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Rembang-Madura-Kangean-Sakala (RMKS) Fault Zone, East Java Basin : The Origin and Nature of a Geologic Border

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ABSTRACT

A major wrench zone, left-lateral slip in nature, strongly deformed a series of Late Oligocene to Pleistocene rocks in the northern coastal line of East Java and its eastern islands and offshore areas. The fault zone trends west – east forming a deformed zone of 15 to 40 km wide and 675 km long from Rembang area in the west through Madura Island and Kangean Islands to Sakala offshore area in the east. The deformed zone is called the Rembang-Madura-Kangean-Sakala (RMKS) Fault Zone.

Based on the regional setting of East- and Southeast Sundaland, it is known that the RMKS Fault Zone occurred at the hinge belt or shelf edge to slope area of a geologic transition from the stable Eastern Sunda Shelf to the north (the Northern Platform) to the deep-water area to the south. There is a contrast of sedimentary facies to the north and south of the RMKS Fault Zone. Tectonically, the stable Eastern Sunda Shelf is considered to overlie the expected micro-continent called the Paternoster-Kangean. Therefore, the RMKS Fault Zone is located at the southern margin of the micro-continent. Basement lithology and configuration to the north and south of the RMKS Fault Zone are different.

A number of mechanisms are considered to origin the RMKS Fault Zone. These include : the westward stress driven by the collision of the Buton-Tukang Besi and Banggai-Sula to the east of Sulawesi, westward stress due to the collision of Australia with Timor and anti-clockwise bending of the Banda Arc, and northward stress due to the subduction of the Indian oceanic crust beneath Java. The initiation of the RMKS Fault Zone was in the upper Early Miocene in Sakala area and younger westward until the Middle Miocene in Rembang area.

Along the RMKS Fault Zone, flower structures are definitely identified on seismic sections, showing basement-involved, deeply-rooted vertical master faults with upward diverging splays/strands that have mostly reverse separations. In map view, these splays are mapped as fold and fault belts trending west-east and west northwest-east southeast. Extensional component of the wrench zone subsided the Paleogene rifted blocks such as the Central Deep and formed a number of normal faults. Tectonic inversion related with both pure and simple shear deformations is observed along the fault zone. Shale diapirism commonly occurs to the south of the fault zone and its occurrence is related to wrench tectonism in thick shale sequences deposited rapidly to the south of the RMKS Fault Zone.

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INTRODUCTION

East Java Basin is located at the southeastern end of the Sundaland. Complex tectonic histories mark this area. Collision of the micro-continents, growing of the continent through coalescence of accretionary prisms, and slivering of the continent through dispersing and rifting of some continental blocks occurred from the Cretaceous to the end of the Paleogene. Further explanation on this matter was recently published by Satyana (2003).

A zone of structural deformation trending west-east borders the northern part of onshore East Java from Rembang area in the west through Tuban, Madura, Kangean Islands and Sakala-Sepanjang offshore areas in the east (Figure 1). This zone is presently located in the middle part of the East Java Basin, forming a zone of central high. Seismic data crossing perpendicular (north to south) to this zone show the presences of inverted structures and flower structures related to wrench tectonism. This inversion/wrench fault zone is called the Rembang-Madura-Kangean-Sakala (RMKS) Fault Zone.

The location of the RMKS Fault Zone is geologically a structural weak zone and a sedimentary inter-facies zone. To the north of this fault zone, is a micro-continent called the Paternoster-Kangean (Satyana, 2003) which also underlies the Northern Platform. Thus, the RMKS Fault Zone borders the micro-continent to the south. To the south of the RMKS Fault Zone is a very deep depression area underlain by intermediate/transitional basement. The RMKS Fault Zone accordingly, separates two basement types : the northern uplifted continental basement and the southern subsided intermediate/transitional basement. Therefore, the location of the RMKS Fault Zone is a location of basement tectonic/structural border.

The location of the RMKS Fault Zone was a major shelf-edge area in the East Java Basin separating the Northern Platform in the present offshore East Java Sea to the north of the Madura Island from the Central Deep to the south of the Madura Island. The Northern Platform was a site for shallow-water carbonate and siliciclastic deposits, whereas the Central Deep was a site for deep-water carbonate and siliciclastic deposits. Therefore, the location of the RMKS fault Zone was a location of sedimentary inter-facies.

Due to located at a zone of both contrast tectonic/structural and sedimentary change, the RMKS Fault Zone occupied a geological weakness zone. When regional tectonism around the southeastern Sundaland showed the presence of westward stress started in the upper Early Miocene due to westward collisions of some micro-continents to the east of Sulawesi and counter-clockwise bending of the Banda Arc by northward movement of Australia and westward movement of Papua, a left-lateral wrench tectonism of RMKS Fault Zone formed in the weak zone of East Java Basin since the Middle Miocene. Movement along its zone has inverted many older structures and uplifted older strata. Inversion was also resulted from northward stress related to subduction of the Indian oceanic crust beneath Java intermediate crust at offshore south of Java.

This paper discusses the geology of the RMKS Fault Zone, including : (1) the role of the RMKS Fault Zone as sedimentary and tectonic/structural borders, (2) the origin of the RMKS Fault Zone, and (3) the structural style of the RMKS Fault Zone.

REGIONAL SETTING

Located at the active southeastern margin of the Sundaland, Southeast Asia, the East Java Basin has recorded an active geodynamic history. The basin developed from an oceanic basin in front of the Late Cretaceous subduction zone to presently a backarc basin behind the volcanic arc. The basin is terminated to the west by the Karimunjawa Arch, passes eastwards into the deep water Lombok Basin, and shallows northwards onto the Paternoster High. Three main structural configurations can be established from north to south : the Northern Platform, the Central Deep, and the Southern Uplift (Figures 2, 3).

Figure 4 shows the stratigraphic succession of the East Java Basin. The sediments consist of synrift middle Eocene Lower Ngimbang siliciclastics, postrift Late Eocene to Early Oligocene Upper Ngimbang siliciclastics and "CD" and carbonates. After a mid-Oligocene uplift, the transgression regionally flooded the basin during the late Oligocene and deposited Lower Kujung (Kujung III and II) siliciclastic and carbonates. Transgression peaked in the early Miocene and developed reefs of Upper Kujung (Kujung I/ Prupuh), deposited Tuban shales and locally growth of Rancak reefs. Tectonic inversion history started in the Middle Miocene, intensively inverted the basin in the Late Miocene and Mio-Pliocene, and peaked in Pleistocene time. Regressive and transgressive sedimentation alternated during the period and deposited the Neogene Ngrayong, Wonocolo, and Kalibeng Group (Mundu, Paciran, and Lidah) consisting of sands, shales, and carbonates.

Two principal structural trends of the Tertiary origin can be distinguished : a northeast-southwest extensional fault trend and an east-west compressive - wrench fault trend (Figure 1). A tensional stress regime was active from the middle Eocene up to the Early Miocene forming rifting in the Eocene and basin-wide subsidence in the Oligocene. Neogene tectonism formed widespread compressive and wrench-related structures from Middle Miocene time to the Pleistocene. A number of west-east structural elements had their shapes in this period, including : the RMKS Fault Zone/Uplift, Rembang Hill Zone, Randublatung Depresion Zone, and Kendeng Fold and Thrust Belt (Figures 2 and 3).

RMKS FAULT ZONE : PRE-TERTIARY BASEMENT TECTONIC BORDER

There is a contrast in basement configuration to the north and south of the RMKS Fault Zone (Figures 5 and 8). Wells penetrating basement are mostly located at offshore East Java Sea or to the north of the RMKS Fault Zone because in this area the basement is shallow.

Pre-Tertiary basement rocks penetrated by wells in the East Java Basin comprise diverse lithologies. These range from low-grade metamorphics (phyllite, quartzite and meta-tuff) in the northwest, through acidic igneous rocks (rhyodacites and vitric tuff) in the central, to intermediate igneous rocks (monzonite and diorite) in the southeastern part. At the eastern end of the basin in the Kangean/Lombok area, four wells penetrating pre-Tertiary basement found metavolcanics, quartzite, chert, and serpentinized amphibolite. Metamorphic radiometric dates range from latest Jurassic to Late Cretaceous, with an apparent modal peak in the mid Cretaceous (Bransden and Matthews, 1992).

Basement lithology and regional geophysical data indicate the presence of a micro-continent to the north and northeast of the RMKS Fault Zone. Wells located offshore to the north of the Madura Island found basement lithology related with acidic to intermediate igneous rocks such as rhyodacites (JS 19 W-1), vitric tuff (JS 19 A-1), monzonite (JS 44A-1) and diorite

(JS 8-1). Based on the basement lithology penetrated by wells around the South Makassar Strait (the Paternoster area), regional gravity area and tectonic map, the micro-continent is considered to extend as far as east of the Kangean islands, to extend northeastward to the westernmost Sulawesi, and westward to the offshore southeast of Kalimantan. The micro-continent is called the Paternoster-Kangean micro-continent (Figure 5). Wells drilled in the Paternoster area found granitic to granodiorite basement (Rubah-1, Pangkat-1).

The RMKS Fault Zone is located just to the south of the micro-continent, bordering it from the basement of southern East Java Basin which is deeply subsided and made up of transitional/intermediate crust and subduction accretionary complex. Therefore, the RMKS Fault Zone is a border of two basements which are different in types and structural configuration. The basement to the north of the RMKS Fault Zone was segmented forming broad low and high areas trending SW-NE like the Bawean Arch, Central Deep and North Madura High/Platform (Figure 6). The basement to the south of the RMKS Fault Zone was also segmented, but forming narrow ridges and deep troughs trending WSW-ENE like the Cepu High, Ngimbang Trough, and BD Ridge. The highs in the southern area gradually trend more W-E more to the east.

RMKS FAULT ZONE : PALEOGENE SEDIMENTARY BORDER

The site of the future RMKS Fault Zone had been active as sedimentary border since the Eocene when deposition of sediments composing the Ngimbang sediments were taking place. Figure 6 shows the paleogeography during the Paleogene when the location of future RMKS Fault Zone was a shelf edge area. To the north of the border, the sediments consist of alluvial, fluvial, lacustrine and marginal marine deposits. Early Oligocene sea transgression resulted in CD limestone and argillaceous carbonate shelf deposits with shoreline sandstones onlap onto structural highs like the Karimunjawa and Bawean Arches. To the south of the border, the Ngimbang sediments were deposited as very thick sequence dominated by bathyal mudstones indicating very rapid deepening. In places, pinnacle reefs growing on local/isolated structural highs like the Cepu High.

After a short-lived mid Oligocene uplift, a continuous sea transgression took place until the end of the Early Miocene during which siliciclastic sediments and carbonates of the Late Oligocene to the Early Miocene Kujung Formation were deposited. Satyana and Djumlati (2003) detailed this Kujung carbonate depositional history in this area. To the north of the shelf edge border, the Kujung Formation is subdivided into three sedimentary units (III, II, I from older to younger) which progressively onlap the paleo-highs (Figure 6). The Kujung III and Kujung II consist of siliciclastic sediments deposited in low areas between highs and reefal carbonates growing at highs. To the south of the shelf-edge border, deeper facies of sediments equivalent with the Kujung III and Kujung II were deposited as transgressive marine clastics and carbonates which partly onlapped onto the southern slope of the north shelf. Maximum transgression during the Early Miocene resulted in extensive growth of the Kujung I carbonate reefs in the area to the north of the shelf edge border. Three carbonate reef facies are recognized within this area : (1) fringing reef at rim of the basement highs, (2) basinal lime mud mound growing in low areas between the highs, and (3) patchreef over platform area. Along the shelf-edge area, one type of carbonate facies is also recognized namely the shelf edge border reef. To the south of the shelf-edge border, Kujung I equivalent sediments were from deep marine (outer neritic or bathyal) facies, represented by Prupuh chalk and Kranji mudstones could be deposited (Burgon et al., 2002). At the isolated highs like the Cepu High, Kujung I pinnacle reefs grew (Satyana and Djumlati, 2003).

RMKS FAULT ZONE : NEOGENE SEDIMENTARY BORDER

The Neogene stratigraphic succession is represented by mostly regressive depositional phase across the entire area. Seismic geometries often show marked downlap onto developing inversion structures (Manur and Barraclough, 1994). Deposition of the sequence commenced with the Tuban shales. Deep marine basinal mudstones with occasional turbiditic sandstones were deposited in most parts of the basin to the south of the shelf-edge border while on the shelf, pro-delta mudstones accumulated. Regional thickness variation is observed in the Tuban shales as rejuvenation of subsidence in the shelfal regions coincides with the start of inversion of the deep marine basinal areas to the south. Figure 7 shows the change of Madura area (and along the RMKS) zone as shelf edge barrier and slope area for deposition during the Paleogene and Early Miocene to presently become an inverted zone.

In the Middle Miocene, the Ngrayong sediments were deposited. To the north of the border, the sediments composed of deltaic and shelfal facies, and as basinal turbidite facies to the south of the border. There is evidence of a Middle Miocene tectonic uplift over a restricted area because of erosion of the Ngrayong. Downlapping seismic facies are observed corresponding to erosional truncation on the upper part of the Ngrayong (Soeparyono and Lennox, 1989). Regional subsidence and transgression established in the Late Miocene and Pliocene resulting in deposition of the Late Miocene Wonocolo fine clastics and the Pliocene Karren limestones. In areas where intensive inversion occurred, the Karren Limestone rests directly upon the Early Miocene Kujung Unit I.

Neogene inversion led to a reversal in basin geometry (Bransden and Matthews, 1992). During the Paleogene, sedimentation was concentrated in axial rift zones, with thinner sediment deposited on the relatively stable flanking platforms. Major reverse movement on the controlling faults led to the sediment thicks being inverted, and new Neogene depocenters forming to the north and south of the inversion zone. These locally have a foreland basin geometry, notably in the Madura Strait and Kangean/Lombok Southern Basins. Reworking of the inversion trend provided some of the sediment fill. In the eastern part of the East Java Basin, the erosion products were largely mud-prone. Whereas, in the west some sands may have been reworked. Further sequence stratigraphic study can resolve eustatic and sediment supply controls for stratigraphic response to the inversion. In the East Java area, continued inversion and differential compaction is a further primary control on sedimentation.

THE ORIGIN OF THE RMKS FAULT ZONE

There was a contrast change of structural episodes from the Paleogene to the Neogene in the East Java Basin. A tensional stress regime was the major structural control from the Middle Eocene up to the Early Miocene. This Paleogene’s rifting phase resulted in segmented basement forming low and high areas. The origin of the tensional stress may relate to a number of mechanisms including : the drifting of West Sulawesi from East Kalimantan (the opening of the Makassar Strait), a back-arc extension due to reduction of subduction rate (subduction roll-back), and a rifting in a fore-arc setting.

In the Neogene, the stress regime fundamentally changed to the compressive and translational stress leading to the widespread inversion. A zone of compressive and wrench deformation occur mostly to the south of the Paleogene shelf-edge forming a linear tectonic disturbance zone called the RMKS Fault Zone.

A number of mechanism is considered to cause the origin of the RMKS Fault Zone (Figure 8) : (1) subduction of the Indian oceanic crust beneath Java, (2) the collision of the Australian continental plate with Timor, and (3) the westward movement of numerous micro-continents detached from the northern Australian Plate. Since the Late Oligocene, subduction of the Indian oceanic crust beneath Java has been parallel with the shelf edge of the East Java Basin. Collision of the Australian continent with a northerly island arc was initiated in the Early Miocene. The interaction of the northerly moving Australian continent and the westerly motion of the Philippine-Pacific Sea Plates resulted in tectonic shaving process causing detachment and westward drifting of some micro-continents. Among these, were Buton-Tukangbesi micro-continent which collided SE Sulawesi in Early to Middle Miocene (Davidson, 1991) and Banggai-Sula micro-continent which collided East Sulawesi in the latest Miocene (Davis, 1990). Westward compressive stress was generated due to these collisions with the effects were recorded far to the west, in backarc regions, into the Sundaland (Letouzey et al., 1990). Continued drive of the Australian continent to the north into the Sunda Trench and Banda Arc has resulted in thrust contraction and inversion along the arc. Major thrusts are interpreted to be located to the north of Flores, Lombok, and Bali (Silver et al., 1983), with continued movement and seismic activity until the present-day. This is considered the principal driving mechanism of inversion in the East Java Sea

The above mechanisms resulted in transpressional stress regime around the SE Sundaland area including the East Java Basin. The transpressional stress was taken as left-lateral movement along the weakness zone of the sedimentary border of the Paleogene shelf-edge area which also played a role as the southern border of the Paternoster-Kangean micro-continent. Inversion occurred as response to both wrench movement on older tensional structures and because of northward compressive stress generated by subduction of Indian oceanic crust beneath Java. Inversions in the eastern Sunda Platform, according to Letouzey et al. (1990), are related to the collision of the Banggai-Sula-Buton continental blocks with the west Sulawesi volcanic arc.

Other possible control on the Neogene fault movement reversal in the RMKS Fault Zone is the compression resulted from blocking of the NW Borneo Trench in the upper Early Miocene (Bransden and Matthews, 1992). However, this stress will result in right-lateral movement to the RMKS Fault which is not observed for this case instead of evidence on left-lateral movement.

Therefore, the change from extension period with graben infill from the Paleogene to the Early Miocene into the Middle Miocene-Recent period of wrenching, inverting, folding. and thrusting reveal changes in the intra-plate stress field which was controlled by the changes in the boundary conditions of the plates : collision on the northern and eastern sides, and inter-plate coupling southward along the Java subduction zone.

STRUCTURAL STYLE OF THE RMKS FAULT ZONE

The RMKS Fault Zone is a zone of tectonic disturbance as long as 650 km long and 15-40 km wide situated at the northern side of East Java from Rembang through Madura and Kangean Islands to Sakala-Sepanjang offshore areas. The fault zone trends west-east (Figures 1 and 2). Nowadays, the fault zone separates the East Java Sea shelf area from the onshore East Java Basin in the western part and the Madura Strait and the Bali Sea in the eastern part. To the west the fault zone abuts a paleo-high called the Karimunjawa Arch which trends SW-NE. To the east, the fault zone bifurcates into two main splays called the

Sakala Fault at the north and the Sepanjang Fault at the south. Within the fault zone, structural deformation related to wrench tectonism, folding, reverse faulting, thrusting, inversion, and shale diapirism is observed.

The discussion of the structural styles of the RMKS Fault Zone is divided into three areas : western part (onshore Rembang-Cepu-Surabaya areas), central part (Madura Island), eastern part (Kangean Islands and Sakala-Sepanjang offshore areas) (Figure 9).

Western Part : Rembang to Surabaya Area

In the western part, the area is included into the physiographic zones of the Rembang Hill and Randublatung (van Bemmelen, 1949) (Figures 3 and 9). Soeparyono and Lennox (1989) and Musliki (1991) provided discussions on structural styles of this area. The RMKS Fault Zone in this area is dominated by zones of anticlinorium trending mostly west-east and WNW-ESE (Figure 9). Reverse faults and thrusts trend in same direction with anticlines, whereas normal faults trend SW-NE. The intensity of deformation is higher in the Rembang Zone than that of the Randublatung Zone. This may relate to the distance of the Rembang Zone to the RMKS Fault Zone which is closer than that of the Randublatung Zone. The anticlines in the Rembang Zone are small and short indicating disturbances by faults, while in the Randublatung Zone the anticlines are mostly big and elongated (Musliki, 1991).

The direction of the folding movement in the Rembang Zone is generally southward, contrast with the Kendeng Zone located to the south of the Randublatung where the strata have been pushed northward (van Bemmelen, 1949) (Figure 3). This two opposite vergencies may form a triangle zone, southward thrusting in the Rembang Zone and northward thrusting in the Kendeng Zone with a subsided zone of the Randublatung Zone in the middle.

Soeparyono and Lennox (1989) argued that the origin of anticlines in the Cepu area, included into the southern Rembang Zone and which mostly trap oils, can be divided into two groups : group I (model of Nglobo-Semanggi area) in the west and group II (Tambakromo-Kawengan) in the east. Group I is related to wrench tectonism and is basement-involved. Deformation in the early Middle Miocene caused reactivation of the basement faults with wrenching and the initial development of flower structures (Figure 10). This deformation caused areally restricted erosion of the main reservoir rocks (Middle Miocene Ngrayong sandstones) in this area. Later Pliocene deformation accelerated the development of the flower structures at approximately 5-6 km depth and reflected at the surface as a series of en echelon, oil-bearing anticlines. Well developed flower structures are identified from north to south seismic lines across perpendicular to the trend of the RMKS Fault Zone. These are positive flower structures because the upward spreading faults have reverse separation on most of their elements. These structures reflect a convergent wrench zone where there is a strike-slip motion on the fault system. Strike slip faults are often associated with a wide range of secondary shear geometries (Riedel shears) which consist a set of en echelon shear fractures.

Group II is related to detached (thin-skinned) compressional structures. The asymmetrical folds underwent southward thrusting along west-east oriented listric reverse faults with detachment at shallow depths (1.5-2 km depth) and the development of oil-bearing folds exist in the subsurface north of the Tambakromo-Kawengan structure. Such folds would be related to imbricate blind thrusts parallel with the Tambakromo-Kawengan thrust.

Intrusion of diapiric shales also characterize the RMKS Fault Zone of this area. Soetarso and Patmosukismo (1976) discussed this diapirism in its relationship to hydrocarbon occurrence in the East Java Basin. All shale diapirism in the East Java Basin occurred to the south of the shelf edge area where deep-water sedimentation took place. Subsidence of this area was approximately equaled by the rise of the Middle-Late Miocene Wonocolo shales. The Wonocolo shales intruded a rapidly deposited regressive sandy sequences of the Late Miocene Ledok Member. The distribution of the Wonocolo diapirs which are aligned with the trend of RMKS Fault Zone shows that these diapirs were triggered by the horizontal stress of the RMKS Fault Zone and may also relate with the inversion. Manur and Barraclough (1994) observed that basinal inversion and related shale diapirism are major structural controls in the region south of the shelf edge. Diapiric structures in this area are generally small, narrow and elongated west to east and characterized by : (1) structural deformations increase in the younger formations, (2) thickening of strata over the anticlinal crests and thinning in the synclines, (3) a few or no reflections in the core of the anticlines, and (4) elevated geothermal gradient.

Central Part : Madura Island

Madura forms the eastward extension of the Rembang Hills. Detailed surface geological mapping by Pertamina (published by Mulhadiono *et al*., 1986) identified 45 faults and nine anticlines (Figure 9). Wrench faulting is designated as the main driver of deformation in Madura Island. The oldest formation affected by the deformation is the Early Miocene rocks equivalent with the Tuban Formation. Madura Island is a breached anticline with Early to Middle Miocene Tuban and Tawun Formations exposed in the core. Relatively simplistic on large scale, but complex in structural detail.

Anticlines in the western, central, and eastern area can be united to form two regional anticlines trending west-east through the whole island with one syncline in the middle. The two anticlines merge towards the west and plunge to the southeast. The two regional anticlines are called the Monceh-Rancak-Mandala Anticline and the Arosbaya-Gunung Edden-Kertegeneh Anticline. The regional syncline in the middle is called the Pereng Sekuning-Gunung Taman-Pegantenan Syncline. These regional folds are disrupted by numerous normal and strike slip faults trending mainly SW-NE and SSW-NNE.

North-south seismic lines crossing perpendicular to the trend of Madura Island reveal the presence of the positive flower structures below the anticlines at shallow depth. Arosbaya faulted anticline sits overlying the positive flower structure (Figure 10). On the southern part, a negative flower structure is also expected to present like in the Camplong and Kertegeneh areas. Therefore, the structural grains of Madura Island are caused by the left-lateral wrench tectonism. West-east trending anticlines, synclines, and reverse faults are shallow and surface manifestations of the upward diverging strands of a flower wrench fault. The master fault is straight and throughgoing into the basement. Numerous normal faults trending SW-NE and shift the folds and reverse faults are normal faults or extension fractures associated with the left-lateral wrench faulting (Figure 9).

A series of paleogeographic map of Madura Island from the Late Cretaceous to the Pleistocene was provided by Mulhadiono *et al.*(1986) (Figure 11). The maps show that during the Early Miocene and Middle Miocene, Madura Island was an open marine where deeper-facies sediments were deposited. This condition partly continued into the Late Miocene. To the north of the island, was a site for carbonate shelf deposition. This means that during the period, the shelf edge was in the northern part of the island. During the Late Miocene and Pliocene, the basinal area of the Madura Island was strongly inverted and high (land) area with no sedimentation was established in the western and eastern part with low areas in the middle and at the southern part. The RMKS Fault Zone is considered to be responsible for the inversion of the Madura Island. In Pleistocene time, almost the whole island, except its southern part, was inverted to become high area with no sedimentation. The Madura Island has been a provenance for siliciclastic sediments since the Mio-Pliocene to be deposited into deep South Madura Basin southward (presenty is the Madura Strait).

Eastern Part : Kangean Islands and Sakala-Sepanjang Offshore Areas

Kangean Islands, located 100 km to the east of Madura Island, and Sakala-Sepanjang offshore areas as long as 250 km to the east of Kangean Islands until the Flores Sea is strongly affected by the RMKS Fault Zone. The effect is even stronger here than that of the Rembang and Madura area. This suggests that the origin of stress causing the deformation of the RMKS Fault Zone is from the east. Inversion is strong in this area. Van Bemmelen (1949) cited a report by Beltz (1944) who reported that 3000 m of Oligocene strata crop out in Kangean Island.

Bransden and Matthews (1992) provided detailed discussion on the structural history of inversion in this area with its stratigraphic response (Figures 9 and 12). The history was started by broadly west-east trending Paleogene rifts or fault zones. The most laterally continuous of these rifts are the Sepanjang Fault Zone to the south and the Sakala Fault to the north (Figure 9). These faults and other faults formed Paleogene rifts where thick Eocene Ngimbang sediments were deposited. The Sepanjang and Sakala Faults border the rifts/depocenter of Kangean and Lombok Central Trough. The eastern extension of the Sakala Fault becomes more complex involving several WSW-ENE trending faults, both north and south dipping. The faults were dominantly normal faults with some important polarity switches in the northern part which may relate with a regional strike-slip component to the movement history in addition to the obvious dip-slip component. Cross sections of these faults show dominantly extensional evolution since the middle Eocene. Preserved thickness variations are observed in the footwalls and hangingwalls of the faults (Figure 12). The regional half-graben geometry is apparent with the Sepanjang Fault controlling this geometry. However, there is also erosional truncation of Upper Eocene sequences, suggesting the possibility of significant local uplift at this time. This may be a result of localized contractional uplift resulting from transpressional component of motion.

Continued drive of the Indian-Australian Plate northward and some collisions of micro-continents in Eastern Indonesia caused inversion started in the upper Early Miocene in this area. Early Miocene and younger uplift has affected a large area of the East Java Sea. The graben and half-graben have been inverted. A range of geometrical styles are observed which suggest reversal of motion on both planar and listric faults. Areas of maximum inversion were at maximum burial prior to the Early Miocene. Extensional geometries have been preserved locally during uplift where the fault movement reversal has been confined to one fault within pre-existing extensional system. Inversion on the Sepanjang Fault produces the largest magnitude uplift in terms of both elevation and along strike continuity within the East Java Sea. East of Kangean Island the uplift is broadly symmetric, and is interpreted to be a function of movement reversal on the Sakala and Sepanjang Faults. The Neogene inversion history is most simply explained by fault movement reversal with the major uplifts reflecting the location of the main Paleogene depocenters, this being a function of the Paleogene fault geometry and linkage. All the Neogene uplift structures currently interpreted can be explained by dominantly dip-slip reverse motion and subsidiary strike-slip motion on pre-existing Paleogene structures, with local generation of new contractional faults.

CONCLUSIONS

1. The Rembang-Madura-Kangean-Sakala (RMKS) deformed zone is a major left-lateral wrench and inverted zones in the East Java Basin occupying the weak zone of geologic borders characterized by contrast sedimentary and basement-structural changes.

2. The origin of the RMKS Fault Zone is related with the Early Miocene to Middle Miocene episodes of (1) westward stress driven by the collisions of some micro-continents to the east of Sulawesi, (2) westward stress due to the collision of Australia with Timor and anti-clockwise bending of the Banda Arc, and (3) northward stress due to the subduction of the Indian oceanic crust beneath Java and Lesser Sunda Islands.

3. The RMKS Fault Zone is characterized by basement-involved flower structures with upward diverging splays that mostly have reverse separations. In map view, these splays represent fold and fault belts trending west-east and west northwest-east southeast. These antiforms are manifested as tectonic inversion. Inversion related to a pure shear deformation of Indian oceanic plate subduction complicate the structural styles. Normal faults are formed as related with the extensional component of the wrench zone. Shale diapirism is commonly formed to the south of the fault zone and its occurrence is related with the wrench tectonism.

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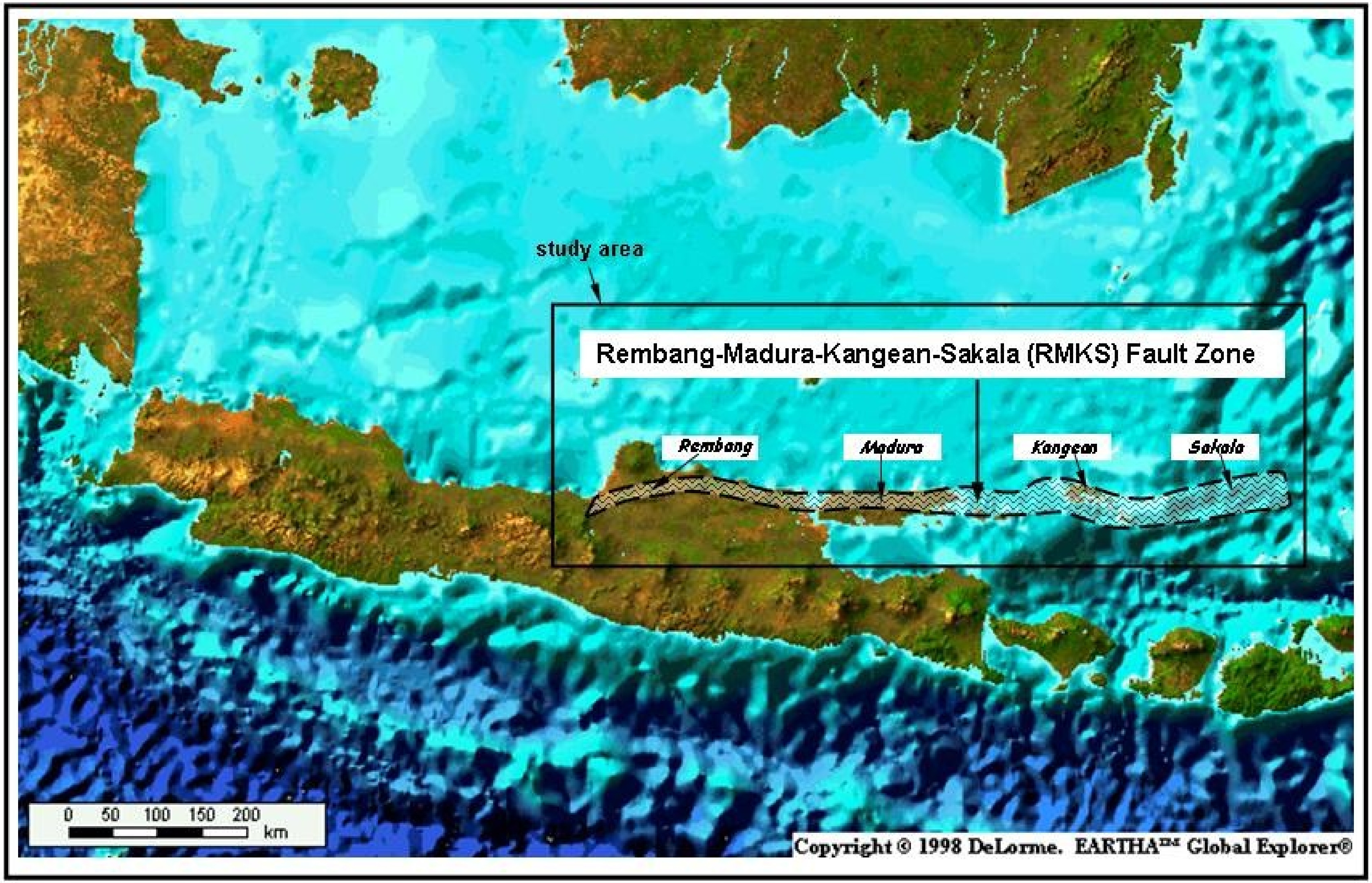


Figure 1 Location of the study area showing the trace of the Rembang-Madura-Kangean-Sakala (RMKS) Fault Zone plotted on the physiographic map of Java and Southeastern Sundland. Geographic locations of Rembang, Madura, Kangean, and Sakala are indicated.

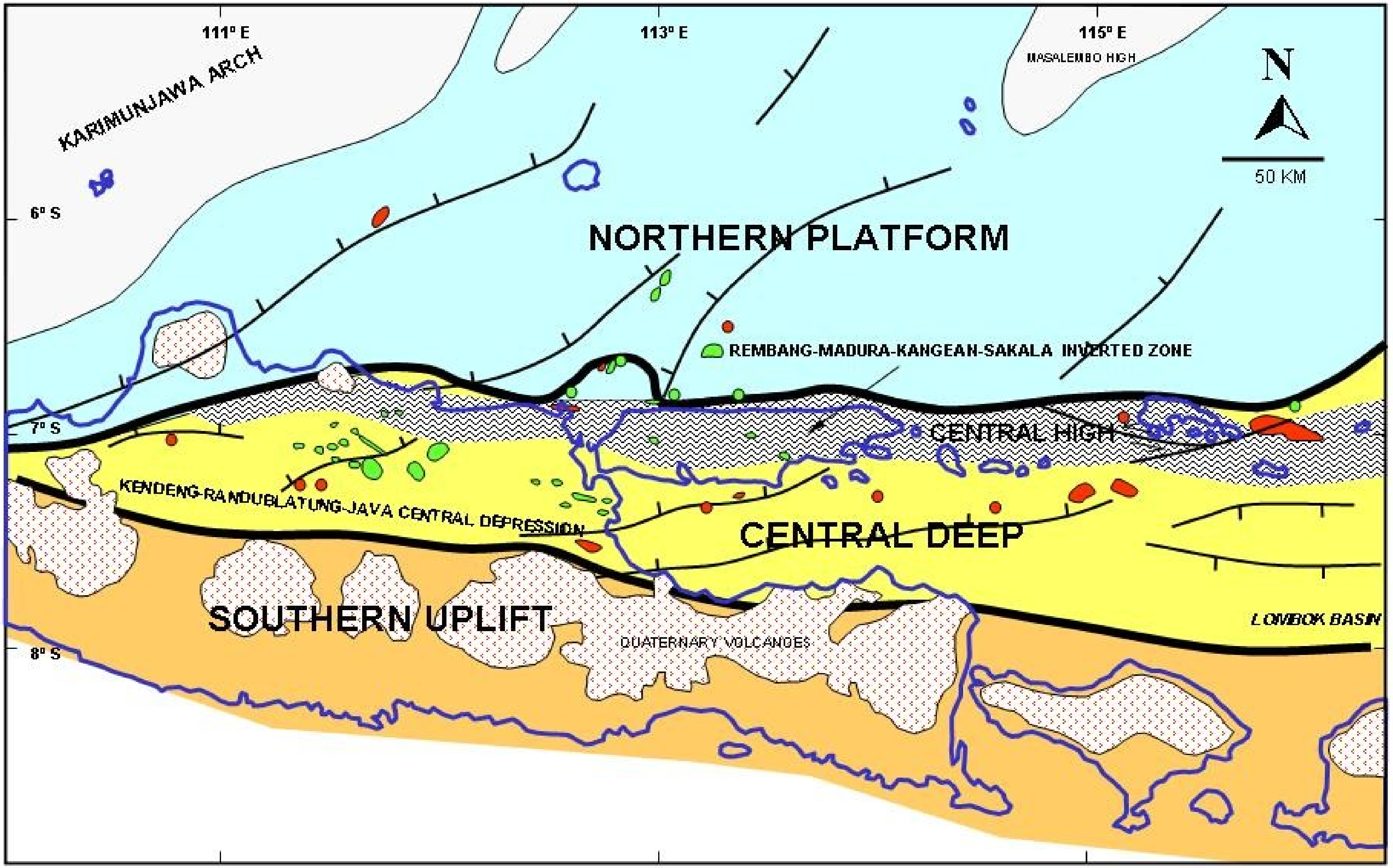
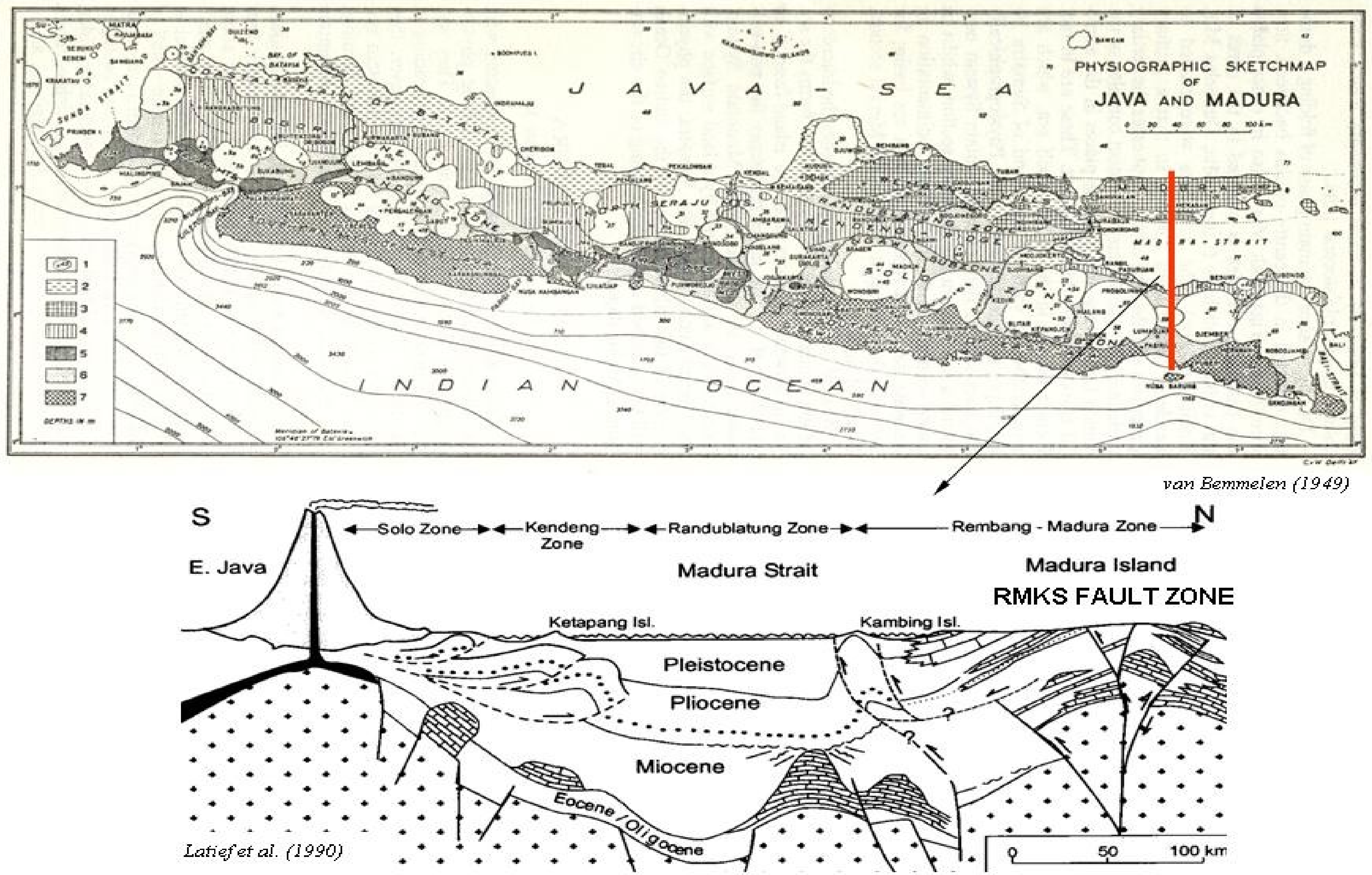


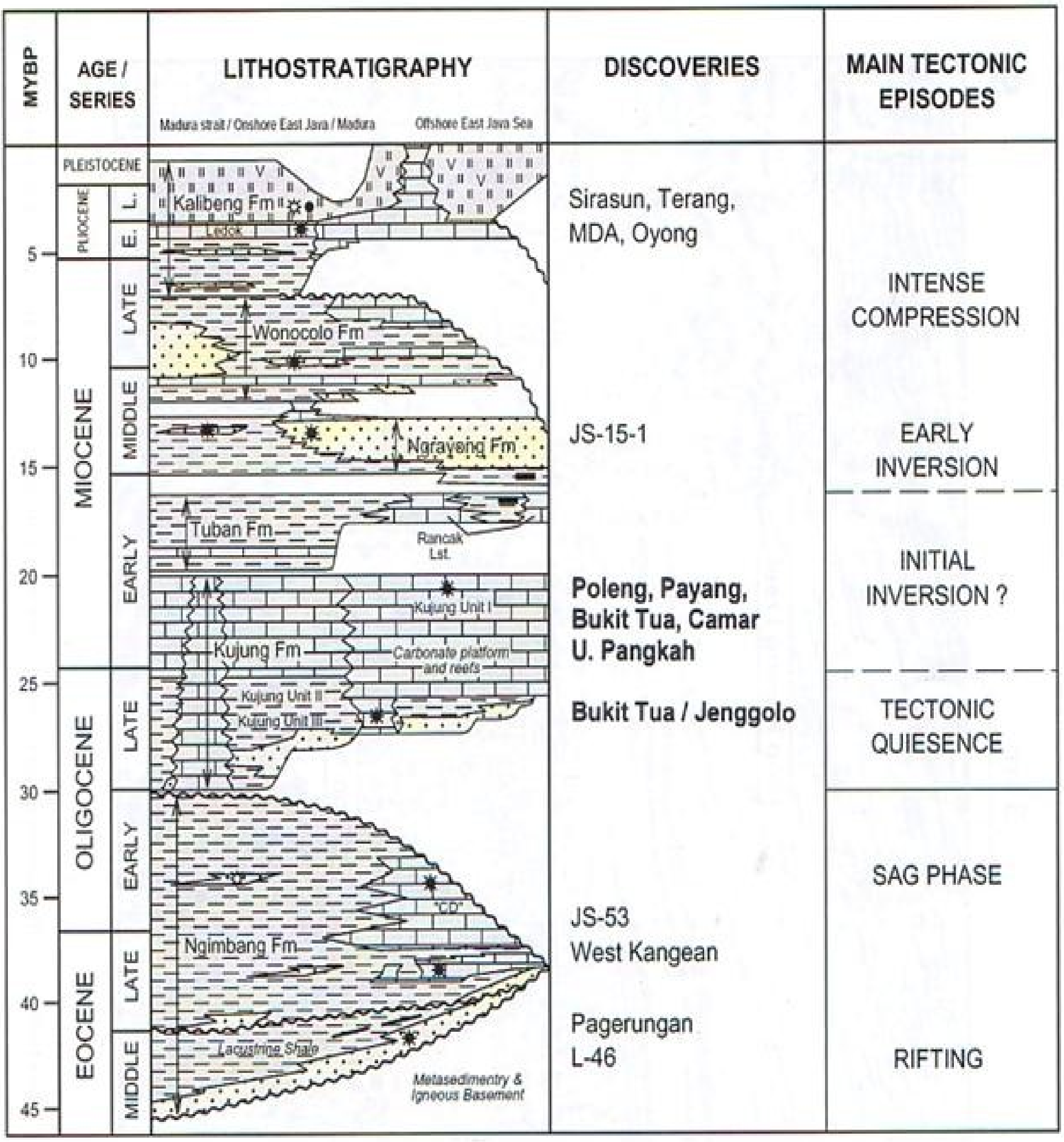
Figure 2 Geologic setting of East Java showing three basic tectonic configurations : shallow Northern Platform, deep and subsided Central Deep, and uplifted Southern Uplift. Inverted zone of RMKS is located at the margins of the Northern Platform and the Central Deep.



van Bemmelen (1949)

Latief et al. (1990)

Figure 3 Cross section of East Java. Note flower structuring of the RMKS Fault Zone in Madura Island.



Johansen (2003)

Figure 4 Generalized stratigraphy of East Java. Note the tectonic inversion episodes during the Miocene. Reservoirs for hydrocarbons are indicated.

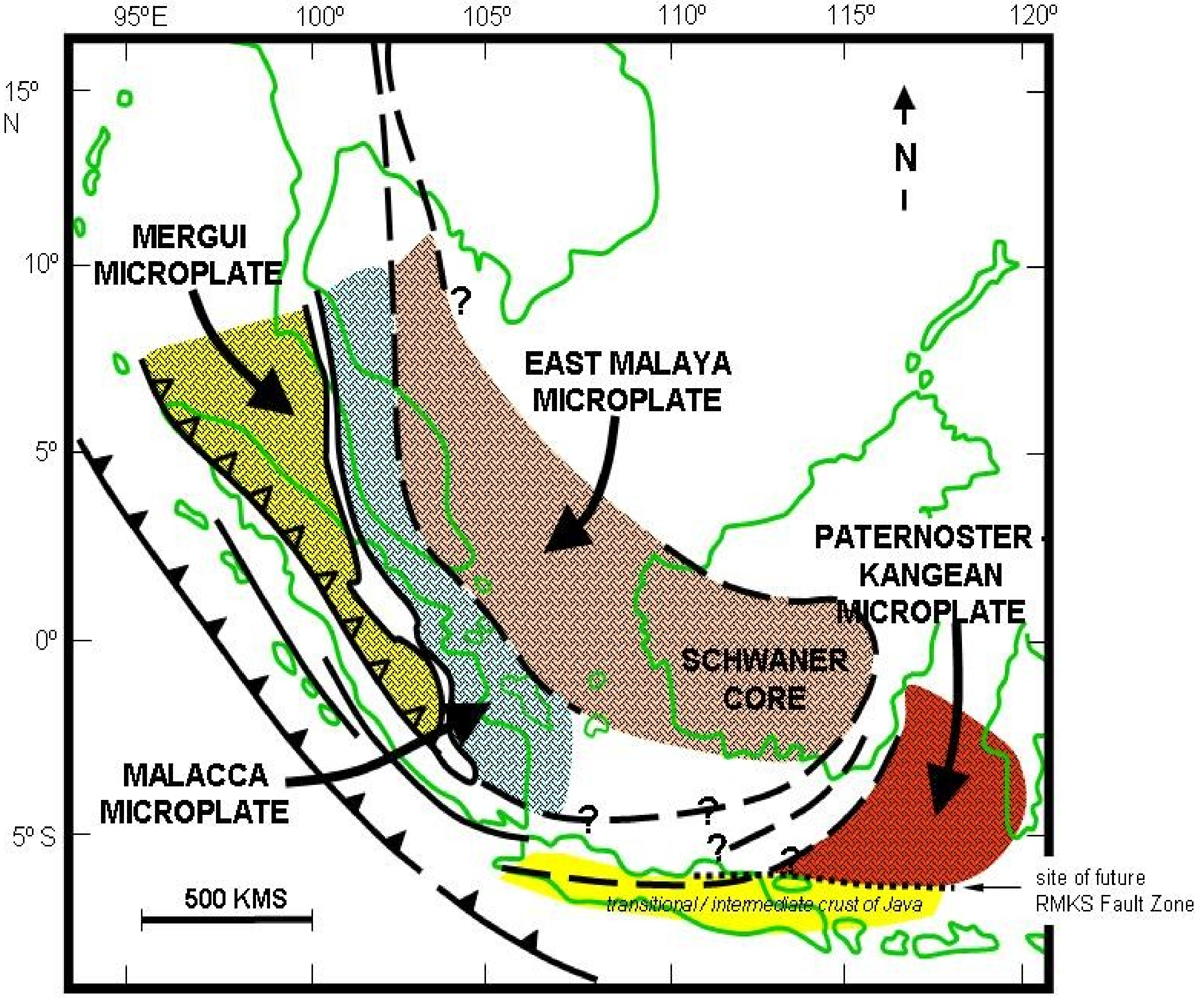
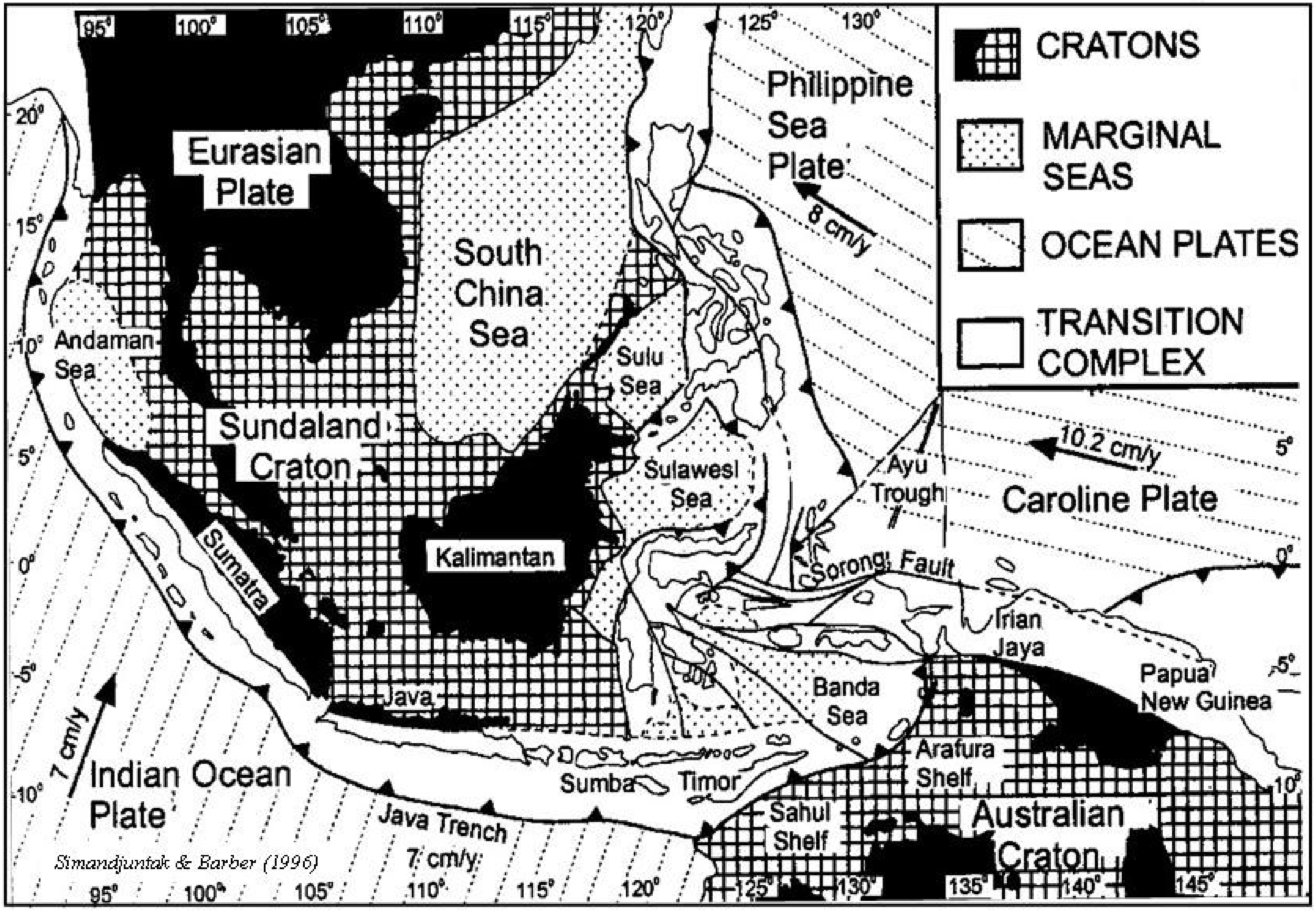


Figure 5 Microplates (continental crust) of the Sundaland. One microcontinent called the Paternoster-Kangean underlies the East Java Sea and terminates southward to transitional (intermediate) crust.of Java. The RMK Fault Zone developed in the middle of the two basement types.



Simandjuntak & Barber (1996)

Figure 6 Tectonic setting and basement configuration of Indonesia. Note that the location of the RMKS Fault Zone in East Java is a border of the two basements : continental crust to the north and transition complex (accretionary prism) to the south. Northward subduction of the Indian oceanic plate and westward movement of some micro-continents in Eastern Indonesia as well as collision of Australian continent are responsible for the origin of RMKS Fault Zone.

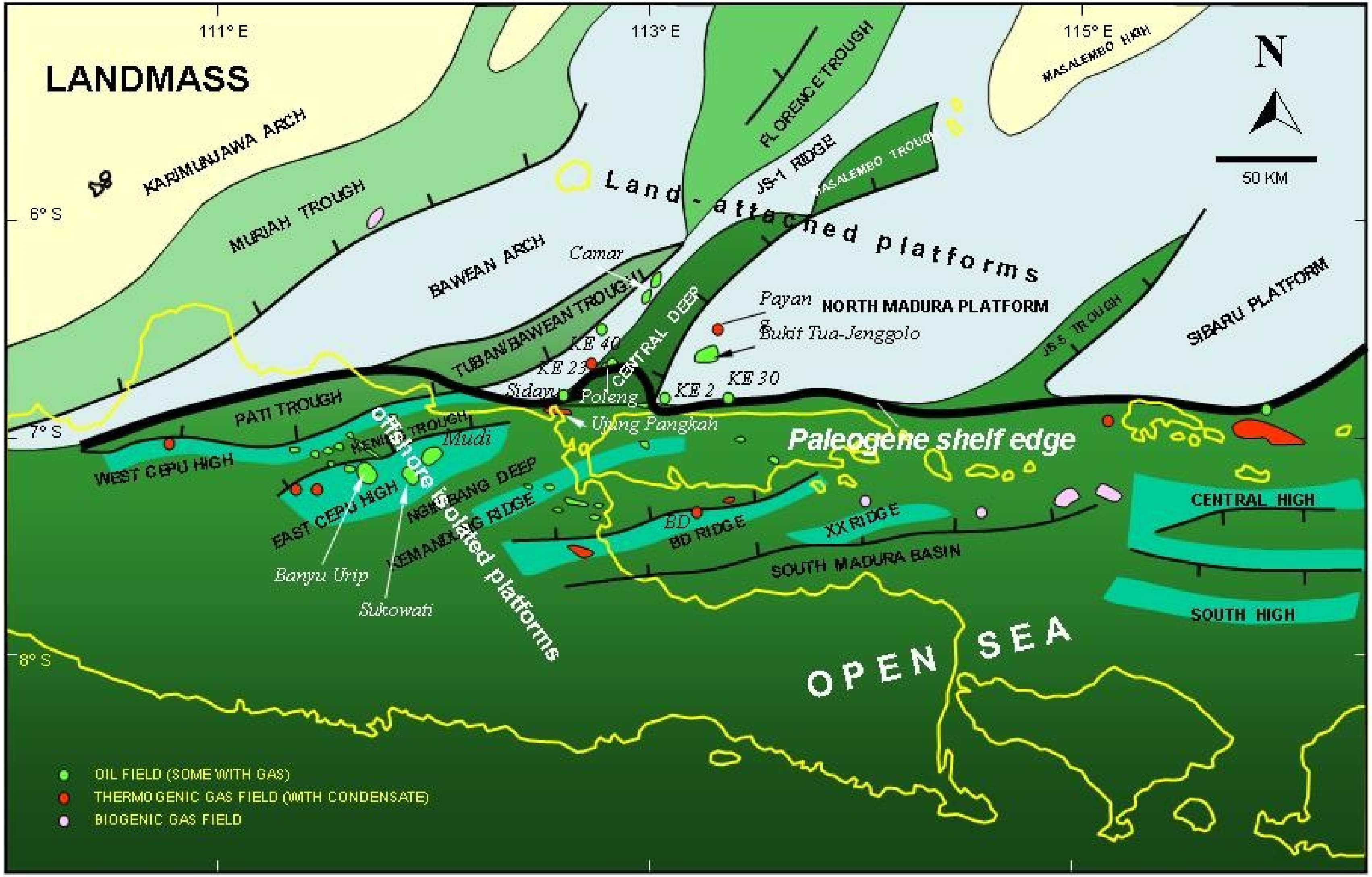
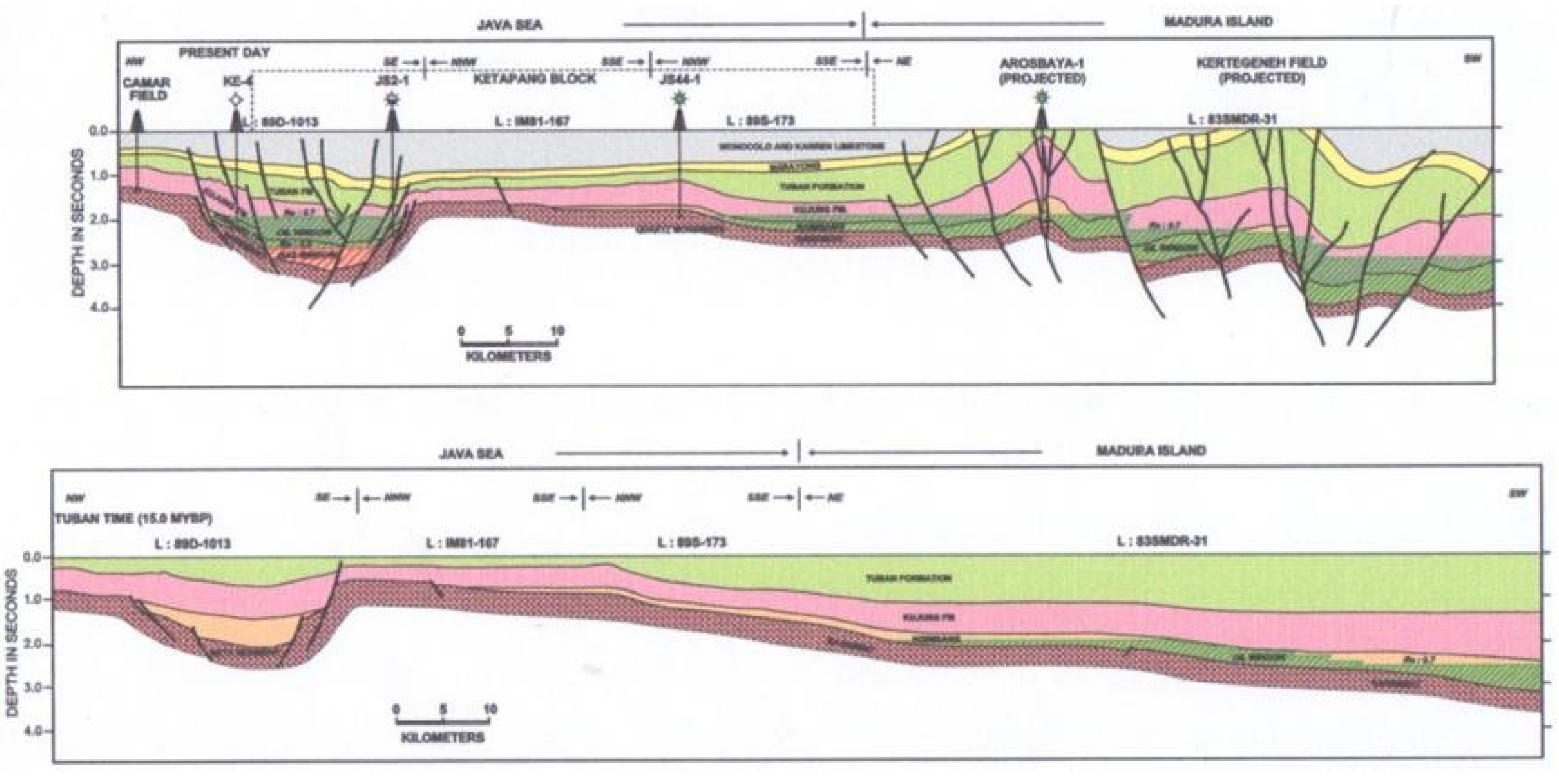


Figure 7 Paleogeography during the Paleogene. A west-east trending shelf edge became a border for sedimentation in marginal marine environment to the north of the shelf edge, and in deep open sea environment to the south.



courtesy of COPI Ketapang

Figure 8 Schematic cross section showing that during the Tuban time (15 Ma) Madura Island was still a deep water area, then it was inverted and uplifted to become Madura Island. The inversion partly occurred through wrench tectonism which also subsided the Central deep to the northwest of Madura Island (as extension fracture in strike-slip terminology)

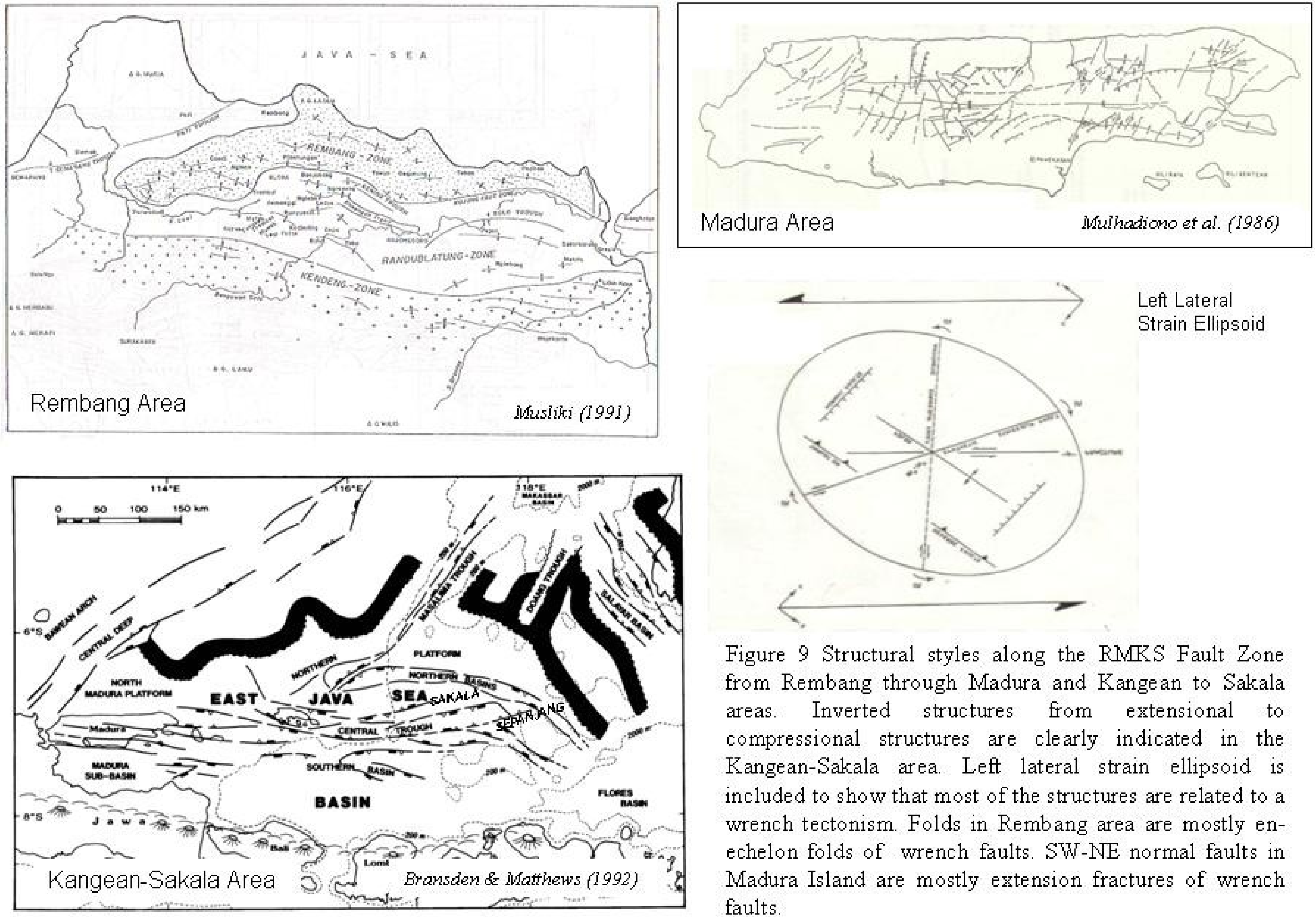
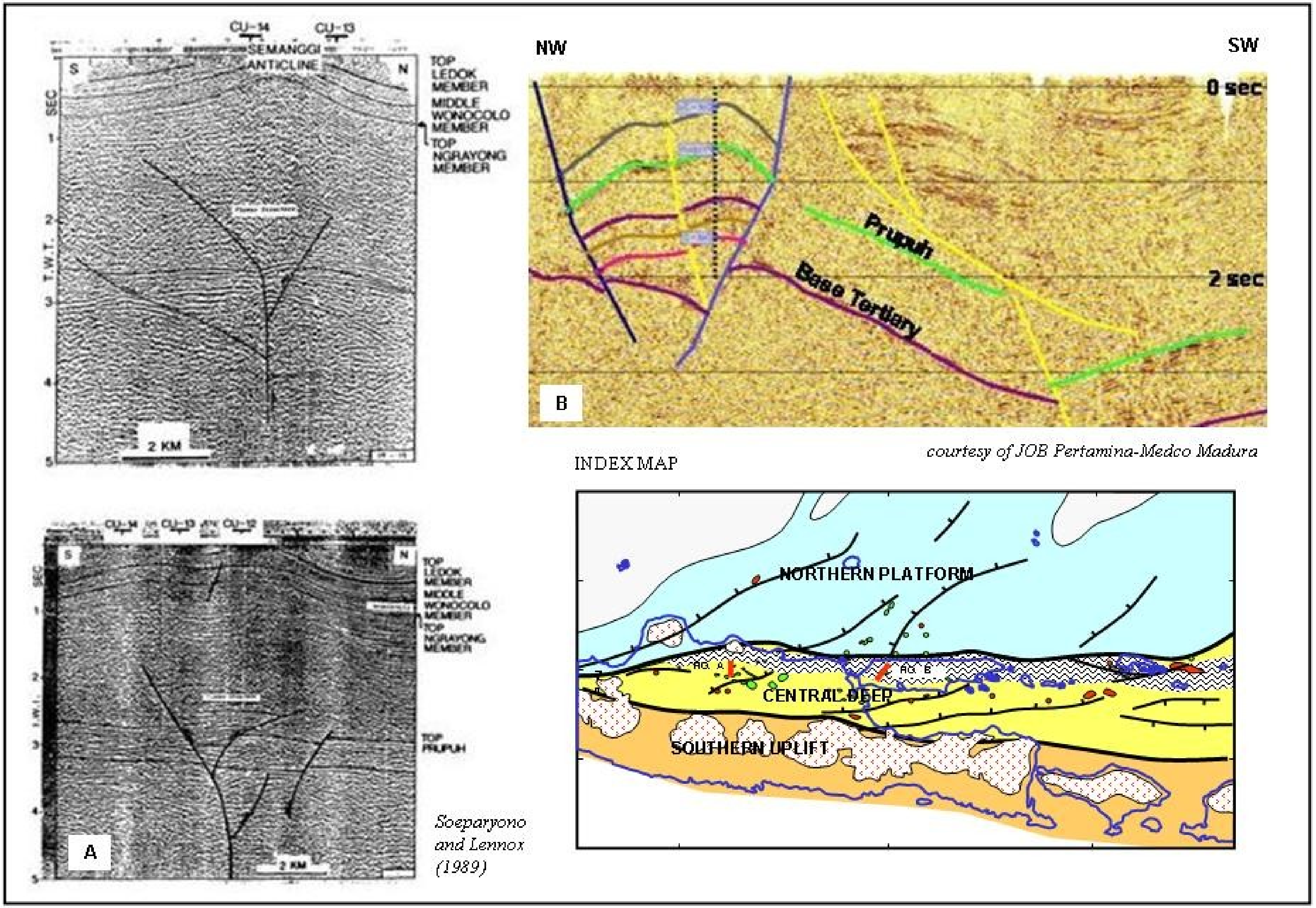


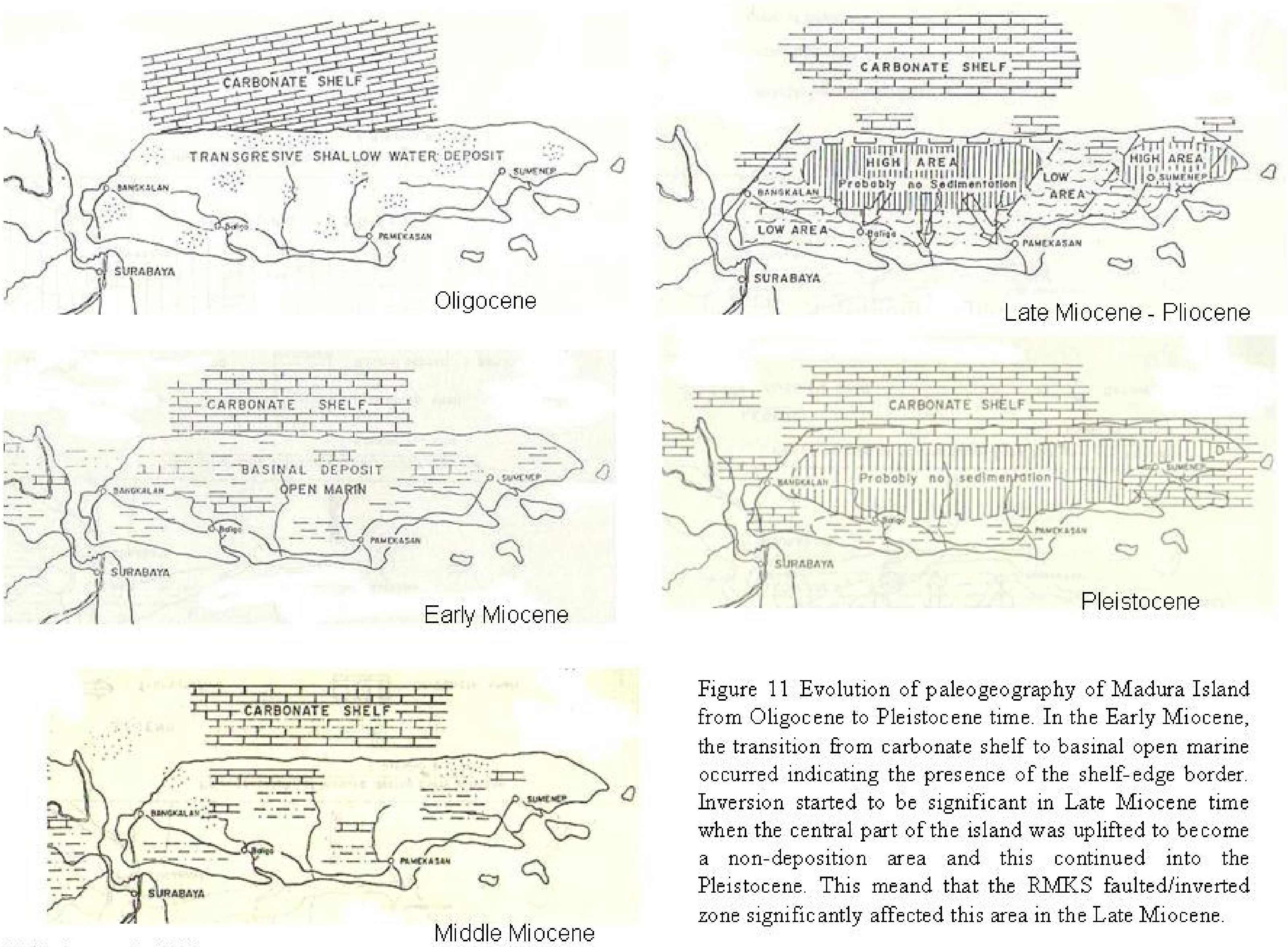
Figure 9 Structural styles along the RMKS Fault Zone from Rembang through Madura and Kangean to Sakala areas. Inverted structures from extensional to compressional structures are clearly indicated in the Kangean-Sakala area. Left lateral strain ellipsoid is included to show that most of the structures are related to a wrench tectonism. Folds in Rembang area are mostly en-echelon folds of wrench faults. SW-NE normal faults in Madura Island are mostly extension fractures of wrench faults.



Soeparyono and Lennox (1989)

courtesy of JOB Pertamina-Medco Madura

Figure 10 Seismic lines at left (located at the Cepu High) and at right (located at the western Madura Island) showing the presence of the flower structuring and inverted zone of the RMKS Fault Zone. Locations of the seismic lines are indicated at the index map.



Oligocene

Late Miocene - Pliocene

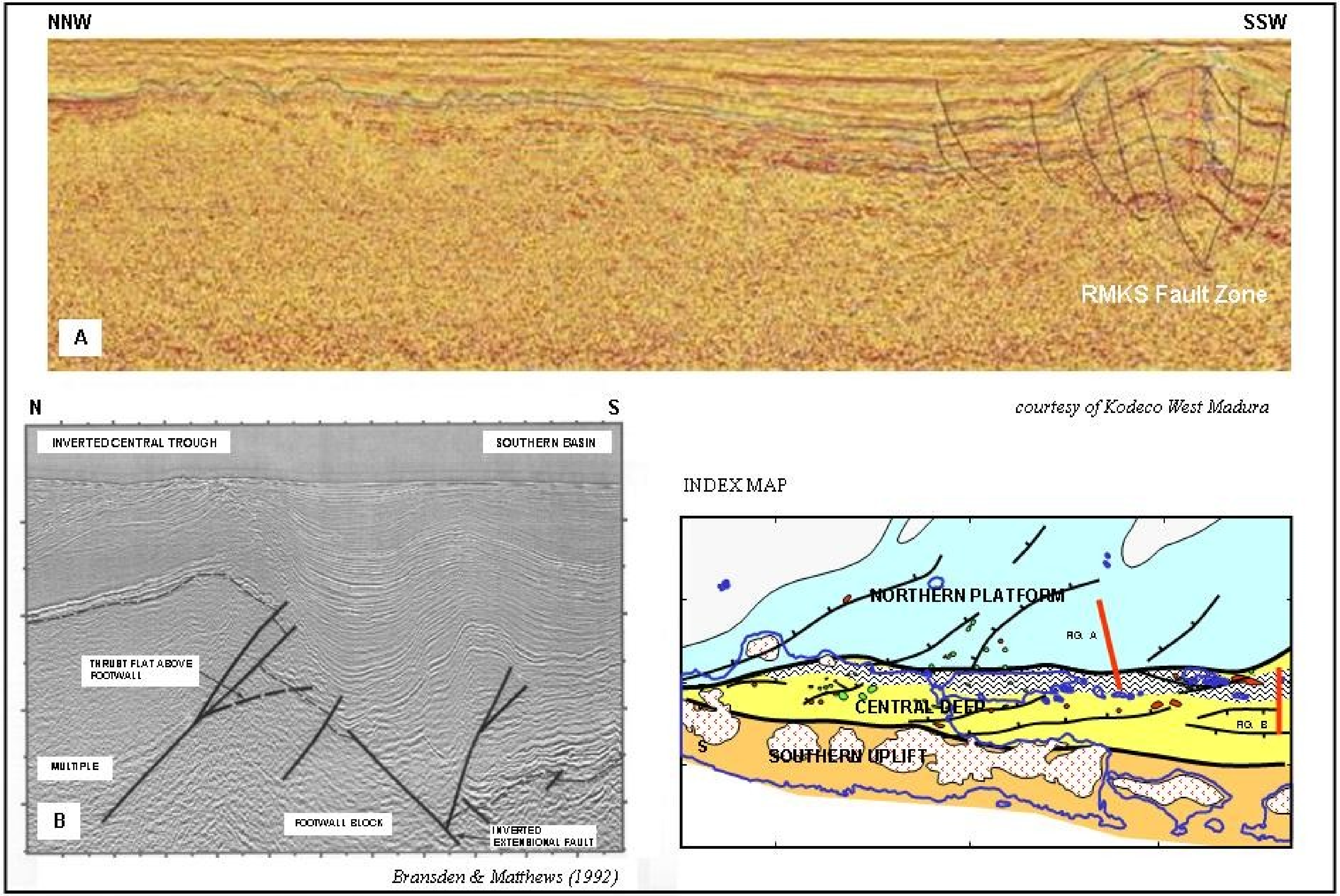
Early Miocene

Pleistocene

Middle Miocene

Mulhadiono et al. (1986)

Figure 11 Evolution of paleogeography of Madura Island from Oligocene to Pleistocene time. In the Early Miocene, the transition from carbonate shelf to basinal open marine occurred indicating the presence of the shelf-edge border. Inversion started to be significant in Late Miocene time when the central part of the island was uplifted to become a non-deposition area and this continued into the Pleistocene. This meand that the RMKS faulted/inverted zone significantly affected this area in the Late Miocene.



courtesy of Kodeco West Madura

Bransden & Matthews (1992)

Figure 12 Seismic lines at above (located to the west of Kangean Island) and at below (located to the east of Kangean Island) crossing the RMKS Fault Zone and showing the presence of the inverted zone of the RMKS Fault Zone. Locations of the seismic lines are indicated at the index map.