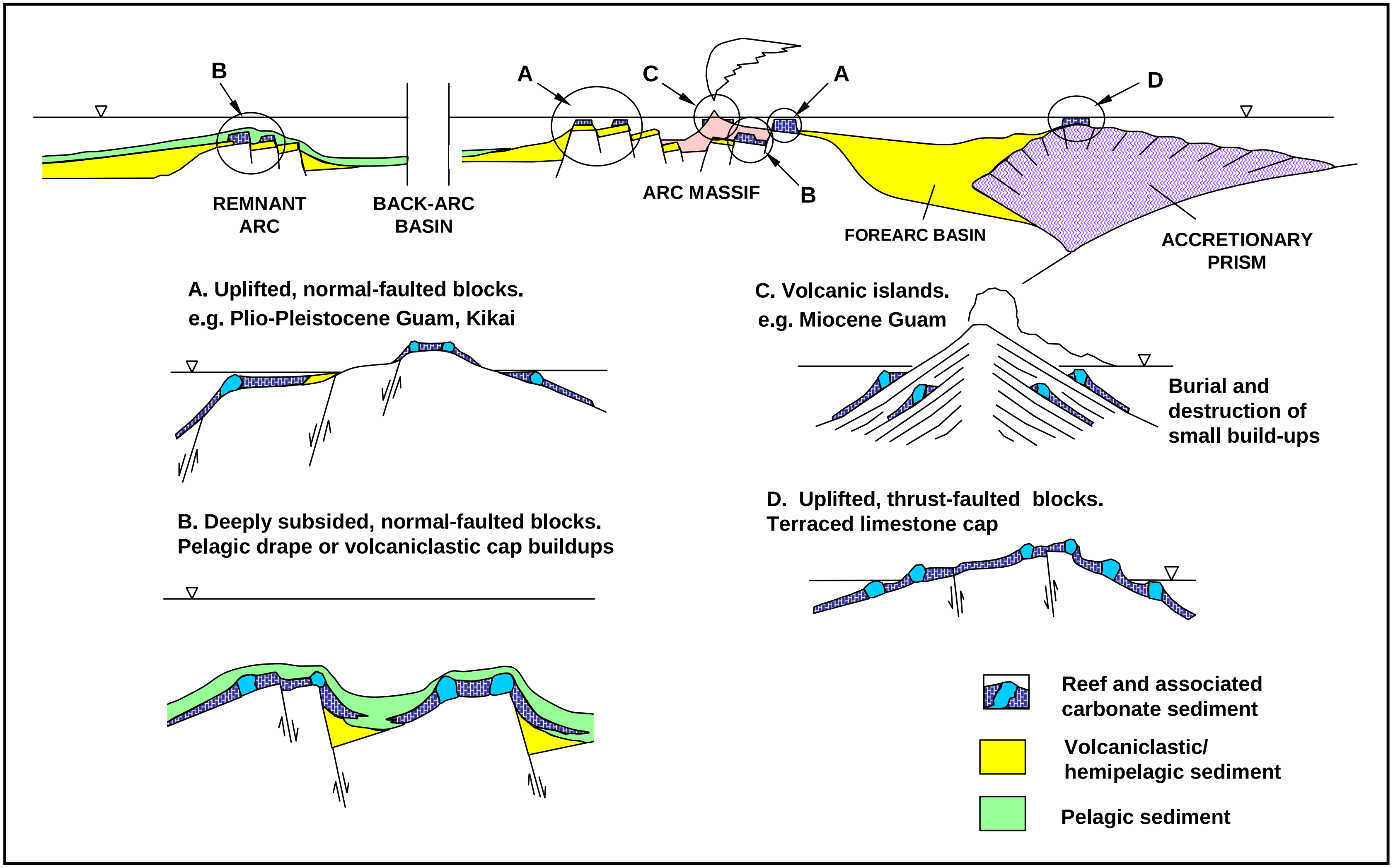

Figure 6 - Cross-section showing potential sites of reef and associated carbonate sediments within an island-arc system. Sites of active deposition and of deeply subsided and buried build-ups are shown. (after Fulthorpe and Schlanger. 1989).

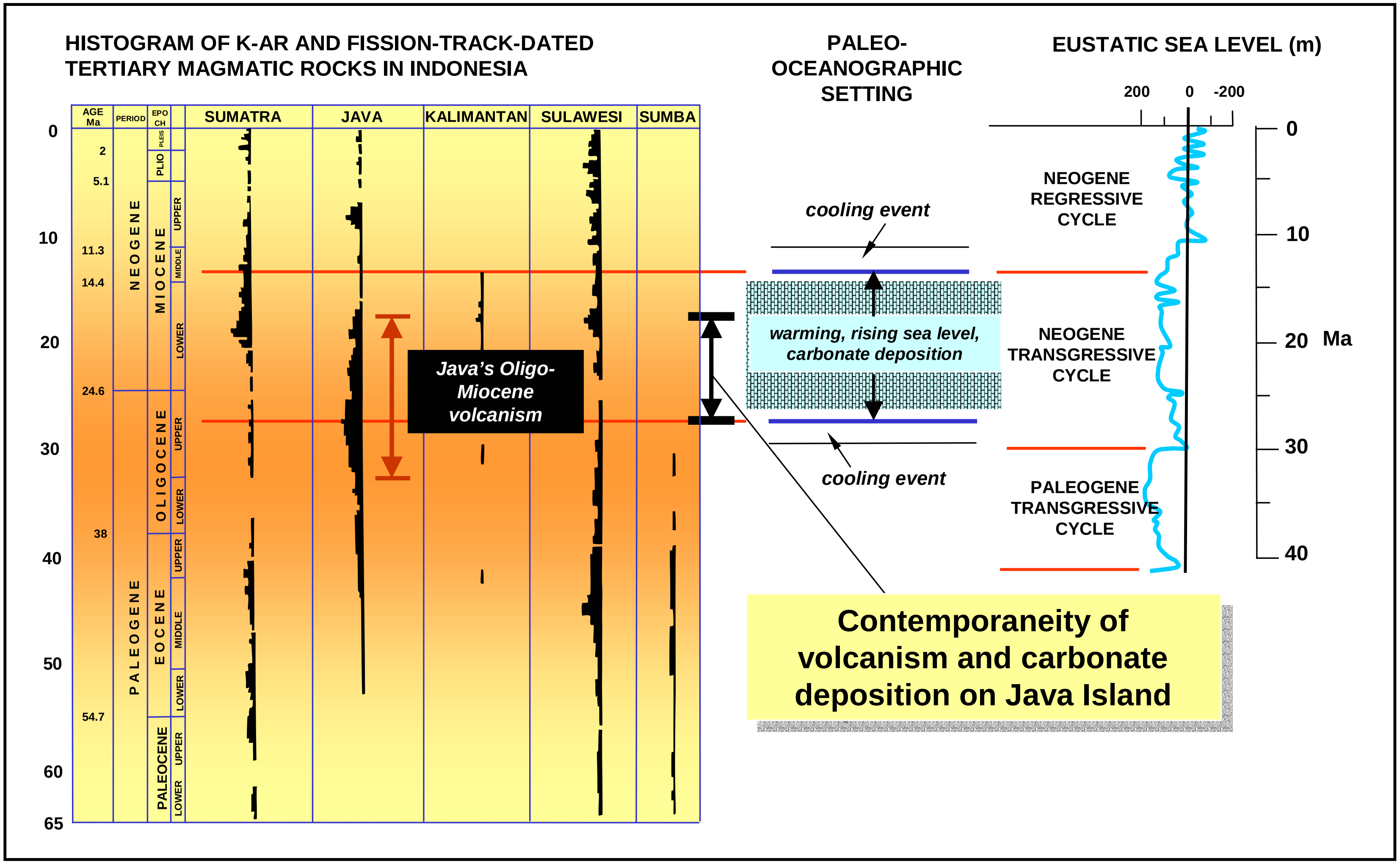

Figure 7 - Relationship between volcano-magmatic period in Java and carbonate deposition during the Oligo-Miocene. Note around 75 % contemporaneity occurred between volcanism and carbonate deposition in Java during the Oligo-Miocene. Magmatic dating from Soeria-Atmadja *et al*. (1998). Paleo-oceanographic setting from Fulthorpe and Schlanger (1989), eustatic sea level from Haq *et al*. (1987).

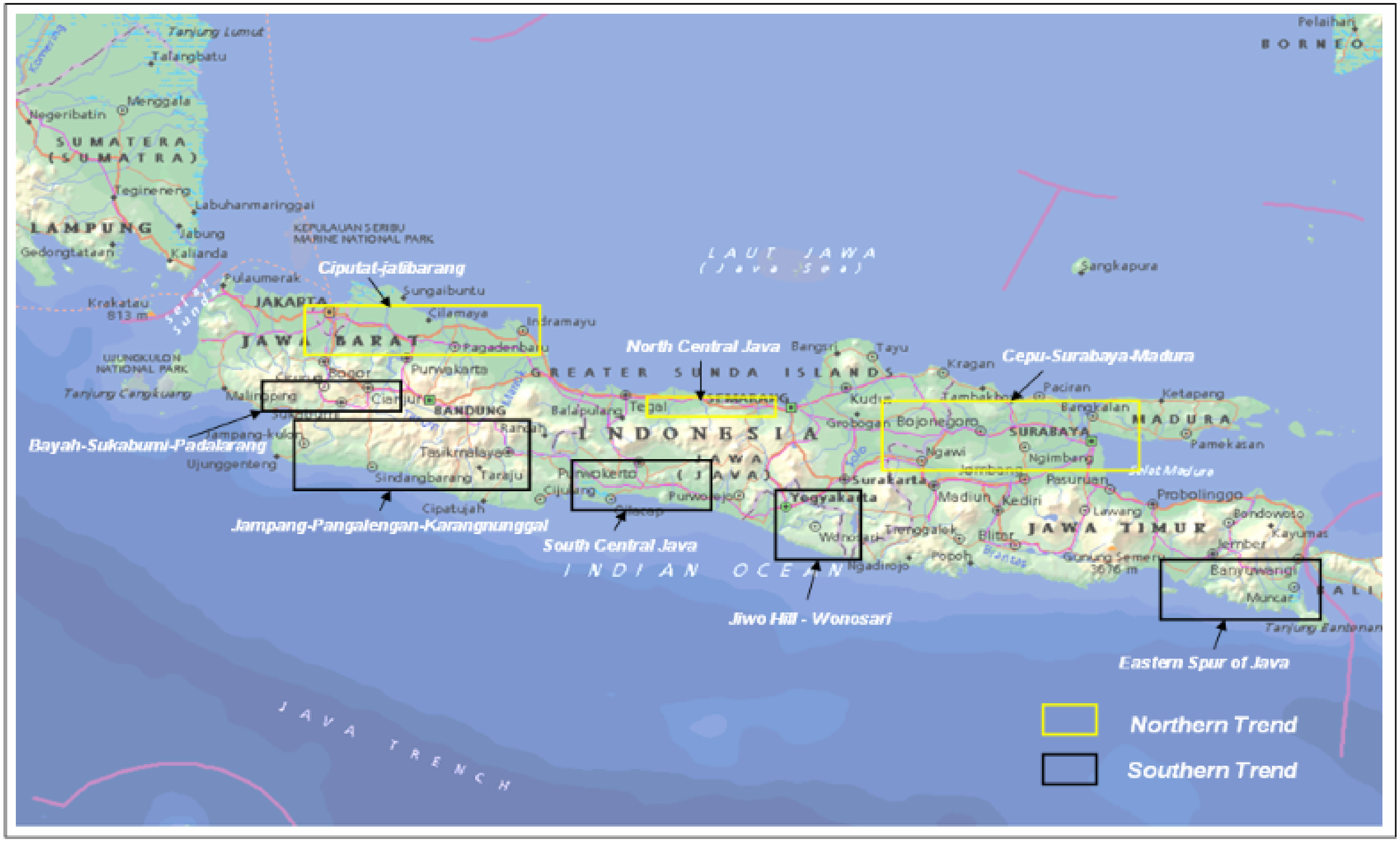

Figure 8 - Location map of study areas (in boxes).

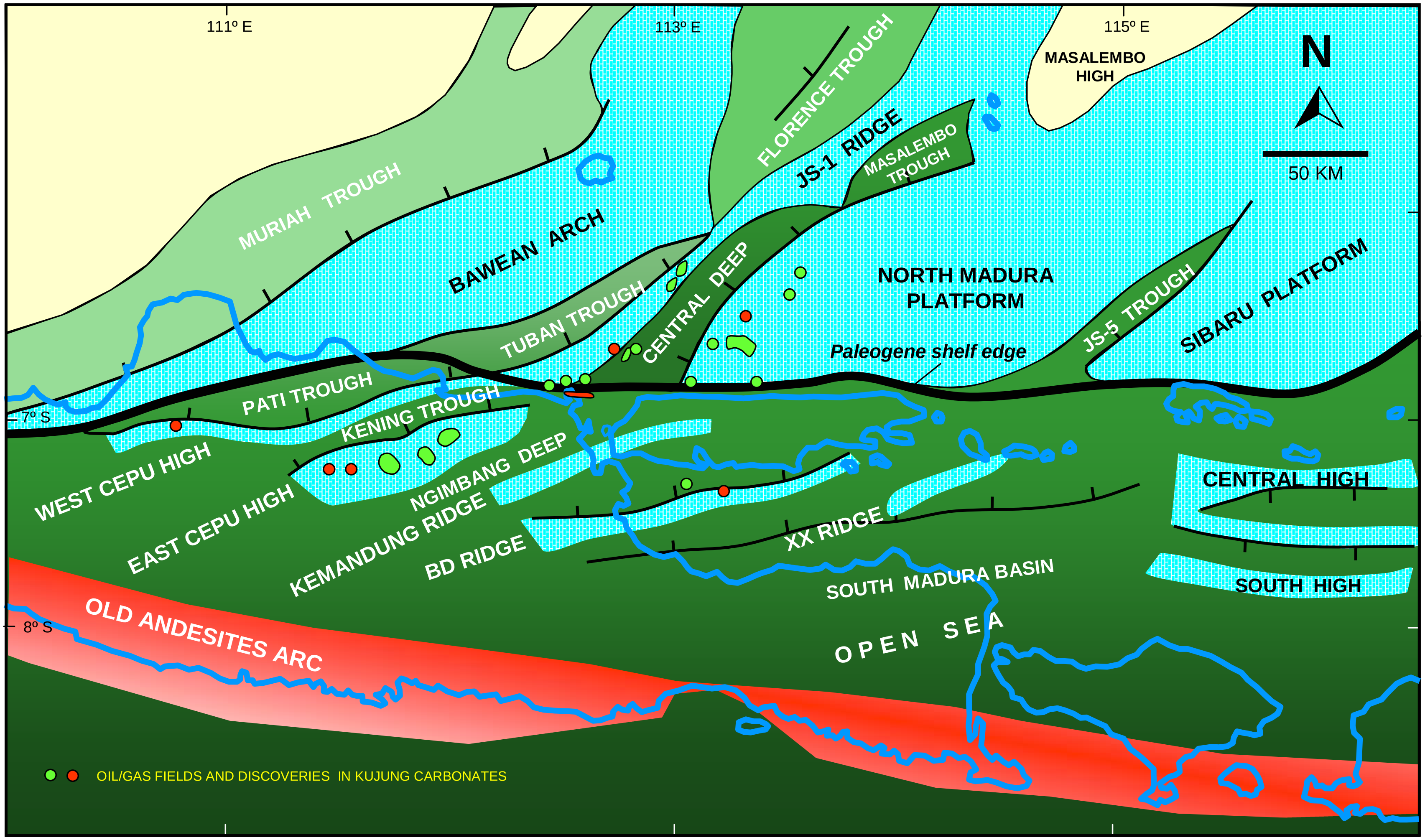

Figure 9 - Paleogene geography of the East Java Basin. Oligo-Miocene carbonates developed on highs/ platform. At the southern shoreline of present-day Java, Oligo-Miocene volcanism (Old Andesites) contemporaneously developed.

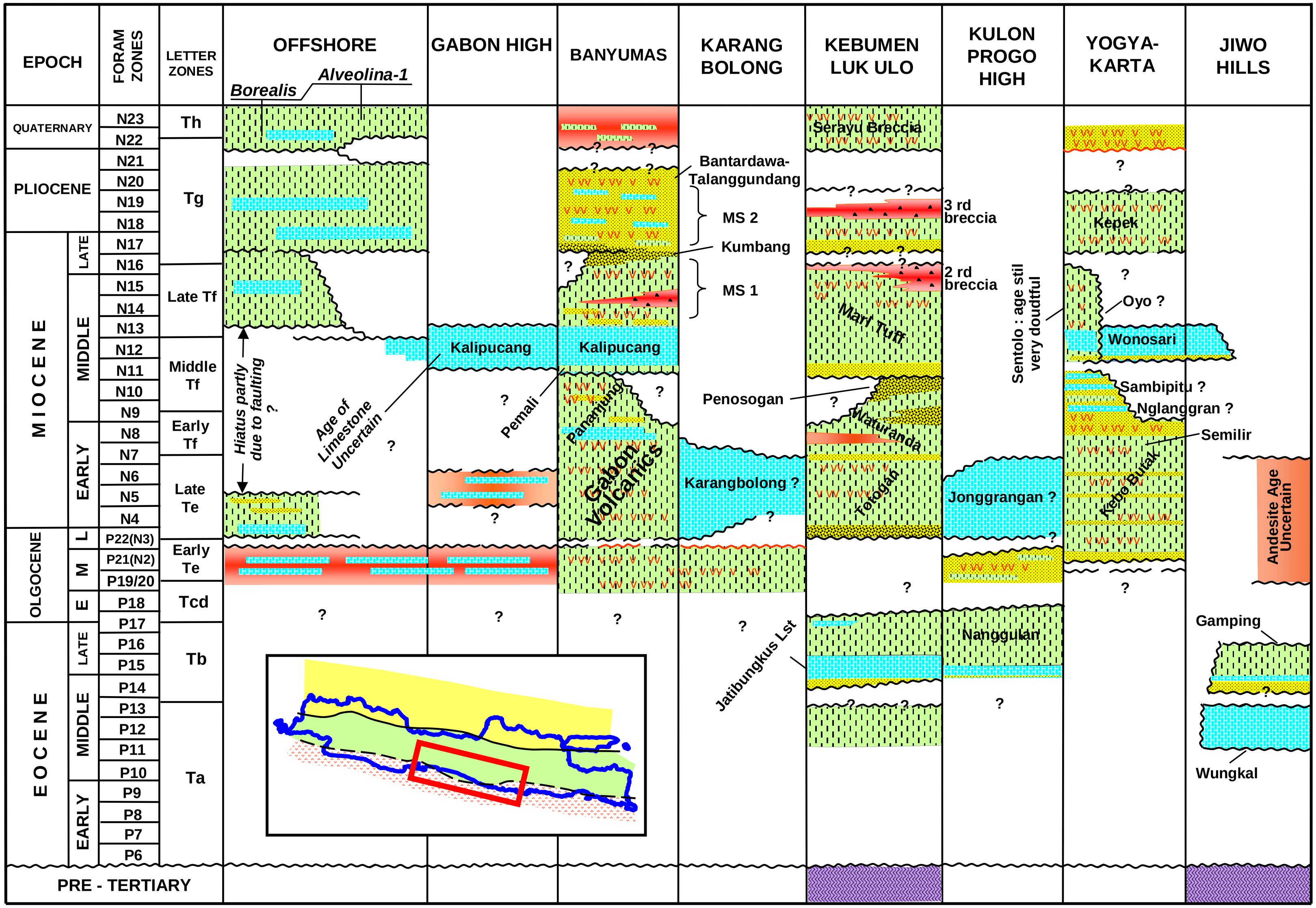

Figure 10 - Stratigraphic summary of South Central Java from west to east. Note the relationship between carbonates and volcanics before, during, and after the Oligo-Miocene. Carbonates developed in areas far from volcanism or when volcanism declined such as during the Middle Miocene. Significant carbonate development occurred during the Middle Miocene (Wonosari-Punung Formations). In Yogyakarta area, there was no contemporaneous carbonate development within Oligo-Miocene volcanic deposits of Kebo-Butak and lower part of Nglanggran.

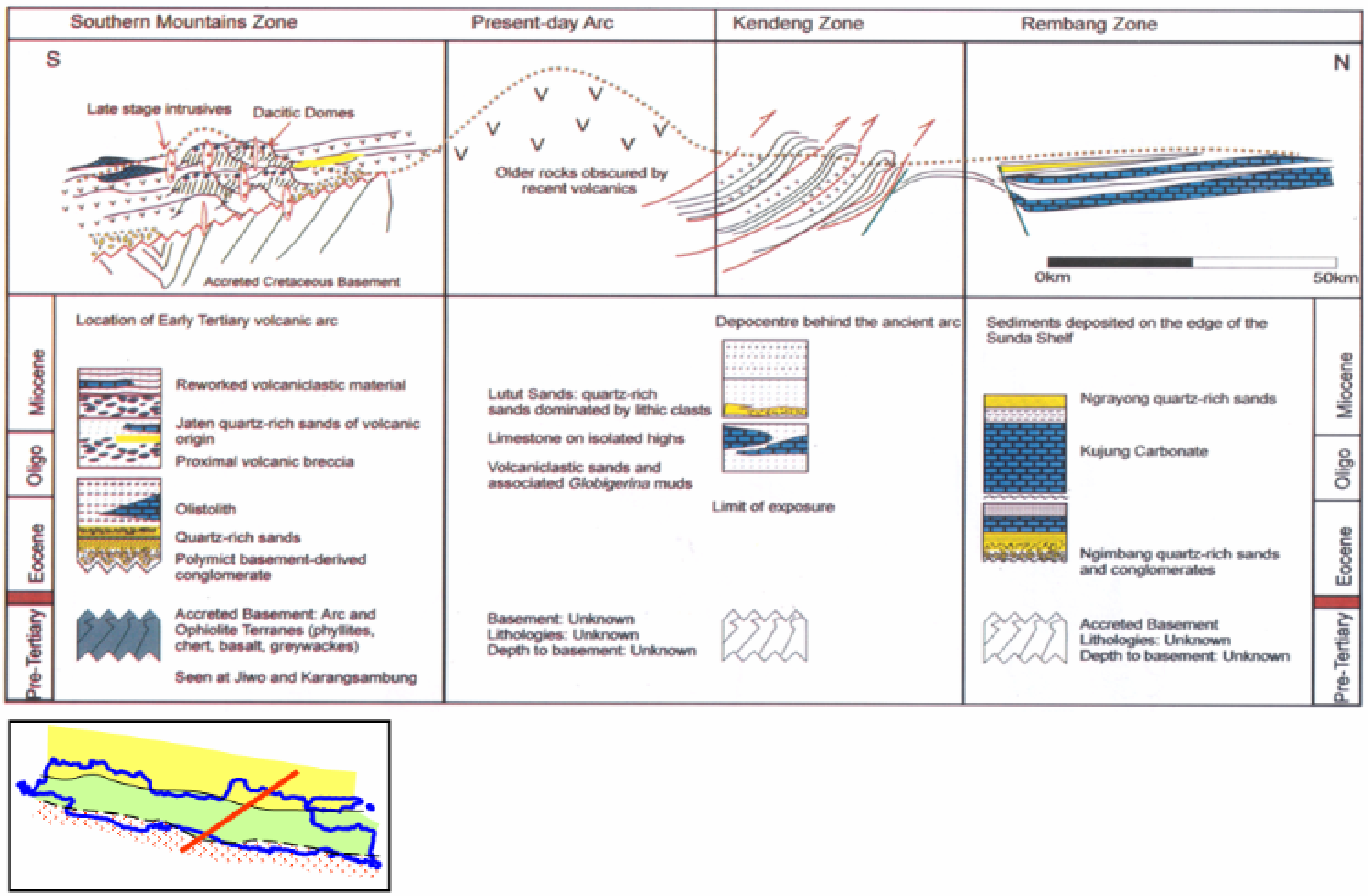

Figure 11 - Schematic regional cross-section across Central-East Java from south to north showing stratigraphic variations in each zone (after Smyth *et al*., 2003). Note the absence of volcanic intercalations/interbeds/impurities within Oligo-Miocene carbonates in the Kendeng and Rembang zones, northern Java. Equivalent carbonates in Southern Mountain Zone developed in close relationship with volcanism.

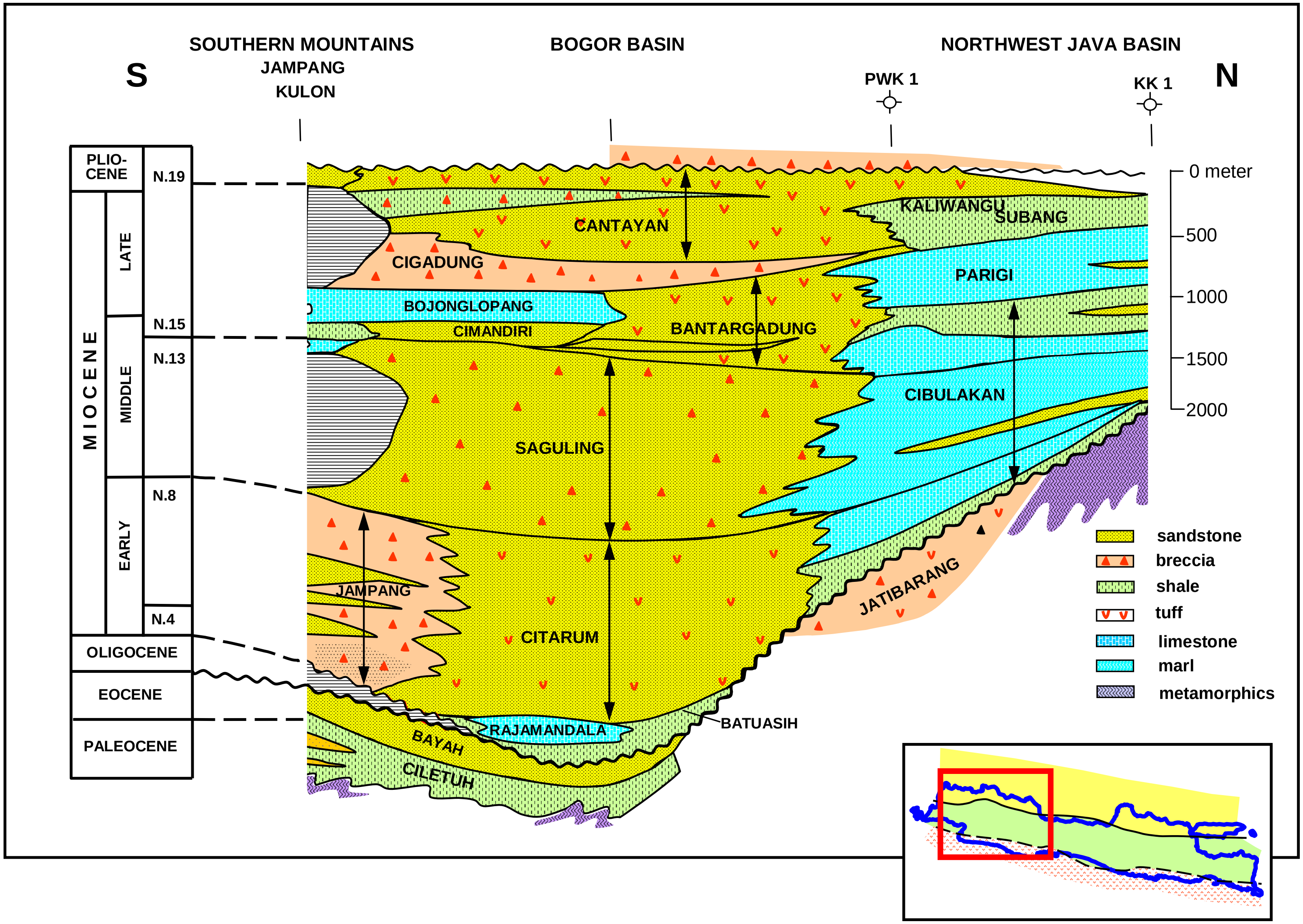

Figure 12 - Schematic regional stratigraphic setting across West Java showing relationships between volcanic deposits and carbonates. Oligo-Miocene carbonates (in blue) of Rajamandala developed before onset of volcanism, Lower Cibulakan carbonates were not influenced by volcanism, mostly deposited within Bogor Basin. (modified after Martodjojo, 1994).

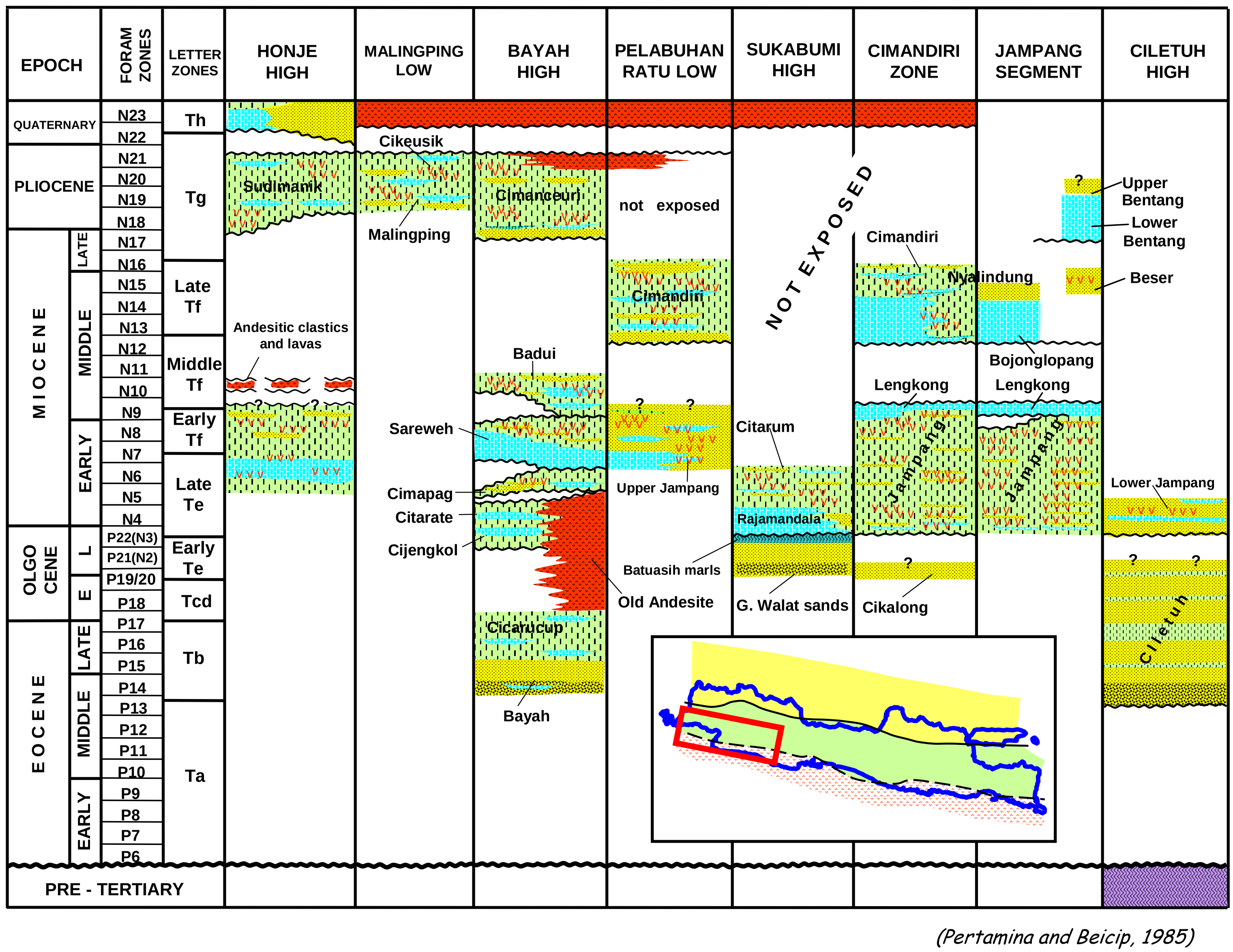

Figure 13 - Stratigraphy of Southern West Java. Note the association and relationship of carbonate development during Oligo-Miocene to the contemporaneous volcanism of Jampang and Citarum. The carbonates mostly developed prior to or after the volcanism periods. (modified after Pertamina and Beicip, 1985).

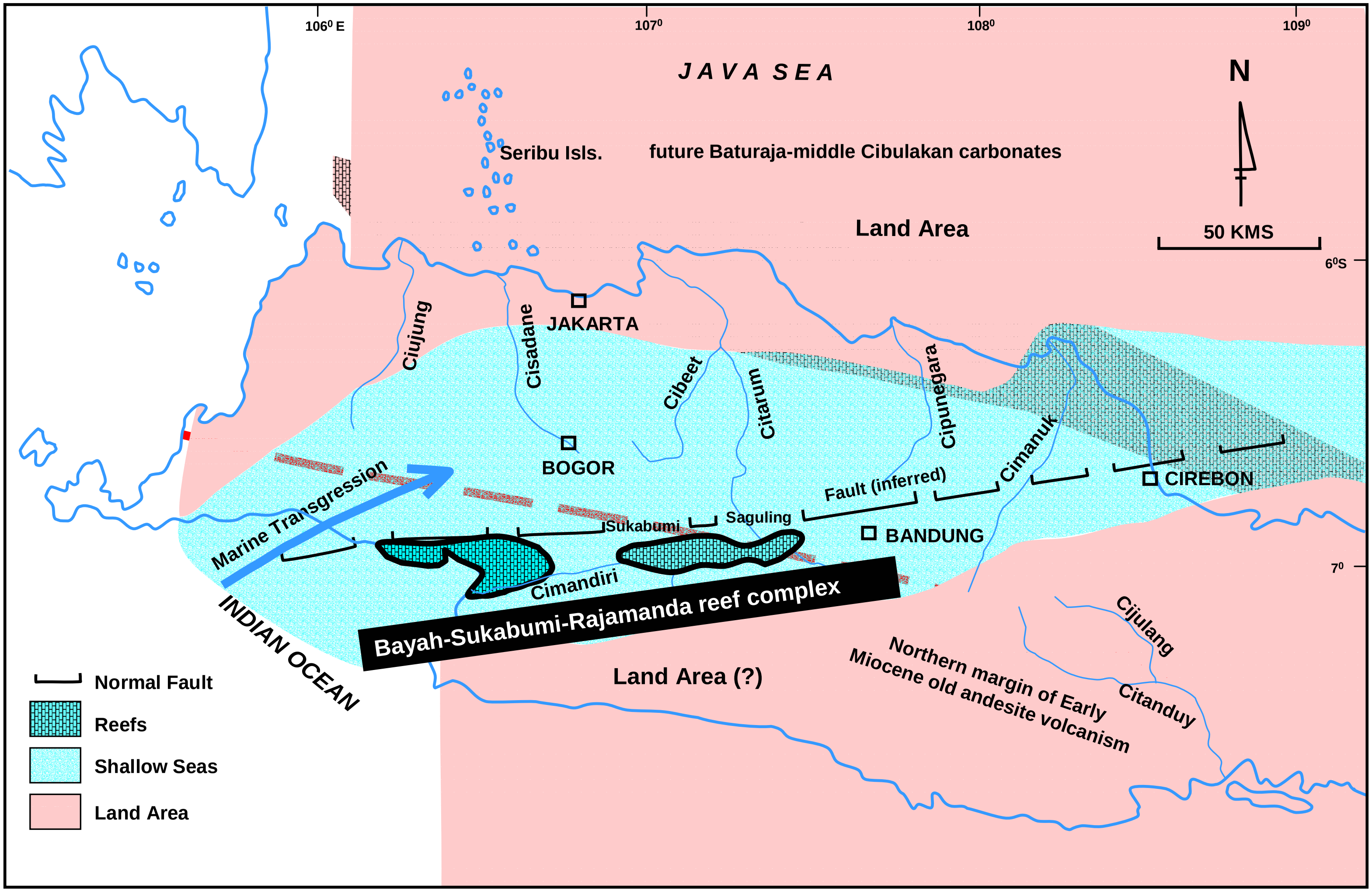

Figure 14 - Palaeogeography of West Java area during the Oligo-Miocene. The Oligo-Miocene Rajamandala reefal carbonate complex extensively developed as fringing reef relative to the interpreted land area to the south in the southwestern part of West Java.

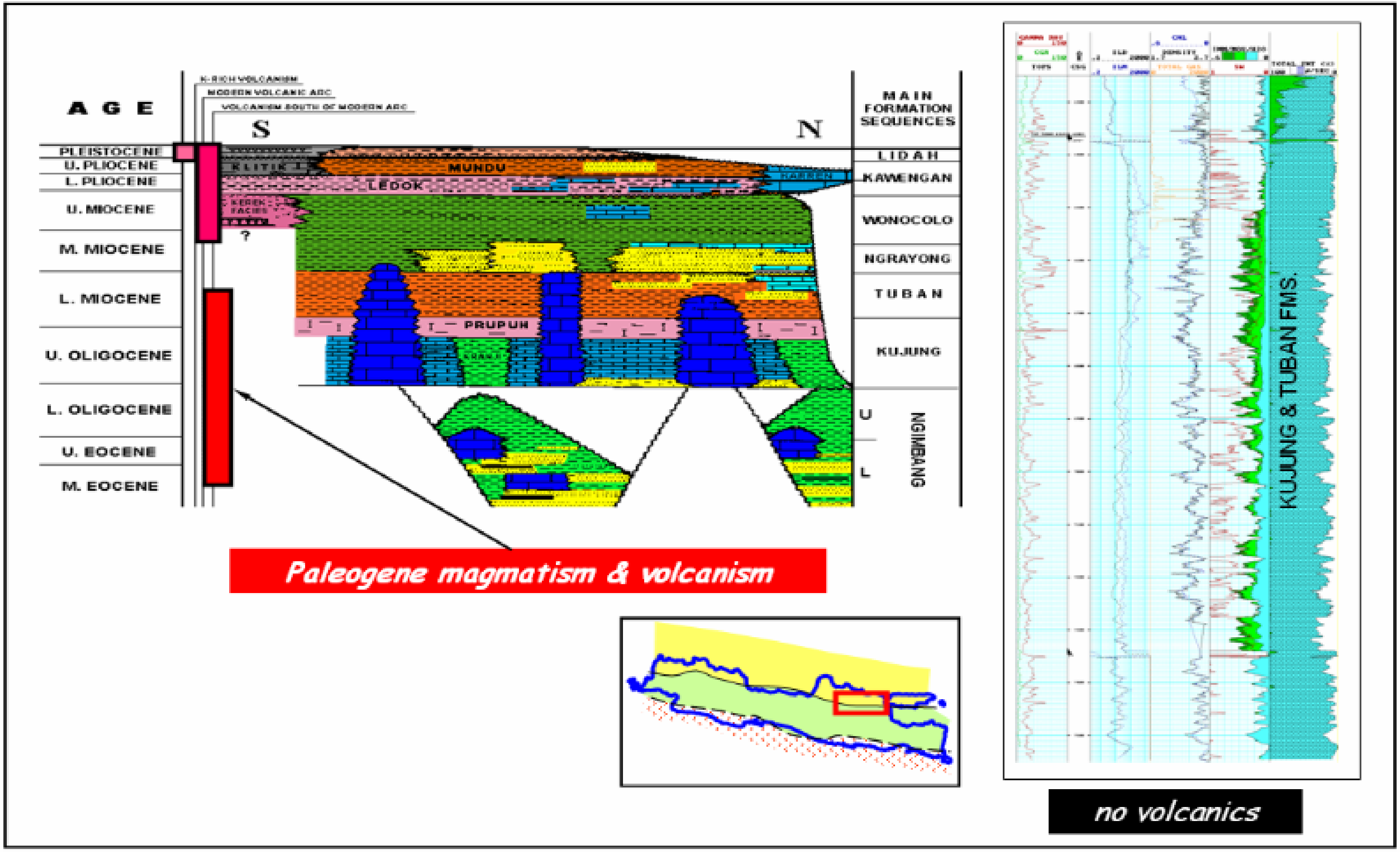

Figure 15 - The association of Tuban and Kujung carbonates of the Oligo-Miocene in onshore East Java Basin with the contemporaneous Old Andesite volcanism. The carbonates have no volcanic impurities as shown by log data of a well penetrating the carbonates. The carbonates are oil-bearing (modified after PetroChina Tuban, 2000 – unpublished).

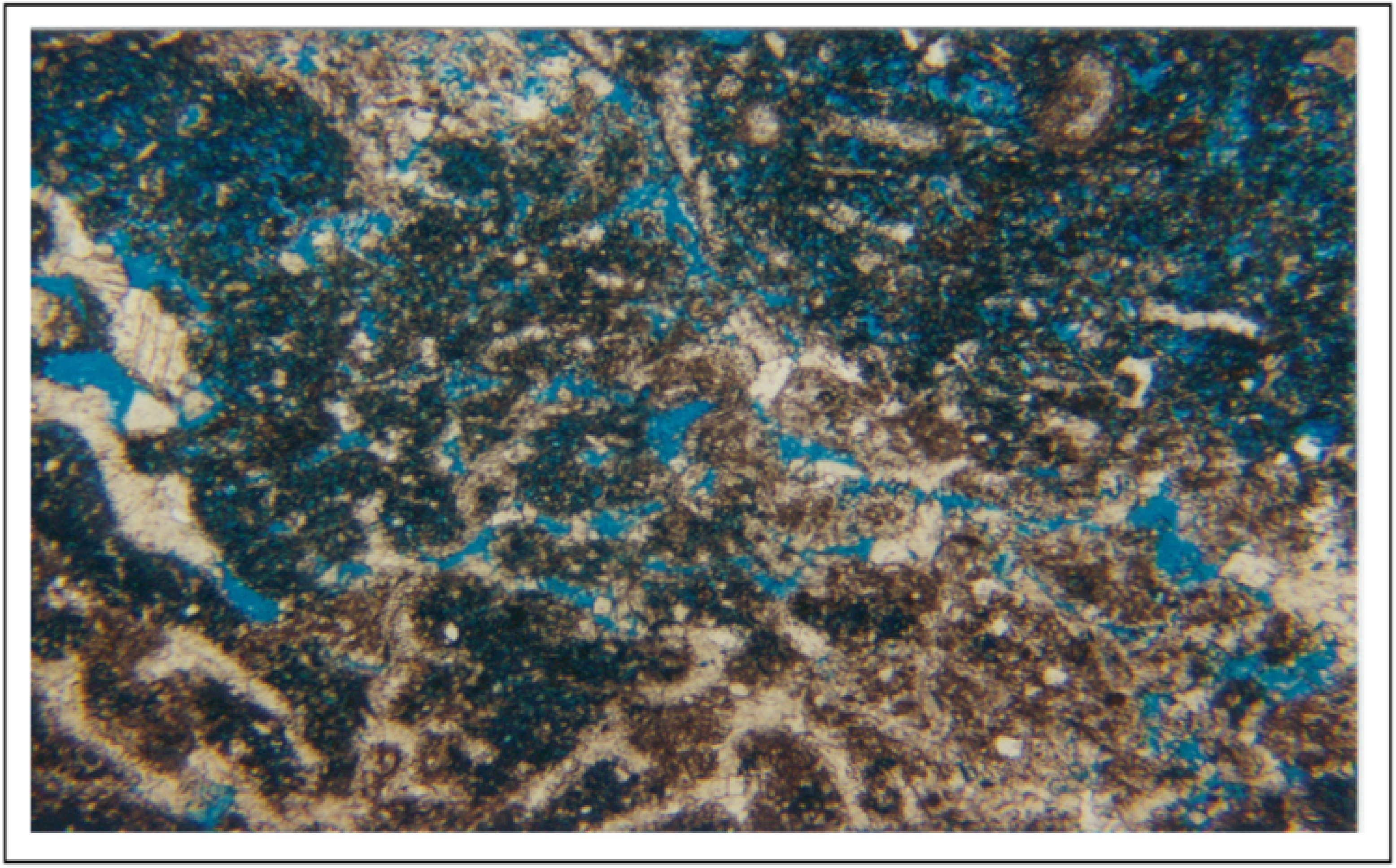

Figure 16 - Photo micrograph of Kujung carbonates, East Java Basin, showing leaching of coral boundstone into pores (blue colored). No volcanic material is reported. The carbonates flow hydrocarbons.