Late Neogene Inversion and Subduction Initiation in the SE Sundaland: Insights from Seismic Observation of Regional Reverse and Back-thrust Faults from East Java to Wetar, Indonesia

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ABSTRACT

The Late Neogene tectonics in East Java region have led to significant geological deformations. For example, the regional structures of the Cepu-to-Central High inversion and Baribis-to-Wetar back-thrust fault are the result of the Australian Oceanic Plate subducting beneath southeast of the Cretaceous Sundaland in an orthogonal direction. These inversion structures and back-thrust faults are prominent and continuously active in onshore East Java in the west and further east.

The west-east regional structure of the Cepu-to-Central High inverted graben remains attractive for hydrocarbon exploration and development in Indonesia. The region has been one of the focal points in the East Java Basin and has two well-known proven petroleum systems. Oil and gas fields have been continuously discovered until very recently in both the Eocene-to-Miocene thermogenic and Pliocene-to-Pleistocene biogenic plays. Hydrocarbon plays in the region have been significantly improved and added since the first oil was discovered by the Dutch in pre-World War II in-line with the use of new exploration concepts and techniques, as well as drilling technology.

The extent of the Baribis-to-Wetar back-thrust fault was seismically defined in onshore East Java towards offshore Wetar. The 2D seismic interpretation indicated that the segment of the Kendeng-Bali back-thrust fault has a low-angle blind-thrust fault system. Towards the east, in the Lombok-Flores-Wetar segment, the blind-thrust fault has developed its thrust style, and the fault thrust-tip line has broken all the way to the sea floor. At this point, the beginning of Flores intra-oceanic subduction initiation might have occurred in the post-Early Pleistocene to form a Flores nascent trench. Along this back-thrust segment, the central to east Sunda Arc is seismically very active and devastating.

Keywords: *Late Neogene inversion, Central High, Madura, Baribis, East Java Basin*

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INTRODUCTION

Several 2D seismic lines were interpreted, and recent seismic images available in published papers were utilised. The seismic lines available for interpretation are very limited and generally in poor quality. These constraints have hampered further detailed analysis and observations. Consequently, any quantitative interpretations are not discussed in this paper, and several published papers are utilised to support the interpretation. However, it is hoped this study will trigger further research in related to the strain-stress analysis model including crustal shortening interpretation in a quantitative mode. As there are still many attractive areas to explore, this study aims to encourage and support further hydrocarbon exploration in the region, specifically the Cepu-to-Central High inversion.

For the sake of argument, the Australian Oceanic Plate has steadily subducted underneath the southeast Sundaland margin in an orthogonal direction from the Late Neogene to the present day. This consistently caused dynamic surface deformation in the overall overriding plate in the form of geological structures, volcanism-related, and/or variation of the sea-level fluctuations, specifically in the Sundaland rim region. The most prominent evidence observable at the surface and subsurface are the folds and faults of the Cepu-to-Central High inversion and Baribis-to-Wetar back-thrust fault in onshore East Java and further to the east in the southeasternmost end of the Late Cretaceous Sundaland margin (Figs. 1 & 2).

PLATE CONVERGENCE

The interior of SE Asia (both the "Sundaland core" as geologically undeformed stable regions, and contiguous "Sundaland rim" as tectonically active and highly mobile regions) or Sundaland block is the whole part of the Sundaland core and its rim (Tjia, 1996; Hall & Morley, 2004; Hall, 2014). The Sundaland core lacks seismic and volcanic activities, with the exception of the rim. Consequently, the Sundaland rim covers all the collision and subduction zones to the west, south, and east of the Sundaland core, with the exception of the north. For example, the Java Trench in the south is the location where the Australian Oceanic Plate subducts beneath Sundaland. In this paper, the Sundaland block is often referred to as "Sundaland" to simplify the term or unless stated otherwise.

Sundaland has been a tectonic entity and coherent block geodetically recognised moving independently and differently from the Eurasian Plate at present, and therefore, it should be separated from the Eurasian Plate, although it is occasionally considered to be part of Eurasia (Rangin et al., 1999; Bird, 2003; Bock et al., 2003; Simons et al., 2007). Similarly, it is necessary to separate the Indian Plate from the Australian Plate (Sella et al., 2002; DeMets et al., 2010; as defined in DeMets et al., 1988).

Based on Global Positioning System (GPS) observations, the undeformed Sundaland rotation is calculated at the rate of 0.336° ± 0.007°/Ma in clockwise orientation with the rotation pole located at latitude of 49.0°N and longitude of 94.2°E in Siberia (Simons et al., 2007). The block is moving 6 ± 3 mm/year eastward with respect to Eurasia Plate as estimated by Bock et al., (2003) or might be to 6-10 ± 1 mm/year according to Simons et al. (2007).

a. **Cretaceous Amalgamated Sundaland**

Sundaland is heterogeneous and was formed by the amalgamation of various continental fragments of different ages, where the oldest one was derived from Gondwana rifted in the Devonian and later docked with the Asian block in the Triassic (Metcalfe, 2017; Hall, 2017). This tectonic unit grew from the northwest to southeast by adding more fragments which later arrived from Australia in Late Jurassic (Hall, 2017; and Advokaat & van Hinsbergen, 2024). Based on the plate reconstructions, and as a lithospheric fragment, the Argoland conceptual continent consisted of multiple continental fragments, simply broke off the offshore northwestern Australian margin identified as the Argo Abyssal Plain, drifted away to the north towards SE Asia, and finally accreted at the Sundaland margin in the late Early Cretaceous to become the western part of the Indonesian Archipelago (Fig. 1)**.** As one of the continental fragments of Argoland, the East Java block specifically arrived in Sundaland during the middle to Late Cretaceous (Advokaat & van Hinsbergen, 2024). The contact between the Sundaland and East Java blocks is the subduction zone and magmatic arc outlined and originally introduced by Katili (1972, and in his Fig. 3) based on radiometric age dating of volcanic and granitic rocks in the onshore islands of western Indonesia and offshore islands.

Following the cessation of Cretaceous subduction, there are unknown geological records for the Palaeocene to Early Eocene period in Java. This is interpreted that the whole Java was in the form of denudation, where the landmass was above sea level. As the new subduction took place between Australian Plate and amalgamated Sundaland with East Java block (Fig. 1), the earliest volcanism began to occur besides initiation and structuration of East Java Basin, and well-developed deposition of lacustrine-to-shallow marine Ngimbang clastics at the base of syn-rift in Middle Eocene. The subduction continued with basement uplift, resulting in a Late Oligocene regional unconformity and the formation of Old Andesite calc-alkaline volcanic rocks, mostly in the southern coast of Java (Soeria-Atmadja et al., 1994, and in their Fig. 4). Late Oligocene to Early Miocene shallow marine carbonates were deposited widely, overlying the unconformity. The latest major tectonic activity occurred in the Late Pliocene, accompanied by volcanism, uplift, and erosion, followed by the presence of Quaternary volcanic cones along the modern Java Arc. This indicates that the southern part of the Sundaland rim was weak and was an active continental shelf throughout the Cenozoic period.

b. **Australian Plate Motion**

The use of numerous high-precision GPS measurements since the 1990s has accurately determined crustal motion. The oceanic crust of Australian Plate is subducting beneath the Java continental crust at a relative motion of approximately 70 mm/year to the NNE direction. The convergence of Christmas Island (XMAS site) with respect to West Java has an observed direction of N11° ± 4°E and an observed magnitude of convergence of 67 ± 7 mm/year which agrees with the rescaled NUVEL-1 plate velocity model prediction of 71 ± 2 mm/year (Tregoning et al., 1994). This direction of subduction is almost orthogonal to the Java Trench strike; therefore, there is no large strike-slip fault in Java, as is the case for the Semangko fault in Sumatra (Natawidjaja, 2021). Specifically, Simons et al. (2007) estimated that a portion of the fully orthogonal convergence of Australia to the Java Trench

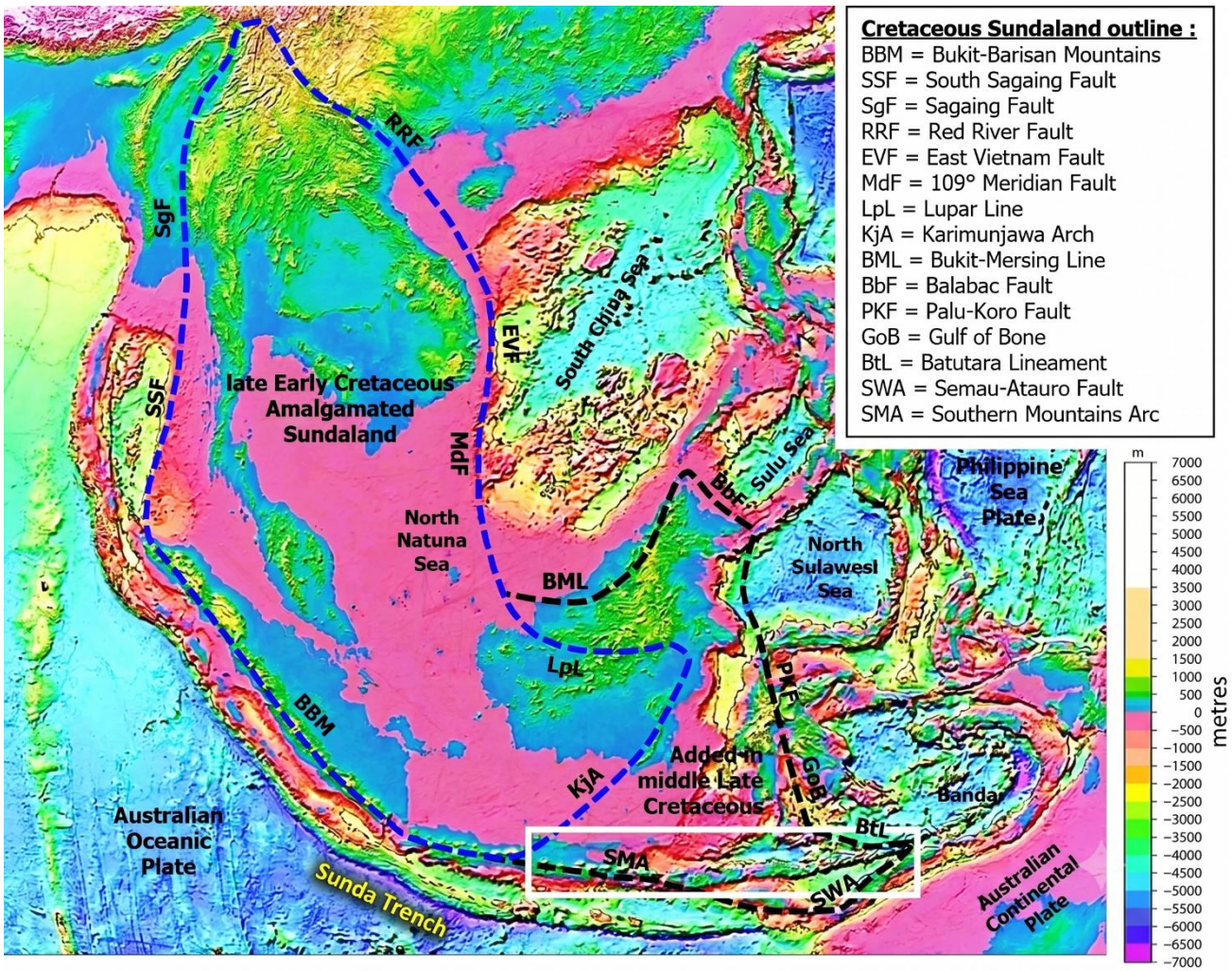


Fig. 1. *Outline of the East Java continental fragment added to the southeastern most part of the Early Cretaceous Sundaland, as marked by the black dashed line. The white rectangle is the focus area discussed in this paper. The TOPEX map was taken from http://topex.ucsd.edu/WWW_html/srtm15_plus.html.*

occurs at a longitude of 109°E–110°E with a motion of 67 mm/year at N14°E within Central Java. It becomes a small oblique towards east at N13° in the south of Bali with a velocity of 70 mm/year.

The convergence velocities increase from 60 ± 0.4 mm/year along the southern Sumatra Trench to 68 mm/year in Central Java (DeMets et al., 2010, and in their Fig. 48). The estimate of the convergence velocity rate of the GPS field survey for the BAKO site relative to the Australian Plate is 63.3 ± 0.4 mm/year in the N14.9° ± 0.5°E direction (Bock et al., 2003). At the same location, the prediction using the best-fitting velocities and MORVEL differed by less than 1 mm/year (=68 mm/year) and 1° (DeMets et al., 2010). The prediction of velocities by DeMets et al. (2010) and Jones et al. (2014) is shown in Fig. 2, and increases towards the Timor Trough to approximately 74 ± 2 mm/year (Genrich et al., 1996).

The number of seismicity increases and becomes shallower towards the south, closer to the Java Trench. Two large earthquakes followed by tsunamis have occurred in the past 20-year period. They produced a wave run-up tsunami height of approximately ten meters, killing several

hundred people. The most notable tsunamigenic earthquakes in the far southern coast of Java in the outer arc ridge near the Sunda Trench (Fig. 2) occurred on 2 June 1994 with a moment magnitude (*Mw*) of 7.8 offshore south of Banyuwangi in East Java, and another on 17 July 2006 with an *Mw* of 7.7 offshore south of Pangandaran in Central Java. Numerous published papers have discussed earthquakes and their implications in the region, for example Abercrombie et al. (2001); Hanifa et al. (2008); and Widiyantoro et al. (2020).

The subducting intra-slab depth range, specifically beneath the northern part of East Java and Madura areas at a longitude of approximately 109°E to 115°E, is under the interval of a pronounced gap of seismicity, as shown by the vertical cross-sections of the tomography profile (Xie et al., 2023). This seismic gap might be a potential future megathrust earthquake in the region located immediately north of the Kendeng back-thrust fault (Widiyantoro et al., 2020).

c. Compressional Stress Crossing Java Island Arc

The seismic energy movement crossing the Java Arc is indicated by the presence of several faults observed along the entire Java Island from west to east. For example: The west-east fault trend called Jawa Trend, is generally present in onshore Java towards east crossing Madura to the Kangean Island region (Pulunggono & Martodjojo, 1994, and their Fig. 8). The estimated age for this trend is Late Oligocene to Early Miocene, coinciding with the initiation of the Late Palaeogene Sumatra-Java subduction. This tectonic event, also observed as the pronounced Late Oligocene unconformity interpreted in seismic lines, resulted in faulting and extensive volcanism in the region along present-day South Java (Bolliger & de Ruiter, 1975).

The Java Trend has two main active west-east-oriented thrust faults: (a) the Baribis back-thrust fault in West Java (Natawidajaja et al., 2017; Damanik et al. 2021; Natawidjaja, 2021; Aribowo et al., 2022; and Widiyantoro et al., 2022); and (b) the Kendeng back-thrust fault in East Java (Natawidajaja et al. (2017). Koulali et al. (2017) indicated the estimated slip rate of the Baribis back-thrust fault at about 5 ± 0.2 mm/year for their kinematic model. The Kendeng back-thrust fault extension to the east of offshore eastern East Java has an estimated slip rate of 5 ± 0.4 mm/year (Koulali et al., 2016). Both the Baribis and Kendeng faults are the main inland back-thrust faults and are interpreted to extend to the west, crossing West and Central Java, to merge and become a regional back-thrust fault called the Baribis-Kendeng thrust fault (Natawidjaja et al., 2017) and Aribowo et al. (2022). This regional fault was originally introduced by Simandjuntak (1993, in his Figs. 1 and 7) and discussed by Simandjuntak & Barber (1996) as a part of the major back-thrust fault in Java and further east to Wetar.

There are several SW-NE active sinistral-slip faults in Java. For example, the most recent destructive earthquake in Central Java was caused by the Opak fault (Natawidjaja, 2016). The devastating Yogyakarta earthquake occurred on 27 May 2006 with a magnitude *Mw* of 6.4, located approximately 5-10 km east of the Opak fault. The estimated slip rate of the Opak fault is 5.7 mm/year (Natawidjaja, 2016). The slip rate of the co-seismic horizontal movement during the earthquake was estimated to be 80 cm in the sinistral direction, with dip-slip components of 26 cm along the earthquake fault length of 18

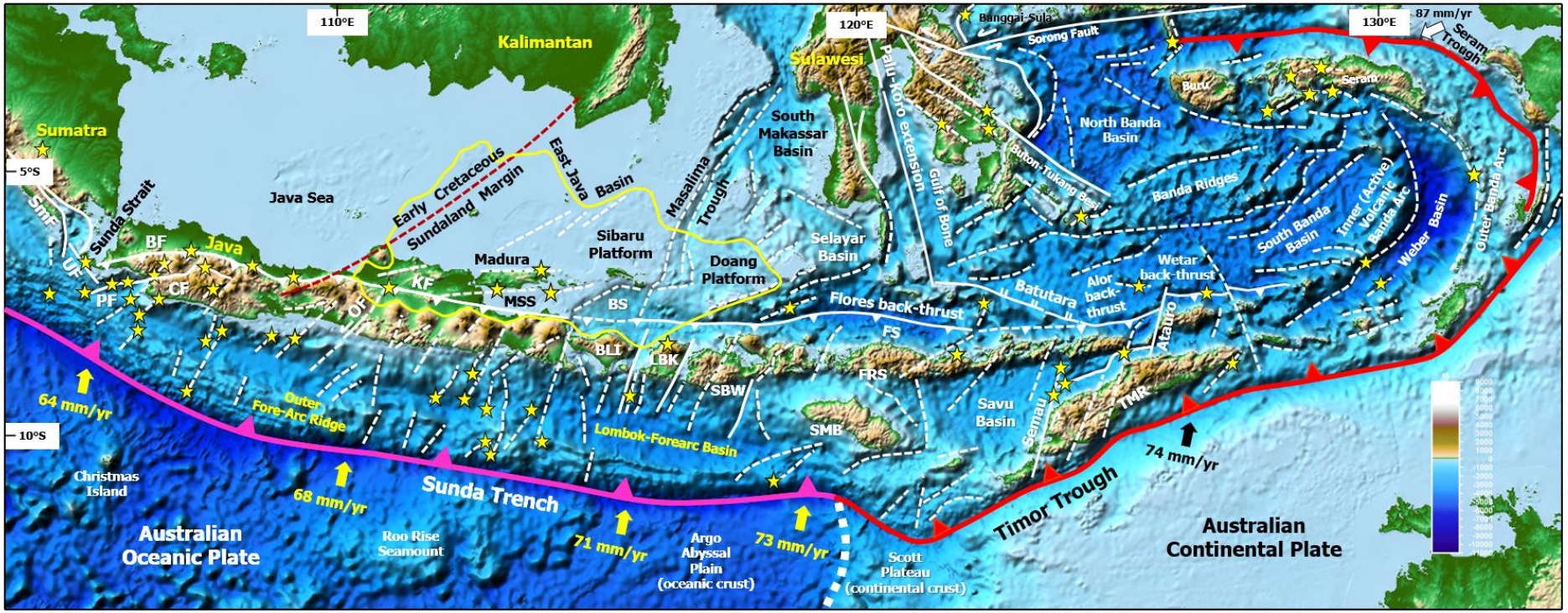


Fig. 2. *The onshore Baribis-Kendeng back-thrust fault extends to the east to merge with the offshore Kendeng-Bali-Flores-Wetar back-thrust fault; it is marked by white solid and dashed lines with solid triangles. White solid and dashed lines are lineaments and/or interpreted faults based on topography and bathymetry images. The locations of the recent earthquakes associated with interpretation of the lineaments are shown in yellow stars. Global relief model map was taken from https://www.ncei.noaa.gov/products/etopo-global-relief-model.*

km. The Opak fault extends offshore north of East Java and to the southern coast to become the western boundary of the Southern Mountains Arc with the Yogyakarta-Bantul Depression (Surono, 2009) in the eastern part of the Kebumen Depression. This arc is not present in Central Java (Fig. 3); however, it left a remnant of the Karangbolong High on the southern coast.

Other SW-NE orientations of strike-slip faults might also be present along the Southern Mountain Arc in the coasts of southern East Java, although they might not yet be fully observed. They are located on the coasts of SE Tulungagung, SE Lumajang, and the western end of the Blambangan Peninsula, as shown in Fig. 3. Perhaps these faults have already extended to the northeast, crossing the Java axis and influencing the development of modern volcanism, but are unrecognisable and have been buried by thick Neogene and Quaternary sediments. Immediately east of the onshore Lesser Sunda Islands, two SW-NE offshore faults are defined on the seismic profiles in the Lombok and Alas Straits (Silver et al., 1983, and in their Figs. 1, 15, & 16; Irsyam et al., 2017).

The structural interpretation of the topographic and bathymetric images along the Java-to-Lesser Sunda Islands arc suggests that there are many SW-NE orientations of lineaments that might be faults, as indicated by the current activity of the earthquakes (Fig. 2, marked by yellow stars). Some of these faults have recently ruptured, causing strong earthquakes and tsunamis, such as the great outer-ridge earthquake with a large tsunami in southern Sumba at the Sunda Trench (Mw=8.3 on 19 August 1977 reference in Gusman et al., 2009), the strong tsunamigenic earthquake of the ENE fault deviating from the west-east Flores back-arc thrust (Mw=7.8 on 12 December 1992 reference in Pranantyo & Cummins, 2019), and the Lombok back-thrust fault (Mw=6.4 culminating in Mw=7.0 on 28 July 2018 reference in Supendi et al., 2020b). The historical seismic activities generally occurred at shallow depth of < 70 km, for examples: Flores earthquake (1992) occurred at depth about 16 km, and Sumba earthquake (1977) focal depth at 21 km (NOAA). These geological settings along the eastern Sunda Arc have the potential to generate large tsunami earthquakes.

d. Cretaceous Sundaland Block Boundary: Southeast and East

At present, there are various interpretations of where the southeastern boundary of the Cretaceous Sundaland block should be placed in the context of the plate tectonics of SE Asia. Bock et al. (2003, and in their Fig. 4) and most of the published papers traditionally defined the southeastern margin of Sundaland as the Sunda or Java Trench (for example, Hall & Morley, 2004; Hall, 2014; and Metcalfe, 2017). Although it is not very clear to define the boundary, Simons et al. (2007, and in their Figs. 3 & 6) indicated that the southeastern boundary is defined by the southernmost part of the undeformed core of Sundaland which is north of the western part of Java, and toward the east bounded by a NE-oriented strike-slip (=Opak fault) at around 110°E. Simandjuntak (1993, in his Figs. 1 & 7); Simandjuntak & Barber (1996, in their Figs. 1 & 3); and Koulali et al. (2017, in their Fig. 1) defined the Baribis-Kendeng regional fault system as the convergence boundary of the Sundaland core and the Australian oceanic crust.

This paper considered the onshore Baribis-Kendeng back-thrust fault as the southern end of the late Early Cretaceous boundary of the Sundaland core (Figs. 1 & 3). Some

tectonic activities occur in the southeastern most part of the core with minor seismicity including some faulting and folding with mud diapirs. The region is the Rembang Zone in the northern part of the onshore East Java region, covering the Cepu region, onshore Madura Island, Madura Strait Sub-basin, and extending further to the east. For the simplicity of the detailed discussion in this paper, the region is defined as a "Transition Zone" to the Sundaland rim in the south. This zone is located immediately south of the North Madura Platform (Fig. 3), where the Cepu-to-Central High inversion is located.

To the east, Rangin et al. (1999); Socquet et al. (2006); and Simons et al. (2007) considered that the easternmost undeformed Late Cretaceous Sundaland core is the western coast of west Sulawesi while Charlton (2000); Bock et al. (2003); Hall & Morley (2004); Hall, 2014; and Argakoesoemah (2017) include the western part of Sulawesi or Makassar block, and Doang and Selayar block with boundary to the east by Palu-Koro strike-slip fault with its extension into southward suture in the Gulf of Bone as seen in the bathymetry expression. This study proposes to define the eastern crustal block boundary of the Late Cretaceous Sundaland core as the Bukit-Mersing Line (BML) – Balabac Fault (BbF) – Palu-Koro Fault (PKF) – Gulf of Bone (GoB) – Batutara Lineament (BtL) (Figs. 1 & 2). Further south, the boundary slightly extends to the east to the Alor back-thrust, follows the Wetar Atauro strike-slip fault to the south, and then follows the Semau strike-slip fault to the Semau-Atauro Fault (SWA), and finally to the Southern Mountains Arc (SMA) (Fig. 1). This crustal block became the East Java continental fragment added to the amalgamated Sundaland in the middle–Late Cretaceous. This continental fragment might be a mosaic consisting of sub-crustal blocks of smaller sizes, bounded by active block-bounding faults separating each sub-block. Note: The Early Cretaceous Amalgamated Sundaland outline covers the Bukit-Barisan Mountains (BBM) – South Sagaing Fault (SSF) – Sagaing Fault (SgF) – Red River Fault (RRF) – East Vietnam Fault (EVF)–109° Meridian Fault (MdF) – Lupar Line (LpL)–Karimunjawa Arch (KjA).

The Palu-Koro strike-slip fault is crucial as the Sundaland core boundary. Recently, the Palu "supershear" earthquake occurred on 28 September 2018 in the Palu region in Central Sulawesi with a mainshock magnitude *Mw* of 7.5, accompanied by a tsunami and massive liquefaction in the Palu Bay region (Supendi et al., 2020b). This devastating earthquake was caused by the activity of the Palu-Koro sinistral strike-slip fault orienting in the NNW-SSE direction and later shifting to the east, merging with the Matano strike-slip fault. Natawidjaja et al. (2021) conducted comprehensive geological and geophysical investigations of the Palu-Koro fault in the Palu region. The quake ruptured 177-km long multi-fault segments including a 110-km submarine fault line, and continued inland for 67 km.

It is interesting to note that the development of a large seamount complex begins growing on seafloor in the foot-wall of the Flores back-thrust in the region between eastern offshore of north Flores and Batutara lineament as shown by the seafloor bathymetric image, Fig. 2. This is interpreted as the boundary line between the Sunda Arc to the west and the South Banda Basin to the east. The Batutara lineament could be an oblique fault in the NW-SE sinistral shear orientation with an expected down-thrown component to the east into the Banda oceanic crustal block. Consequently, the Batutara lineament became part of the eastern end of the East

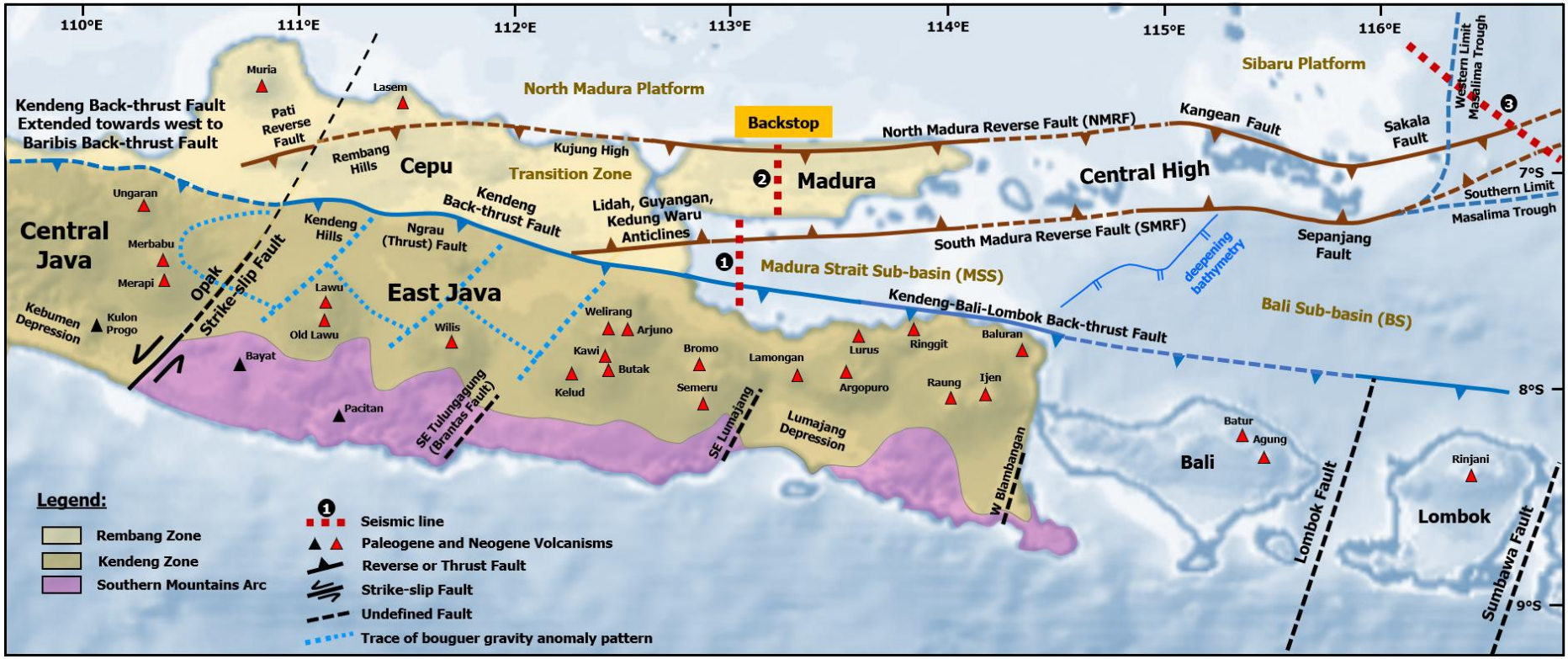


Fig. 3. *The Cepu-to-Central High inversion is located in the Transition Zone bounded by NMRF and SMRF. The 2D seismic lines in the Madura Strait sub-basin indicate that the onshore Baribis-Kendeng back-thrust fault switches to the east-southeast and merges with the offshore Kendeng-Bali-Flores-Wetar back-thrust.*

Java continental fragment. In fact, the Batutara region is a triple-junction complex of active tectonic settings among Sundaland, Australian (oceanic and continental), and Pacific plates. Does this geological phenomenon also indicate that the South Banda Basin partially collided to the southwest of the Batutara lineament and Alor Island, or perhaps a product of tearing of the subducting plate in Batutara?

e. Southeast Sundaland Rim: Kendeng Zone

The region south of the Baribis-Kendeng back-thrust fault to the Java Trench is interpreted to be the Sundaland rim. The rim generally covers the strongest damage zone, receiving the most immediate horizontal forces from the Java Trench. It is tectonically active and the weakest zone along the southeastern margin of the Sundaland core in the south. It was severely deformed, as shown in Fig. 3. This includes the Kendeng Zone, Southern Mountains Arc, and all areas south of offshore East Java to the Java Trench. In this belt of the deformation zone, there are volcanic and tectonic activities, including intense seismicity with large earthquakes, many active volcanoes, and intense folding and faulting in the overlying part of the overriding continental crust of Sundaland. Simandjuntak & Barber (1996, and in their Fig. 9) and Koulali et al. (2017) defined this deformed Sundaland zone as the Mesozoic Accretionary Complexes.

At the surface, the Kendeng zone consists of Neogene to Quaternary deep marine sediments, mostly argillaceous clastics and volcaniclastics (de Genevraye & Samuel, 1972). The fault has been interpreted to occur at the time of the major tectonic phase during the Plio-Pleistocene. The Java subduction activity is likely responsible for the northward continuous compression, causing the Kendeng zone to be uplifted and faulted until present day, and partially forming the Kendeng anticlinorium.

Several mud volcanoes are also present in the region, generally controlled by associated faults. This uplift marks the Plio-Pleistocene unconformity and volcanism. de Genevraye & Samuel's (1972) field survey also reported the frequent presence of tightly folded with steep, vertical or reverse-flanks, and longitudinal northward thrust faults parallel to the west-east anticlinorium axis. These reverse faults are transversely cut by numerous deep-seated trending strike-slip faults, either NW-SE or NE-SW, oblique to the Kendeng zone axis, resulting in several transversely delineated blocks. The tectonic activity appears to decrease in the eastern region.

There are two Tertiary magmatic belts observable in the Kendeng zone (Soeria-Atmadja et al., 1994 and in their Fig. 4) in the Sundaland rim; (1) Late Eocene-to-Early Miocene or Paleogene in the Southern Mountains Arc, and (2) Late Miocene-to-Pliocene or Neogene in the Kendeng zone, Fig. 3. The most dominant feature in the Kendeng zone is the presence of a west-east trend of active modern volcanoes along the axis of onshore East Java. Evidence of Palaeogene volcanism was observed in outcrops in the Southern Mountain Arc in the regions of Kulon Progo, Bayat, and Pacitan due to Late Neogene uplift. Palaeogene volcanism consists of island-arc tholeiitic lava flows, whereas Neogene volcanism consists of medium-K calc-alkaline magmatism (Soeria-Atmadja & Noeradi, 2005). The Paleogene volcanism trending SW-NE follows the Luk Ulo - Meratus trend or Early Cretaceous Sundaland margin, and is consistent with pattern of the bouguer gravity contours and values immediately south of the Kendeng back-thrust fault, Fig. 3; while the Neogene

volcanism follows the Java Trend in west-east direction.

SEISMIC INTERPRETATION AND THE EXTEND OF REGIONAL FAULTS

Based on regional seismic interpretation, folding and thrusting appear to be the main structures in the modern East Java Basin. The north-south 2D seismic cross-sections from the southernmost Sundaland core (or North Madura Platform) to the Transition Zone consisting of onshore Madura Island and Madura Strait Sub-basin (MSS) show three (3) major thrust faults with strike in west-east direction: North Madura Reverse Fault (NMRF), South Madura Reverse Fault (SMRF), and Kendeng back-thrust fault (KBTF), Fig. 3. The north-south 2D seismic line crossing the MSS suggests that the sub-basin has been down-warped by two (2) thrust faults: the SMRF in the north and the KBTF extension in the south.

The quality of the 2D seismic lines across the onshore Madura Island are generally poor. The dense population on the island and numerous "rumpon" or traditional fish traps near the island have hampered the implementation of a new 2D or 3D seismic acquisition program, particularly for deeper targets. However, by combining seismic interpretations in the north and south of the island, and surface geology, the confidence of the presence of a large pop-up structure over the whole Madura Island region has improved. The top Kujung carbonates have been used as the key horizon to divide seismic stratigraphic sequences. The Shuttle Radar Topography Mission (SRTM) topography and bathymetry surfaces, in addition to relevant Geological Research and Development Centre (GRDC) surface geological maps, have been utilised to provide a better definition of the fault termination and Cenozoic stratigraphy.

Although published geological and seismic interpretations are generally inconsistent with each other along the fault length, they are useful for observing the extent of the faults, as shown in Fig. 3. Better seismic images with recent interpretations are available in Fu-zhong et al. (2011), Granath et al. (2011), and Weimin et al. (2019). Whenever possible, an attempt to re-interpret some better images of the 2D seismic lines was made solely without sufficient ties to other lines to see the existing structures.

a. North Madura Reverse Fault (NMRF)

The north coast of Madura Island is interpreted to be a "static Madura backstop" for any northward horizontal stress received by the Transition Zone due to subduction along the Java Trench in the south (Fig. 3). The backstop roughly, structurally infers as a west-east oriented basement fault although it is difficult to recognise it seismically due to the lack of continuous seismic lines crossing the backstop and the island.

Although the seismic lines are generally of poor quality, the fault is interpreted to be indicative of a dip-slip reverse fault and thus becomes the NMRF. A recent 2D seismic interpretation across north-south onshore Madura Island by Fu-zhong et al. (2011) also showed that the fault is a dip-slip reverse fault which later its hanging wall has been experienced with other strong complex of thrust faults and some reactivated older normal faults produced a large pop-up structure as shown in Fig. 4.

The pre-NMRF basement fault is interpreted to have originally been intermittent and active, probably during the Late Eocene to Early Miocene, owing to

tensional stresses, as indicated by the East Java depositional facies and paleogeographic reconstructions. Later, the fault was reactivated to be a dip-slip reverse fault in Latest Miocene to Early Pliocene as suggested by seismic interpretation shown in Fig. 5, and GRDC surface geological maps of Madura Island by Azis et al. (1992), Supandjono et al. (1992), and Situmorang et al. (1992); and also the most recent surface map by Htwe et al. (2015).

Structurally, it should be noted that the NMRF bounded Madura Graben, later in Plio-Pleistocene during compression and uplift could regionally connect to the Kendeng thrust to be part of a Kendeng decollement, and became basal-detachment surface of south-dipping thrust of the Kendeng back-thrust fault extent in response to the northward continuous horizontal compressional stress from Java Trench, Fig. 3.

Further west, there are several relatively parallel anticlinal and synclinal structures generally oriented in the WNW-ESE direction in the Rembang Hills, just west and north of Blora, as seen in the SRTM topographic images and GRDC surface geological map of the Rembang quadrangle (Kadar & Sudijono, 1993). These structures are possibly caused by the combined activities of the NNE-extended segment of the Opak strike-slip fault and the western part of the NMRF (Fig. 3). Hence, this westernmost tail of the NMRF is interpreted to be the same as the Pati reverse fault. This WSW-ENE Pati reverse fault is proven to be active, as indicated by some shallow earthquakes in the 1800s and recently in 2019. The slip rate of this reverse fault is estimated to be 0.1 mm/year (Sulaeman et al., 2020). Note: The name of the Pati reverse fault discussed in this paper is sometimes interchanged with the Lasem fault in published papers.

Manur & Barraclough (1994, and their Fig. 4) introduced a Rembang-Madura-Kangean (RMK) wrench zone as a major sinistral shear zone covering over the northern half of onshore Madura. The zone was bounded by the southern shelf edge of the North Madura Platform to the north. This RMK zone extends westward through the Kujung thrust belt and finally to the North Rembang zone. To the east, the zone extends south of the Kangean High. Hence, Manur & Barraclough (1994) interpreted the northern boundary of the zone as a sinistral strike-slip fault that might also merge with their Sakala strike-slip fault in the Kangean-Sakala area. Furthermore, Satyana et al. (2004) extended the RMK wrench zone to the east to include the Sakala offshore area to become the Rembang-Madura-Kangean-Sakala (RMKS) fault zone. The wrench zone extends from Rembang area in the onshore East Java in the west to the offshore Kangean-Sakala region in the east, with a total length of at least 600 km.

The most recent seismic interpretation across the onshore Madura Island, for example, was published by Fu-zhong et al. (2011), as shown in Fig. 4. This north-south section shows the presence of a series of uplifted Tuban fold and thrust faults forming thin-skinned deformation with a detachment. These structures overlay the reactivated normal faults of the pre-Kujung or Tawun and basement, which were subsequently inverted. This seismic interpretation clearly portrays a strong northward continuous push of the orthogonal horizontal stress, resulting in a strong Madura inversion with no sense of lateral slips and no obvious flower structures. Furthermore, the stress favoured early thin-skinned deformation.

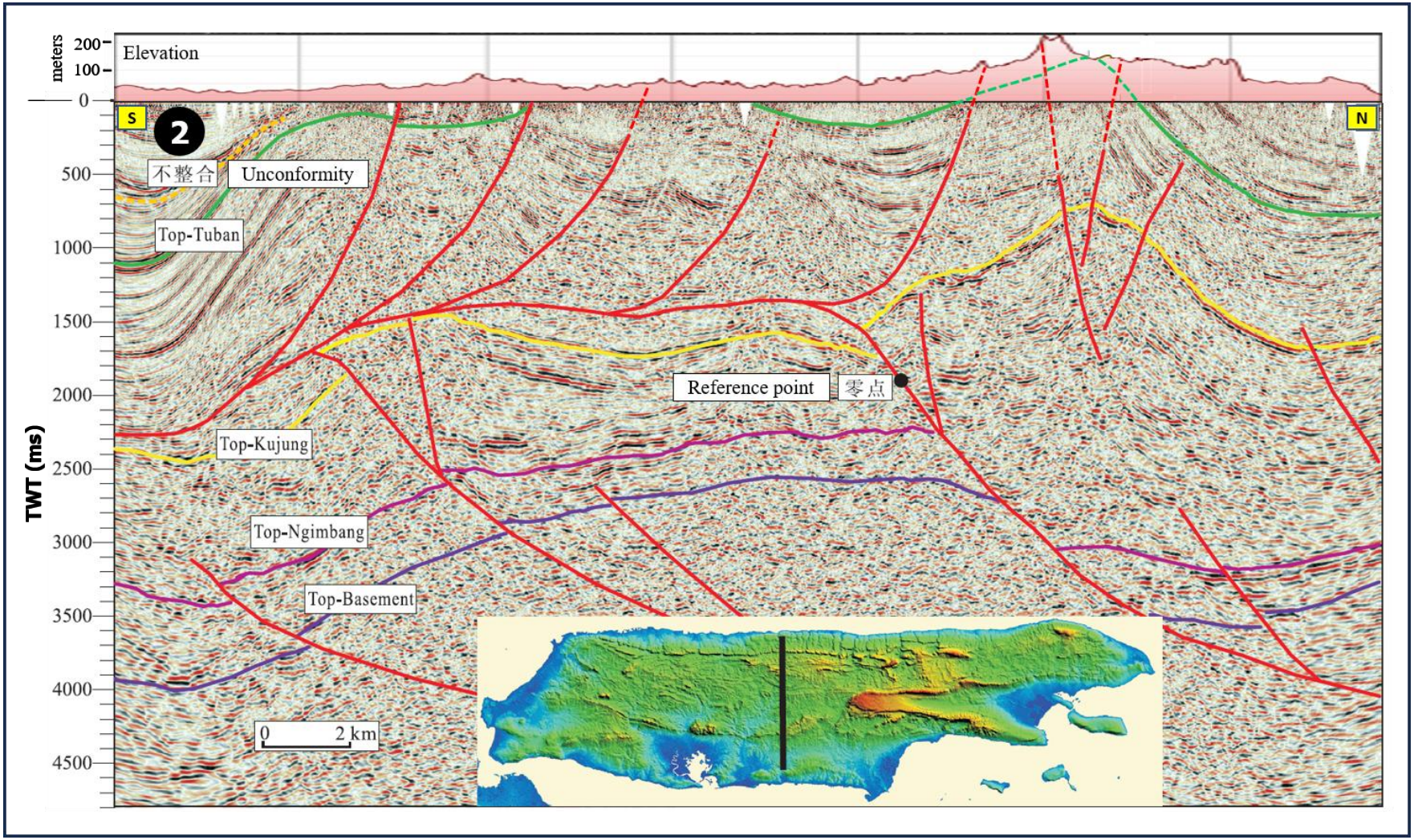


Fig. 4. *A published 2D seismic interpretation across onshore Madura Island showed the complexity of the structural development. This clearly suggests that a strong northward continuous compression of the orthogonal horizontal stress resulted in strong inversion with no sense of lateral slips and no obvious flower structures. Note: Elevation is added along the 2D seismic line, and the Tuban horizon and faults are extended in dashed lines to illustrate the formation cropped-out at the surface. Original seismic interpretation was from Fu-zhong et al. (2011) and the original notes were translated by the current author.*

Similarly, by utilising the pre-stack depth migration seismic line, Mitra (2004) interpreted the Sakala structure as a fault-related inversion structure resulting from north-south extension compressed in the same general direction. The structure was formed along the south-dipping Sakala Fault, as shown in Fig. 3. According to Mitra (2004), the Sakala structure is interpreted to be an inverted structure formed by the Late Neogene compressive reactivation of the early Middle Eocene extensional structure. The Sakala Fault is a compressive reactivation of a normal fault that occurred by fault-bend folding and was accompanied by fault-propagation folding. Similar reactivation of the compressive normal faults also occurred on the Kangean and Sepanjang faults.

Eastward, the NMRF exists and extends further, crossing the southern end of the NNE-SSW Masalima Trough (Figs. 2, 3, & 6). Consequently, the NMRF merges with the Kangean fault just north from the Kangean Island to be a NMRF-Kangean thrust fault as the northern boundary of the Paleogene feature in the southern Sibaru Platform. Further towards east, this fault merged with the Sakala fault and terminated at Doang Platform as indicated by the images of topography and bathymetry relief model map. This has been clearly shown by a long-offset, long-record crustal-scale 2D seismic survey completed in early 2008 in the Java Sea (Granath et al., 2011).

b. **South Madura Reverse Fault (SMRF)**

The 2D seismic line shows the development of a reversed-fold tip immediately above the main SMRF thrust fold suggesting continuous strong energy to force the MSS northward to the SMRF. This has been partially transmitted upwards through the up-thrown side or hanging wall of the thrust, resulting in an inverted formation, as indicated by the growth of a rim syncline and a continuous anticlinal bulge to the north (Fig. 5), and is continuous until the present day. The strong and relatively rigid MSS, specifically the Madura Strait Platform (MS Platform) as a structural flat-lying platform with thick aggraded sediments immediately in the south, has likely played an important role in developing the fold and thrust of the SMRF, and in contrast to much thicker sediments but flexible sediments, the southern part of the Rembang zone to the north.

The north-south 2D seismic line indicated that the pre-SMRF characteristic of tension began active in Late Oligocene to early Early Miocene during and controlling the deposition of the Tawun Formation in the Madura graben (Fig. 5). Later, the pre-SMRF normal fault was reactivated to be a reverse fault or SMRF. This reverse fault is interpreted to mainly occur during early deposition of the Madura Formation, approximately in the Latest Miocene to Early Pliocene. Furthermore, the Early Miocene Tawun Formation and younger formations have been cropped out at the surface on Madura Island (Htwe et al., 2015).

To the west, the SMRF is consistent with high gravity anomalies and patterns of onshore (w)-to-offshore (e) East Java, and holds the Lidah, Guyangan, and Kedung Waru anticlines in eastern onshore East Java, as shown in the GRDC geological map of Surabaya (Supandjono et al., 1992). These anticlines are interpreted to form as a result of the western end of the SMRF terminating and merging with the Kendeng back-thrust fault (Fig. 3). The Ngimbang anticline located immediately west of the Lidah anticline is likely also folded and inverted to surface due to the impact of this SMRF.

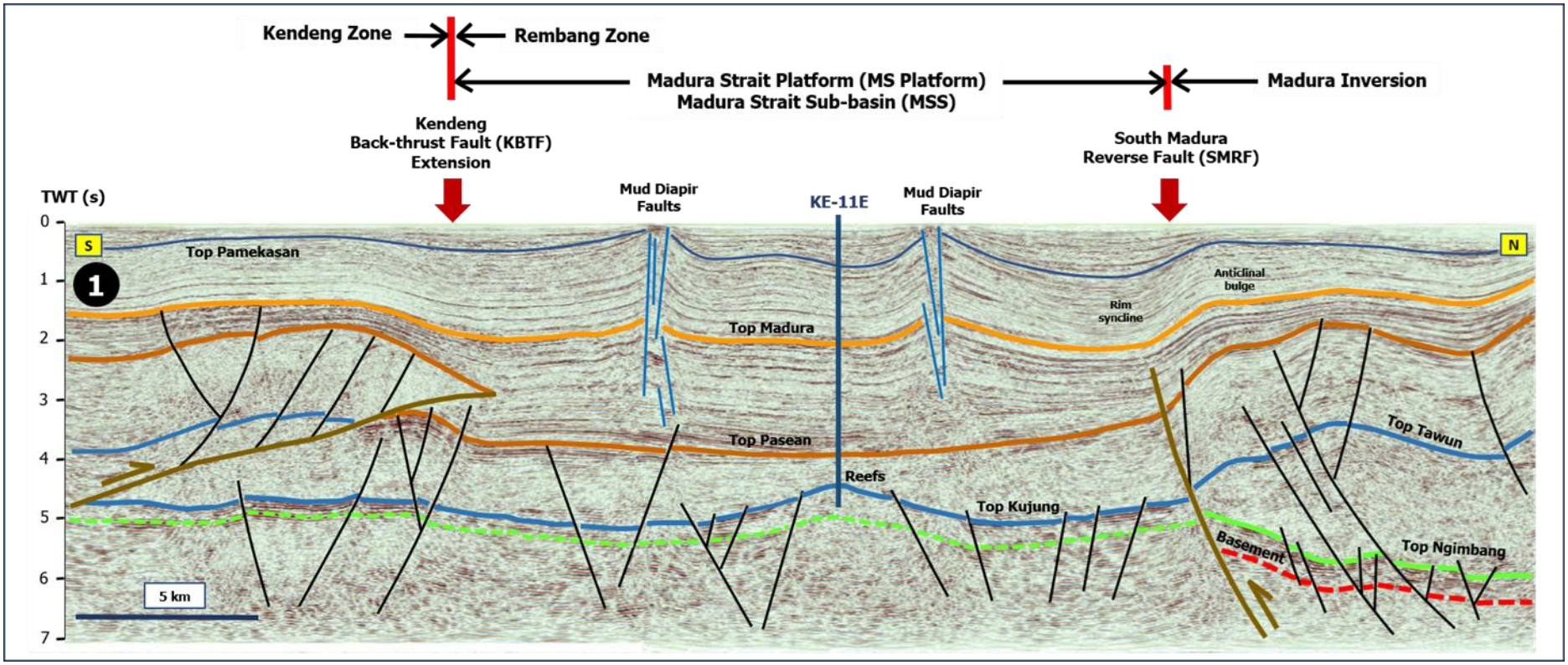


Fig. 5. *Re-interpretation of a north-south 2D seismic line acquired in the Madura Strait sub-basin (MSS). The original interpretation is available in Weimin et al. (2019). The KBTF is an active growth structure formed a "blind-thrust" fault system with a fault plane dip of < 45°. Both the KBTF and SMRF are interpreted to have occurred in the Early Pliocene. Seismic interpretation was modified by the author after Weimin et al. (2019).*

Towards east, the SMRF presence has also been observed and merged with the Sepanjang fault causing Kangean uplifted with abrupt lows toward south into Bali Sub-basin. Further to the east, this SMRF-Sepanjang thrust fault crossed the southern end of the Masalima Trough and also became the southern end of the Sibaru Platform (Figs. 2, 3, & 6). Finally, this fault terminated in the Doang Platform. Perhaps all of the faults orienting north-south in the Masalima Trough might be terminated to the south at this SMRF-Sepanjang thrust fault system.

It should be noted that both SMRF and NMRF with the total length of about 600-750 km each as shown in Fig. 3 are two distinct reverse fault systems. Both are not simple fault traces, but each fault may have many separate en echelon fault segments. Another note is that the NMRF- and SMRF-bounded Cepu-to-Central High inverted graben are unlikely to be related to the development and result of the microplate rearrangement in the east, for example, East Sulawesi.

c. Offshore Kendeng-Bali Back-thrust Fault (KBTF)

As observed in the 2D seismic lines, the back-thrust fault is present in the back arc of collision zone of the Sundaland rim along the central and east Sunda Arc. The back-thrust fault developed due to continuous stress transfer from Sunda subduction in the south perpendicular to the Sunda Arc chain, and the change of subduction mode in the west and central Sunda Arc to collision toward east to the Timor Trough. This is in contrast to the lack of back-thrust faults in onshore Sumatra due to oblique subduction where the stress associated with the subduction is absorbed by dextral strike-slip fault zone of the Great Sumatran Fault (Widiyantoro et al., 2024).

Geologically, the Baribis-to-Wetar back-thrust fault can be subdivided into three (3) segments based on the nature and associated structure of the thrust. The first segment is the onshore Baribis-Kendeng back-thrust fault along onshore of West-to-East Java; it has been discussed above. The second segment is the offshore Kendeng-Bali back-thrust fault, covering the MSS region offshore northern Bali (KBTF). Hence, the geological interpretation of the 2D seismic lines in the MSS indicates that both onshore and offshore back-thrust fault systems are clearly outlined and strongly interconnected in a west-east orientation (Figs. 2 & 3). The third segment is the offshore Lombok-Flores-Wetar back-thrust fault (FBTF). These three segments are clearly well-interconnected seismically and likely to develop at the same time.

The onshore Baribis-Kendeng back-thrust in Java physiographically separates the outcrops of the Pliocene and Older sequences from the Quaternary sediments. In West Java, the Baribis back-thrust fault was assigned to the Pliocene to Recent (Aribowo et al., 2022). The Kendeng back-thrust fault in East Java is equivalent to the Ngrau (thrust) fault determined by surface geology, as shown in the GRDC geological map of the Bojonegoro quadrangle (Pringgoprawiro & Sukido, 1992), and the fault was considered to occur in the Late Pliocene. By utilising the regional SRTM topography images, the fault regionally extends to the west and east in the WNW-ESE orientation. In onshore East Java, the Kendeng back-thrust structurally separates the Rembang and Randublatung zones to the north from the uplifted Kendeng zone in the south, Fig. 3**.**

As the first segment, the onshore Baribis-Kendeng back-thrust fault suggests a regionally continuous eastward and merges with the second segment. The fault clearly

swings in the ESE orientation into the MSS, as defined by some 2D seismic lines, as shown in Fig. 3. The north-south section of the 2D seismic lines in the MSS shows that the KBTF formed a "blind-thrust" fault system with a fault plane dip of < 45° (Fig. 5). Over the MSS, the KBTF is an active growth structure with syn-kinematic succession showing sediment thickness variation, a thrust ramp structure, and progressive unconformity pinching-out against the thrust sheet. The growth is interpreted to have occurred during the syn-deposition of the lower Madura Formation approximately in the Early Pliocene and continued until present-day; however, the fault activities diminished and were insignificant during the deposition of the Pamekasan Formation in the Pleistocene.

The KBTF low angle blind-thrust is also observed in the 2D seismic lines acquired in 2001 in the region offshore north of Bali (Xue et al., 2002), along the back-thrust strike, it continued to develop to the east in the offshore north of Lombok. The thrust sheets show a "model" of possible thin-skinned thrust fault system in northward-propagating thrust with piggy-back syncline and back-thrust limb. The top roof is placed by the Plio-Pleistocene Madura Formation. This nature of the fault, combined with the northern end of the Lombok fault, might be one of the causes of the devastating and tsunamigenic earthquakes that occurred in 2018.

d. Offshore Lombok-Flores-Wetar Back-thrust Fault (FBTF)

The KBTF back-thrust system is continuous further east, merging with the third segment in offshore Flores-Wetar (Fig. 2) at varying fault dips. The total length of this active "mega" back-thrust system of the Baribis-Kendeng-Bali-Flores-Wetar chain is approximately 2500 km.

The 2D seismic interpretation suggested that the KBTF twin low-angle blind-thrusts observed in the offshore Bali Sub-basin changed their thrust style to the east into the FBTF segment. Hence, the fault thrust-tip line has broken all the way to the seafloor to be emergent thrusts to form fault propagation folds starting in offshore north Lombok. A regional seismic line also recorded the structure (Matthews & Bransden, 1995, in their Foldout 1). The most recent 2D seismic interpretation of the region indicated that these twin thrusts lined up into complex thrust sheets, as seen offshore north of Sumbawa (Yang et al., 2020). It should be noted that the blind thrust in offshore north Bali could emerge from the seafloor and trigger large earthquakes and tsunamis in the future.

The bathymetric feature is very different from that in offshore Flores towards west of offshore north Bali (Fig. 2). The geological interpretation of the FBTF marine bathymetric images indicates the presence of the deepest seafloor with a strong sutured line, which is invisible in offshore north Bali. The sutured line gradually changed eastward to a very narrow and almost straight line in the west-east direction, forming a strong distinct lineament over the Flores Sea. This is consistent with the map outlining a complex of multi-back-thrusts on seafloor using modern 2D seismic lines by Yang et al. (2020) over the offshore north Bali to Sumbawa.

The presence of offshore Sumbawa-to-Flores and Alor back-thrust faults were included by Hamilton (1979) in his tectonic map of Indonesia region. Silver et al. (1983) originally interpreted and introduced the extent of propagation of the FBTF further

west to offshore Lombok and the Bali Sub-basin and east to Flores and Alor-Wetar based on seismic reflection profiles. Tomographic imaging also showed a south-dipping back-thrust in the region, as discussed by Widiyantoro & Fauzi (2005) and Widiyantoro et al. (2011). Magnetic and gravity modelling also showed the presence of a back-thrust (Zubaidah et al., 2014). The extent of the Alor back-thrust to Wetar is cut by the Wetar-Atauro sinistral strike-slip fault (Breen & Silver, 1989), as is also clearly shown in the seafloor bathymetry images in Fig. 2. The offset movement of the strike-slip was significant, approximately 50 km.

For the amount of shortening of the FBTF, Silver et al. (1983) interpreted approximately 30 km of shortening or 60 km at the most for the Flores back-thrust fault, while the crustal shortening for Wetar is less than 10 km. The back-thrust in the Bali Sub-basin is estimated to have a seismic slip rate of 4 ± 2 mm/year over the past 25 years (McCaffrey and Nabelek, 1987), but the slip rate in the offshore central Flores was estimated to be 0.8 ± 0.1 mm/year (McCaffrey, 1988). The Alor-Wetar back-thrust fault is interpreted to have occurred in the Pleistocene (Hinschberger et al., 2005).

***e.* Flores Subduction Initiation**

TOPEX gravity-magnetic and SRTM bathymetry maps and 2D seismic interpretations indicate that the Flores Sea could be an oceanic crust. The crust becomes thicker and shallower and finally transitions to become the continental crust to the west offshore of north Bali, as seen in the 2D seismic lines. The presence of oceanic lithospheric crust in the offshore north Flores was indicated by previous researchers, for example: Curray et al. (1977); Hamilton (1979 as discussed on page 121 and Fig. 56C); Silver et al. (1983); McCaffrey & Nabelek (1984, 1987); Prasetyo (1992); Granath et al. (2009, and their Figs. 2 & 9); Zubaidah et al. (2014, and in their Fig. 7); Supendi et al. (2020a, and in their Figs. 3 & 4); and Andikagumi & Bradley (2024, and in their Fig. 5).

Hamilton (1979) introduced the presence of Flores Trench dipping southward as an incipient arc reversal, and similarly Silver et al. (1983), for the presence of subduction polarity reversal. However, another interpretation is that the Flores Basin is a back-arc basin caused by eastern Sunda subduction, while the eastern Sunda volcanic arc emerged in the Late Miocene (kinematic model of Hinschberger et al., 2005). A similar interpretation was suggested by Widiyantoro & Fauzi (2005); and Hall & Spakman (2015), who stated that the basin is a complex back-arc basin related to the Pliocene collision in the Timor Trough; therefore, it is unlikely to be underlain by oceanic crust. Part of the reason is that the dimensions of this Flores trench-like basin are considered to be very narrow and short, although its seafloor is sufficiently deep at approximately 6000 m.

The seismic earthquake zone dipping southwards from the Flores Sea is shallower than 30 km, suggesting that it only penetrates the upper mantle; therefore, the Flores subduction remains unresolved (McCaffrey, 1988). Zubaidah et al. (2014) indicated that the very young age, shallow earthquake depths, and thin oceanic crust caused the Wadati-Benioff zone to be unclear. The oceanic crustal thickness to Moho is approximately 10 km (Granath et al., 2009, in their Fig. 2). A tectonic model cross-section of an arc-continent subduction initiation was introduced by Yang et al. (2020) based on 2D seismic images and seismicity beneath Lombok.

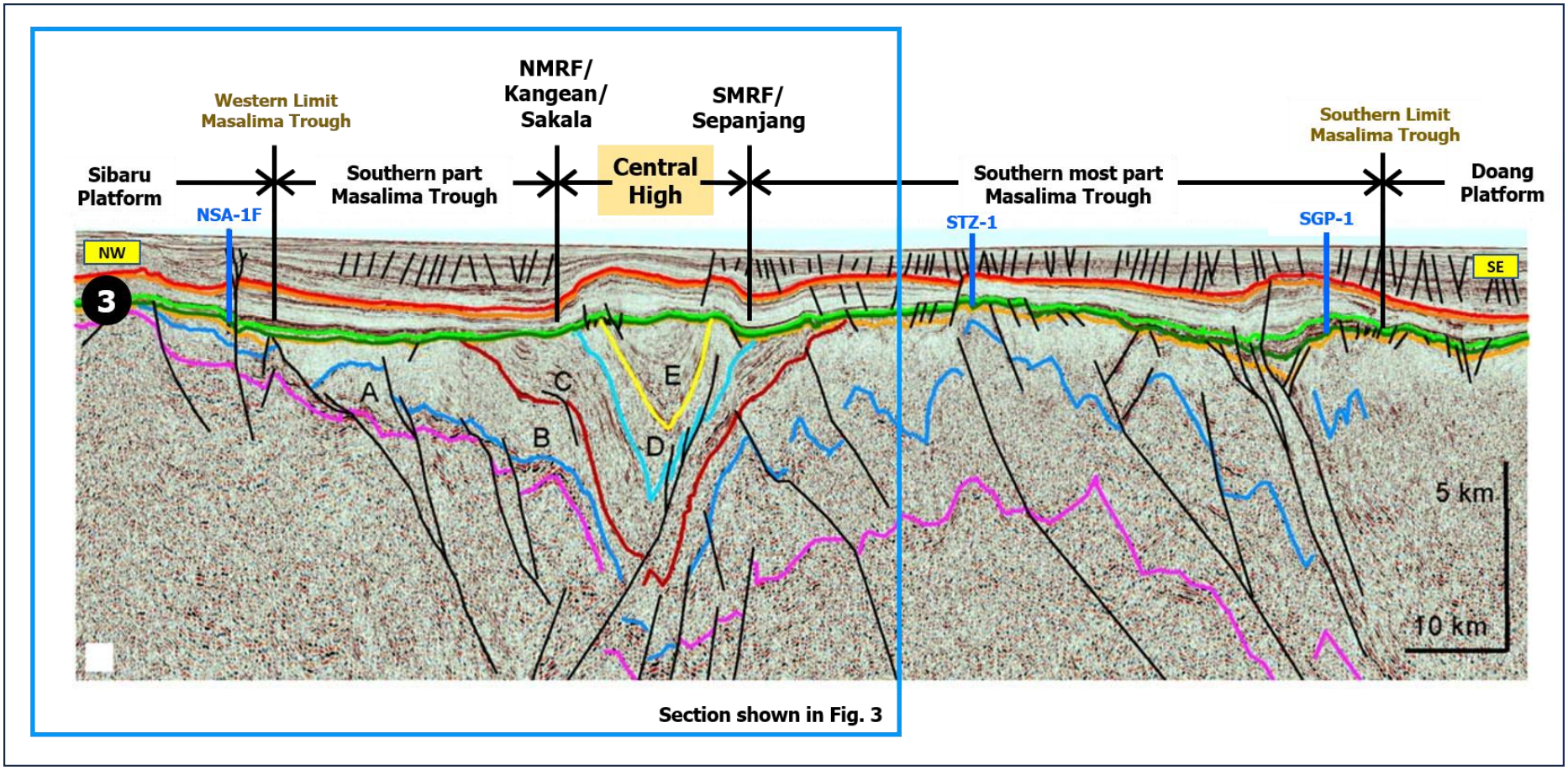


Fig. 6. *The northwest-southeast 2D seismic line showing the eastern end of the Cepu-to-Central High inversion structure crossing the Masalima Trough. Seismic horizons: Red = Early Miocene and Light green = Mid-Eocene. The lithostratigraphy of horizons A to E is assigned to the Pre-Cambrian to Paleozoic in age by Granath et al. (2011). Original seismic interpretation was from the same authors, while the geological feature names were added by the current author.*

Integrated magnetic and gravity modelling and tomographic imaging responses along offshore north Sumbawa and Flores suggested the presence of a subduction initiation (Zubaidah et al., 2014; and Supendi et al., 2020a, in their Figs. 3 & 4). Images of the 2D seismic lines crossing offshore north Sumbawa from Yang et al. (2020) and Andikagumi & Bradley (2024, and in their Supporting Information) show the beginning of an arc-oceanic subduction. Immediately to the east, it switches to an intra-oceanic subduction initiation, as illustrated in Fig. 7b. The change of subduction initiation is consistent with the change of lithospheric crusts from continental crust in the offshore north Lombok to the west, to transitional with a narrow oceanic crust over offshore north Sumbawa, and finally to well-developed oceanic crust over offshore north Flores (Fig. 7a).

The mechanism of Flores intra-oceanic subduction initiation is interpreted to originally begin with a very short period of opening as a back-arc basin due to tectonic activities in the Sunda subduction and Timor collision in the south. Hence, the possible presence of a subduction roll-back induced back-arc basin formation should not be ruled out. These tectonics, with northward and continuous compressional stress, together with the KBTF impact propagating to the east, resulted in an intra-oceanic subduction initiation in the form of a Flores "nascent" trench stage. Its subduction line occurs along the west-east back-thrust fault strike as a weak zone starting offshore north Lombok in the west to the east toward Batutara. Fig. 7b shows a sketch of the tectonic model for the Flores subduction initiation crossing Sumbawa and Flores.

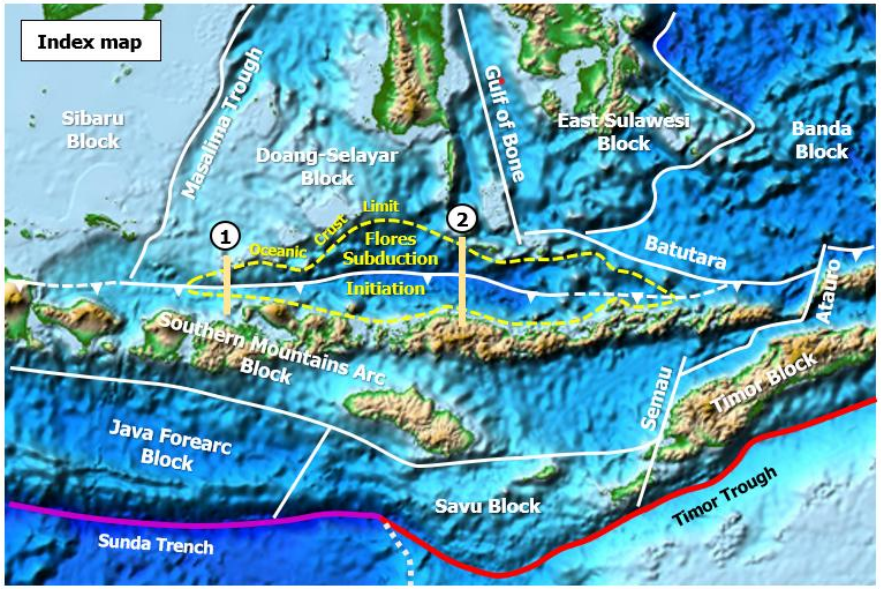
Specifically, collision of the Scott Plateau propagated continuous stress in NNW orientation to Sumba and Flores, and this finally transmitted to the Flores back-thrust fault development, Fig. 2, in Early Pleistocene (Roosmawati & Harris, 2009, and in their Figs. 3 & 12; and Harris et al., 2009). The probability of subduction initiation is likely greater for a young oceanic crust, such as the Flores Basin. This occurred at nearly the same age as FBTF development in the post-Early Pleistocene. The block-bounding faults assigned to the Late Cretaceous East Java continental fragment in the eastern Sunda Arc are also shown in Fig. 7a.

BRIEF TECTONO-STRATIGRAPHY OF THE EAST JAVA BASIN

The East Java Basin is located in the SE Sundaland active margin and was initiated in the Palaeogene and developed during the Cenozoic. Geologically, it is located in a trench-parallel back-arc of the Java Trench (Fig. 2). The discussion in this paper will mainly focus on the region south of the "backstop" line, Fig. 3.

Typically, the onshore East Java structural zones, stratigraphy, and sedimentary depositions are generally reflected by their on-land physiography extending in a broad west-east orientation. van Bemmelen (1949, vol IA, mainly on pages 29-31) introduced the terminology of East Java regional physiography divided into five zones which each of zone has specific geology and attribute. From north to south are Rembang, Randublatung, Kendeng, Volcanic Arc, and Southern Mountains Arc (Fig. 3). This study included the Randublatung zone in Rembang for simplification.

The northern most part is occupied by the Rembang zone covered by relatively rigid



The block-bounding faults assigned for the Late Cretaceous East Java continental fragment in the eastern Sunda Arc, are shown to illustrate relative tectonic block and sub-block movements in response to the continuous compressional forces from Sunda subduction and Timor collision in the south. This region is a triple junction complex of the tectonic settings among Sundaland, Australian, and Pacific plates.

Fig. 7a

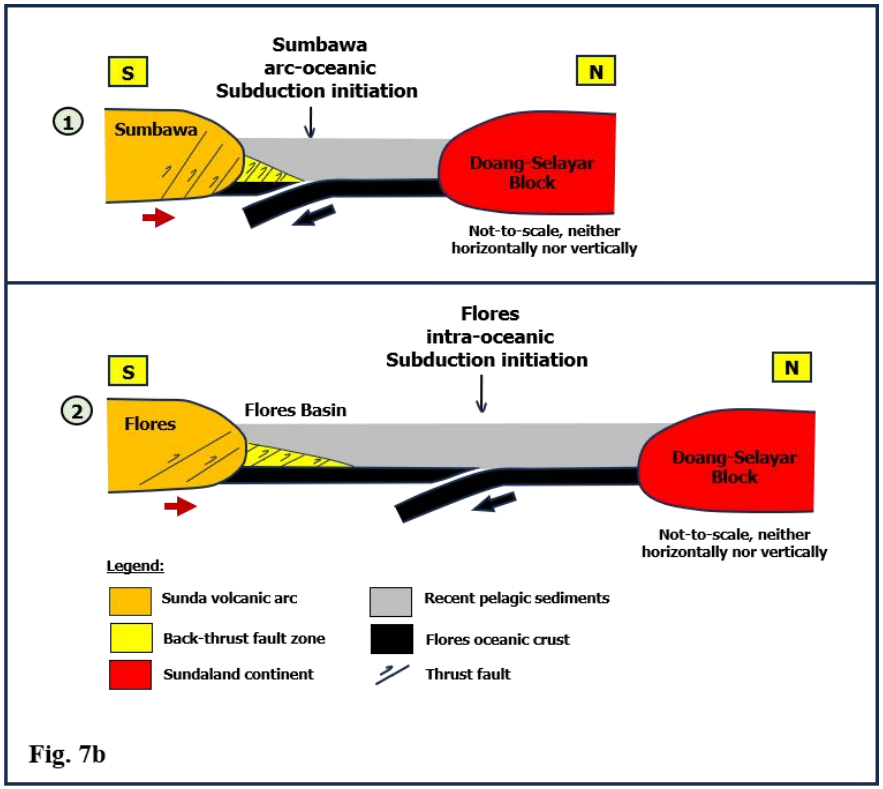


Fig. 7b

Fig. 7a. *The oceanic lithospheric crust in the offshore north Flores is interpreted to be present only in the "oceanic crust limit" outlined in yellow dashed lines.* ***Fig. 7b.*** *Tectonic models of the Flores Subduction Initiation across offshore Sumbawa (arc-oceanic) and offshore Flores (intra-oceanic).*

and stable continental shelf edge of the Sundaland including the North Madura Platform and Transition Zone, Fig. 3. The zone has predominant rocks of sedimentary clastics of syn-rift deposited in the fluvial and lacustrine, post-rift shelf fine-clastics and carbonates, and continental-shelf clastics during the thermal sag and compressional phases.

The southern boundary of the North Madura Platform is located at the northern edge of the onshore Madura Island (Fig. 3). Stratigraphically, the platform feature is a widespread, shallow basin margin and a west-east major shallow marine continental shelf. This is the boundary of a coastal depositional “break” in deeper marine settings in the south. The 2D regional seismic mapping of the basement structure and isopachous overlying maps also confirmed the boundary outline. The tectono-stratigraphy over the platform is relatively simpler, where the region is actively influenced by some uplifts and unconformities, specifically those that occurred during the Neogene.

Immediately south of the boundary, the geology is controlled by continuous, thick argillaceous depositional sediment settings, which were contemporaneously and later heavily folded and faulted along with the Late Cenozoic deformation. This Sundaland shelf region is generally a west-east shallow marine of the Madura graben since the early Middle Eocene Ngimbang syn-rift to at least Early Miocene Kujung post-rift depositions (Figs. 8a & 8c). Later, the shelf started to experience thermal sag and compressional stages, where the Ngrayong coastal to shallow marine sandstones began to deposit southward in the early Middle Miocene. Finally, it was uplifted during the Plio-Pleistocene due to compressional tectonics, followed by sea level lowstand in the Pleistocene, where the Pamekasan Formation was deposited. Inconsistent stratigraphic nomenclatures of onshore and offshore East Java, including Madura Island, have been used in published papers.

Several folds and faults are present within the Rembang zone, resulting in the Rembang Anticlinorium in onshore East Java which has produced significant amounts of oil and gas, mainly from the Early Miocene reefal Kujung carbonate reservoirs. Immediately to the south of the Baribis-Kendeng back-thrust fault, the basin abruptly deepened and was predominantly filled with deep marine sediments. Effectively, this fault is originally separating shallow marine in the north in transitional to neritic marine environments with stable stratigraphy, to deep marine in the south in neritic to bathyal settings.

The next southwards zone is the severely uplifted and faulted, deep-sea deposits of the Kendeng zone, as a central depression in west-east axial trough of East Java. To the south is Volcanic Arc zone that comprises a series of present-day chain of volcanoes in WNW-ESE direction, and finally, the southernmost zone is the Southern Mountains Arc which generally consists of Paleogene uplifted volcanic sediments later covered by Neogene karst topography. All of these reflect the ongoing plate convergence in East Java at present day.

The oldest known basement rocks of East Java are the continental crust underlying the Southern Mountains, which contain Archaean to Cambrian zircons of Gondwana crust affinity of the west Australian origin (Hall, 2017). Toward the north, the basements of the Transition Zone and North Madura Platform are generally Cretaceous-Jurassic acidic-to-

transitional basement rocks encountered by exploration wells. The granites, slaty metasedimentary, and basic to silicic volcanic rocks from offshore north of onshore Madura Island were generally dated to around 100-140 Ma or Early Cretaceous (Katili, 1972).

CEPU-TO-CENTRAL HIGH INVERSION

One of the most prominent regional structures in East Java and to the east is the west-east oriented, inverted structure of the Cepu-to-Central High. The shape geometry of inversion began in Cepu region in the west in the onshore north of East Java, extending across onshore Madura, narrowing to the east to the Central High in the Kangean-Sepanjang, crossing the Masalima Trough, and finally dying out in the southwestern part of the Doang Platform region (Figs. 2, 3, & 6). From the west to east, in general, the inversion is geographically divided into three segmented grabens: (1) Cepu, (2) Madura, and (3) Central High segments.

The detailed internal features of the individual inverted structure segments are complex owing to folding and faulting, causing uncertainty in interpretation. Poor seismic quality and insufficient seismic coverage are the main drivers of these difficulties unless better seismic images are available for interpretation. To solve this challenge and simplify the discussion, this study assumes that the inversion took place to the sizable structural low as topographic depression along the structural orientation discussed above, which could be any type of down-dropped feature, such as a graben, half-graben, or valley. The shape and outline of the orientation were also simplified, assuming the formation of a continuation of the segmented structures.

a. Cepu Inverted Graben

The Cepu graben is located in the Rembang zone and covers onshore immediately to the north of the Kendeng zone. The northern limit of the graben is interpreted to be the NMRF, whereas the southern boundary is the Kendeng back-thrust fault (Fig. 3). The regional surface geological map clearly shows that the surface structures in the Rembang zone are generally irregularly shaped and covered widely by Late Pliocene to Quaternary sediments (Gafoer & Ratman, 1999). The Rembang zone is dominated by shallow marine carbonates and shelf-edge clastics observed in outcrops and encountered by numerous hydrocarbon wells.

The Rembang zone was largely a Sundaland paleo-continental margin in the Early Oligocene to Early Miocene at the beginning of the deposition of the Ngimbang carbonates in transition to the Kujung carbonates. The margin deepened to the south into the present-day Kendeng zone, where deeper marine sediments were deposited. Seismic interpretation suggested that the graben has been inverted to about 6,000 feet around the Kujung Highs. The width of this inverted Rembang graben at the surface could range from 20 to 60 km.

The Cepu-graben inversion reaches as far as the Rembang Hills and Pati reverse fault to the west and northwest direction. To the east, the inversion is structurally continuous to onshore Madura. The northern part is bounded and controlled by the NMRF as a static backstop, causing high deformation and uplift. The uplift is occupied by the Rembang Hills and Kujung Highs where the Oligo-Miocene sediments have been cropped-out along the northern coast: Kujung, Tuban, Ngrayong, Bulu, Pasean, and Madura Formations, as shown in the geological map of Gafoer & Ratman (1999).

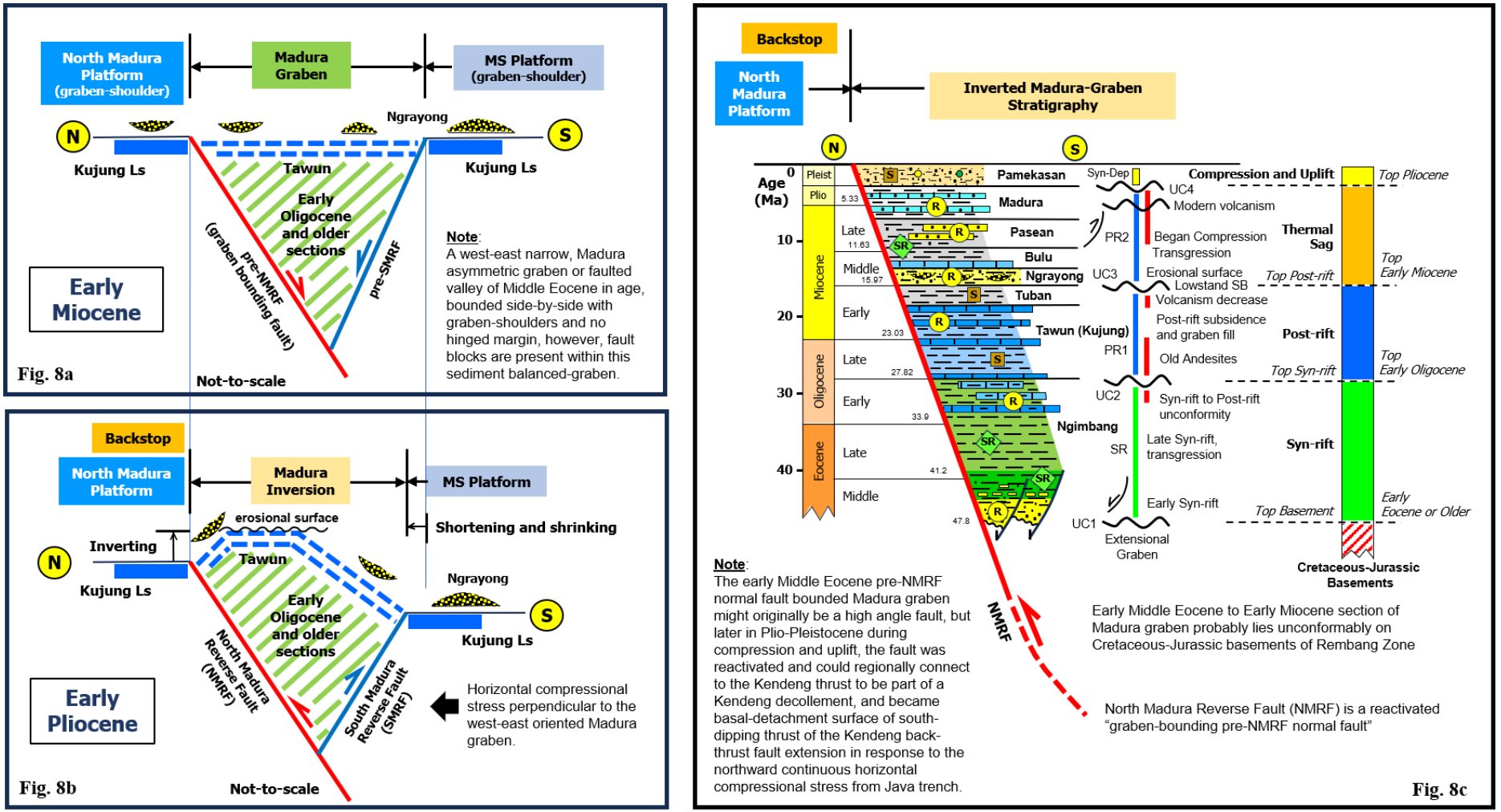


Fig 8. *Reconstruction of the Madura graben and inversion profile model based on 2D seismic interpretation. Stratigraphic nomenclature refers to the stratigraphy utilized in the GRDC surface geological maps of onshore Madura Island published in 1992.*

In the western part, specifically the northwest Cepu, several WNW-ESE and WSW-ENE trending folds are present, structurally building a Rembang Anticlinorium where numerous oil fields were discovered by the Dutch at shallow depths on anticlinal structures of shallow marine sandstones of the Early Pliocene Ledok (=Madura) Formation.

Further towards the southeast, the inversion produced much simpler fold structures. There are at least three large, major anticlinal structures that are very close to each other: Lidah, Guyangan, and Kedungwaru, with the axis plunging in a relatively west-east orientation. The Pleistocene Lidah (=Pamekasan) Formation cropped-out to surface at the crest of the structures (Supandjono et al., 1992). Although the structures are young, Dutch's exploration discovered some shallow oil fields in the late 1880s.

***b.* Madura Inverted Graben**

The GRDC surface geological maps and SRTM topographic images covering the whole Madura Island clearly show variation of the main west-east oriented fold structural elements particularly the most obvious Pakong syncline in the east with its associated anticlines and faults, and those crossing the island (Htwe et al., 2015; and Situmorang et al., 1992). Although it is difficult to observe in a vertical view since most of the existing 2D seismic lines in the region are generally of poor quality, besides the complexity of the subsurface geology, the whole structure of the Madura inversion strongly suggests that it is largely the product of an inverted graben.

As part of the East Java Basin, and seen in the 2D seismic lines, the Madura inversion is interpreted to originally be a west-east narrow, asymmetric graben or faulted valley of the Middle Eocene in age, (Figs. 4, 8a, 8b, & 8c), bounded side-by-side with graben-shoulders of the North Madura Platform to the north, and by the MS Platform to the south. The thickness between the top Tawun and Ngimbang Formations increases significantly from the MS Platform (footwall) to the uplifted hanging-wall across the SMRF. The thickness also increases gradually away from the fault zone (Fig. 5). The thickened section in the uplifted block (hanging wall) of the Madura graben suggests the presence of a structural inversion.

The syn- to post-rift fills consist of Middle Eocene to Early Miocene sections that are fine-grained shallow marine clastic sediments with some thin carbonate stringers of the pre-Tawun or Upper Ngimbang. The base of the section mostly remains undrilled, and likely consists of fining-upward fluvial to alluvial deposits (Figs. 8a, 8b, & 8c). The whole depositional sequences filled in the graben suggested a form of sediment balanced-graben. However, the accommodation space of the graben still existed in early Middle Miocene allowing sea-level lowstand coastal to shallow marine depositions of the Ngrayong Formation into the graben.

Prior to the Neogene compressions, the NMRF and SMRF are interpreted to be originally major normal faults that were relatively parallel bounding of the Madura main graben. Some west-east smaller horsts and half-grabens could be present within the main graben deeper to the northern part. At present-day elevation, the Madura inverted graben is approximately 40 km wide (Fig. 3). The horizontal compressional stress perpendicular to the west-east oriented Madura Graben reactivated the bounding normal faults of the pre-NMRF and pre-SMRF (Figs. 8a & 8b), causing inverted-graben structure with shortening and shrinking of the graben

during Early Pliocene. Although there is lack of data to clearly define, the possibility of Kendeng decollement present connecting together all of the NMRF, SMRF, and KBTF faulting systems, should not be ignored (Fig. 3).

The presence of the Madura backstop wall, MS Platform, and orthogonal compressive horizontal stress from the south are crucial and play major roles in controlling the primary structural development in the Rembang Transition Zone in the Late Neogene. The continuous perpendicular horizontal forces northwards from the subduction of the Australian Plate with Sundaland in the Java Trench have pushed the MS Platform to the Madura steep graben to initiate the NMRF and SMRF, and finally resulted in the Transition Zone or the southernmost part of the Rembang zone to be uplifted (Figs. 3 & 8b). Hence, both the NMRF and SMRF are responsible for the development of a pop-up structure of the Madura inversion. Consequently, the Madura Graben becomes narrower with some degree of shortening. If the shortening is 20-30 % or about 10-15 km, the pre-inverted graben could originally be around 50 km in width.

A great structural uplift of the onshore Madura Island seems to occur at approximately 12,500 feet based on interpretation of the seismic event of the top Kujung (=Tawun) horizon observed in the 2D seismic lines crossing the MS Platform and the island (Figs. 4 & 5). This might be the lower estimate since the Tawun Formation was cropped out to the surface (Htwe et al., 2015). The Madura inversion began in the Latest Miocene at the time of early deposition of the Madura Formation and continued intermittently until the present day (Figs. 5 & 8b).

***c.* <u>Central High Inverted Graben</u>**

The inverted Madura graben feature is continuously observed to the east to the eastern Kangean and western Masalima Trough area along-strike of the NMRF and SMRF immediately south of the Sibaru Platform, as shown in Figs. 3 & 6. The width of the inverted Central High graben is about 50 % narrower than that of Madura, or only around 20 km. This north-south width of the inversion could finally disappear in the southern part of the Doang Platform. The cause of the narrowing graben in this region remains uncertain. The regional tectonic activities might contribute to this nature and its graben shape within a regional complexity among larger structural grains of the Sibaru Platform, Bali Sub-basin, southern part of the Masalima Trough, and southwestern part of the Doang Platform (Figs. 2 & 3).

The entire length of the Cepu-to-Central High inverted graben now exceeds 650 km with a width range of 20-60 km. This W-E-extending inverted graben is a prominent structural feature in East Java in terms of both uplift magnitude and continuity (Fig. 3). This eastern part of the Central High was interpreted as a nucleated Paleogene extensional feature that were subsequently inverted during Late Neogene resulted in and was responsible to the structuration of the Kangean region (Granath et al. 2011). The timing of inversion remains uncertain, but it is likely similar to that in Madura graben which was at the Latest Miocene as suggested by continuation of the bounded NMRF and SMRF to the Kangean region. Based on geo-history modelling of the vitrinite reflectance data for the West Kangean-2 well, the uplift of the Eocene Ngimbang carbonates is 5,000 feet to the present depth of about 7,000 feet (Siemers et al., 1992). Toward the southwestern flank, particularly Terang-Sirasun

structure indicated more than 1,000-foot uplift during Early Pleistocene (Basden et al., 1999).

The tectono-stratigraphy of the Central High graben differs from those of the Cepu and Madura grabens. The Central High consists of Early Eocene sediments at the base of the Cenozoic section and is clearly underlain by Late Mesozoic remnants (Fig. 6). Matthews and Bransden (1995) indicated the presence of Late Cretaceous sediments of highly indurated claystones interbedded with siltstones and sandstones. Similar sequences were reported to exist in the outcrops of onshore SW Sulawesi. The Palaeozoic and Precambrian lithostratigraphy was assumed to exist in the graben of the Doang Platform. The A to E horizons described the stratigraphy of pre-Cambrian to Palaeozoic, overlain by the top Cretaceous unconformity (marked in dark green), and finally overlain by Cenozoic section (Granath et al., 2011, and in their Figs. 5 & 6).

The regional Cepu-to-Central High graben and associated stratigraphy observed in outcrops and exploration wells indicate that the Central High grabens were probably initiated earlier than those to the west in the Cepu and Madura segments during the Early to Middle Paleogene period. This allowed deposition of the pre-Ngimbang fluviatile sediments in the Paleocene to Early Eocene, while the Cepu-Madura part might have largely remained paleo-high and in the denudation mode. The transgressive phase continued where the Ngimbang clastic material was deposited in a fluvio-deltaic environment during the Middle Eocene. This was followed by marine transgression, which resulted in widespread deposition of Ngimbang reefal carbonates. The carbonate distribution became laterally restricted and ended completely in the Late Eocene, when it was subsequently buried in upper bathyal argillaceous sediments; hence, the Ngimbang shale was initiated. The upper bathyal marine was gradually shallowing to the upper shelf, where carbonates of the Kujung were deposited in the Late Oligocene to Early Miocene, following the beginning of inversion.

PROVEN PETROLEUM SYSTEM

A brief discussion of the exploration history and petroleum system in this section is limited to the oil and gas discoveries in the Cepu region in the west to Kangean in the Central High region in the east. Numerous hydrocarbon discoveries immediately to the north of the NMRF in the North Madura Platform are beyond the scope of this study.

a. Cepu Onshore Region

The East Java basin has been the focus of hydrocarbon exploration since pre-World War II. At the time, Kuti was the earliest commercial oil field discovered by Dortsche Petroleum Maatschappij just south of Surabaya in 1888 (van Bemmelen, 1949; vol II, pages 32-36). All Kuti, Kruka, and Lidah oil fields are located on the Lidah and Guyangan anticlines (Fig. 3) and generally produced oil at shallow depth around 2000 feet in the Kalibeng Beds (=Pliocene Madura) as discussed in van Bemmelen (1949; vol II, pages 33-34). Stratigraphically, they are equivalent to the Globigerinid Wonocolo (=Late Miocene Pasean) and Ledok (=Early Pliocene Madura) sandstone reservoirs of Soetantri et al. (1973).

Towards the south, a gas field called the Wunut field was discovered in 1994. The gas accumulated in the Pleistocene volcaniclastic reservoirs of the Pucangan

(=Pleistocene Pamekasan) Formation. It is generally poorly cemented, with porosity ranges of 20-45 % and permeability ranges of 25-195 mD. Intra-formational clays are the top seals for gas reservoirs. The gas is thermogenic possibly sourced from deep mature shales of the Ngimbang Formation. The gas gravity and wetness increase with depth. The gas could be originally trapped in the Early Miocene Kujung carbonates later migrated upwards to the Wunut field due to fault-breaching or seal collapse (Kusumastuti et al., 1999). Nearby gas fields include Carat (2002) and Tanggulangin (2002).

Many shallow, old oil fields are also present to the north-northwest of the Rembang zone. In the surrounding Blora and the region between Blora and Cepu, the Cepu uplift has produced many NW-SE and W-E series of simple, oil anticlines as part of the Rembang Anticlinorium. At least twenty-five old waxy oil fields were developed in the latest the 1800s and earliest the 1900s by the Dutch, for example: Ledok (1893) and Kawengan (1894). All of the oil fields were discovered at shallow horizons of the Ngrayong, Wonocolo, and Ledok Formations (Soetantri et al., 1973). The crude oils collected from the Wonocolo sandstone of the Dutch Cepu old oil wells have low maturity (immature). The sources of organic matter vary not only from oxic depositional environment with terrestrial higher plants but also bacteria and algae deposited in marine and lacustrine environments (Zetra et al., 2021). The source rocks of this Cepu immature oil are possibly shales of the Wonocolo Formation.

Recently, some oil and gas fields were discovered further to the west and north-northwest of Surabaya around Bojonegoro, for examples: Sukowati and Mudi fields, and in Gresik: Suci gas in the latest 1990s. Several oil seepages are also present in the region. The reservoir targets changed from the early Dutch drilling of shallow stratigraphy to Oligo-Miocene Kujung reefal carbonates. Suci-1 (2000) well flowed gas from Early Oligocene Ngimbang carbonates (Panuju et al., 2017). In the earliest 2000s, the exploration focus shifted to the region immediately southeast of Cepu, where several large oil and gas fields were discovered in the Kujung reefal carbonates. For example, The Banyu Urip carbonate build-up was discovered in 2001 at the shallowest depth of about 4000 foot-ss (top) and 7000-8000 foot-ss (base). The structure of the Banyu Urip carbonate build-up is the largest and tallest, with approximately 1000 ft-thick oil columns by 1500 acres. It is a giant oil field contains over 1 billion barrels of oil in-place (Musgrove & Sun, 2012).

The Banyu Urip build-up is an isolated carbonate platform that was karsted and fractured, and surrounded by some smaller build-ups. Excellent reef build-up geometry has been clearly visualized in modern 3D seismic images. The top seal is provided by late Early Miocene Tuban claystones. The reservoir quality was controlled by diagenetic processes. The carbonates were interpreted to have been deposited in a high energy, open marine margin environment.

The oils were derived from terrigenous, terrestrial Type III kerogen and humic coals. The average of oil gravity is 31.5° API (Ditya et al., 2014). The potential source kitchens for the oil and gas are the Eocene Ngimbang source rocks. The Sukowati and Mudi oils were generated from deltaic to marginal marine of Lower Ngimbang shale source rocks. The Eocene Lower-Ngimbang carbonaceous shales from Kujung-1 (1980) and Ngimbang-1 (1974) wells, also suggested that the Lower Ngimbang source rocks were humic and mixed kerogen (type II) deposited under transitional

environment with terrestrial (type III) inputs (Devi et al., 2018).

b. Madura Onshore and Madura Strait Sub-basin Region

There are several oil seepages in the onshore regions of Cepu, Gresik, and Madura. In the late 1800s to earliest 1900s, several oil fields were found by the Dutch at shallow depths of about 400-2000 feet in the surface anticlines in onshore Madura, for examples, Bujur (1897), Kertegeneh (1898), Durbuk (1903), and Lerpak (1916), Exploration continued in late 1900s: Arosbaya-1 (1973) discovered a non-commercial oil, condensate, and gas; but Gigir-1 (1974) seemed to be unsuccessful. A fractured reservoir play of the Kujung carbonates failed to be tested by the Kurnia-1 (2007) well on the southern coast of Madura Island. ENC-1 (2012) and ENC-2 (2018) were drilled in southeast onshore Madura with reported gas discovery.

Several gas discoveries took place in the late 1900s offshore south of Madura, just south of the SMRF (Fig. 3). Geologically, the discoveries are located in the MS Platform. Hence, Oligo-Miocene Kujung carbonates are the primary exploration target, and Tuban marine shales are the main top seal. Gas production has been largely produced in this MS platform.

In the MSS region, several reefal carbonates were drilled, and a large amount of gas besides oil and condensate was discovered. For example, BD-1 (1987) well tested significant oil and gas in the Early Miocene carbonate build-up of the Kujung Formation. The oils are 34° to 43° API gravity, paraffinic with a moderately waxy and pour point of 105°. The oil maturity estimated to be 0.8 to 0.9 %Ro, were generated from a mixed algal (brackish to terrestrial) organic facies that may have been reworked by bacteria (Widjonarko, 1990). The source rocks were deposited in a shallow lacustrine-fluvial flood plain. The gas has a maturity of 1.0–1.5 %Ro. The oils have experienced moderately long-distance migration from source rocks. The source rocks are likely to be Middle to Late Eocene Ngimbang shales just north of the MS Platform margin in the Madura graben (Fig. 3). The oils discovered in the Jeruk (2004) field were likely sourced from the same source rocks of the same graben.

A large amount of gas has also been discovered in a very shallow, young stratigraphic reservoir. For example: Early Pliocene Globigerinid detrital carbonates of the Paciran and Mundu (=Pliocene Madura) Formations by Maleo-1 (2002). The gas composition was 99 % methane, which is primarily biogenic in origin. The porosities range 39-50 %, but the permeabilities are only < 1 to 400 mD (Triyana et al., 2007). Foraminifera tests comprise the primary framework grains make up 55-95 % of the foram biota and are moderately to intensely bioturbated. The source rocks of this biogenic gas are assumed to be the claystones and siltstones of the Paciran and Mundu Formations, which have abundant methanogenic bacterial activity. The top seal is provided by Lidah (=Pleistocene Pamekasan) claystones.

It appears that the Early Pliocene Globigerina carbonate gas play is spread out in the MSS, specifically over the MS Platform, for example, MDA (1984), Oyong (2001), Wortel (2006), Peluang (2009), MBH (2011), and MAC (2012). Some other biogenic gas discoveries drilled in the mid-late 2010s in this region are likely associated with this play as they are located at the same west-east Globigerina distribution track: Melewis (2016), and Paus Biru (2018). Thin oil legs could be present in this play, as occurred in the Oyong field (Sutadiwiria & Prasetyo, 2006).

The exploration of this play remains attractive and should be pursued further in the region.

***c.* Central High Region**

The gas reservoirs in the Pagerungan-1 (1985) well are the Middle-Late Eocene clastic sandstones and basal massive sandstones of the Ngimbang Formation at the southern end of the Sibaru Platform. The Pagerungan gas field has an estimated OGIP of 1.4 TCF (Widiantoro et al., 2025). Immediately to the north, the JS 53A-1 (1977) well flowed more than 1500 BOPD from the Eocene Ngimbang carbonates (Tyrrel et al., 1986), and this became the trigger for development of the Pagerungan Utara oil field. Further to the south, the Sepanjang Island-1 (1990) well, located onshore west of Sepanjang Island, tested oil 1,400-2,800 BOPD in the same Ngimbang carbonate reservoirs. In the western flank of Kangean Island, the West Kangean-1 (1988) well also flowed 21 MMCFGPD from the Ngimbang carbonates (Siemers et al., 1992).

The southern end of the Sibaru Platform is a prolific region, as proven by the presence of some oil and gas fields that are partly still producing. The Late Eocene Ngimbang carbonates become the productive reservoir in the Kangean region besides the underlying Eocene clastic flowed gas in the Pagerungan field. The conventional cores of the Ngimbang carbonates cut in the West Kangean-2 (1989) well suggest that the carbonates are tight and moderately recrystallized, but have a complex of fractures with abundant stylolites and experienced several periods of subaerial exposures. It was dominated by near-vertical fractures and locally showed open fractures. The carbonates were interpreted to occur in a restricted, low-energy carbonate platform. Refer to Siemers et al. (1992) for a detailed description and interpretation of West Kangean-2 conventional cores.

Seismic stratigraphic study of the Late Eocene carbonates in the region of the JS 25-1 (1977) well and to the west of Sepanjang Island indicates that there are several carbonate build-up features grew over basement highs, and trending west-east (Kohar, 1985). This development of reefal carbonates is interpreted to be present in the graben margin along the SMRF-Sepanjang fault (Fig. 3). Later, all carbonates were overlain stratigraphically by the Latest Eocene Ngimbang shales as the primary top seal for any Ngimbang play.

Another Ngimbang play in the region is the Middle-Late Eocene Ngimbang clastic sequence encountered by oil and gas fields, including the L46-1 (1984) well. The Pagerungan-5 well encountered the entire 300-foot section of the Ngimbang clastics. The section shows a major transgressive sequence of fining-upward sandstones at the base, grading to interbeds of finer-grained sandstones, shale, and coal stringers. The sequence changes to meandering and/or deltaic systems by the development of claystone beds, coal stringers, and thinner and finer grained sandstones. Porosity ranges from 14 to 24 % with an average of 20 %. Permeability ranges 40-2570 mD with a mean of 666 mD. A detailed description and interpretation of the Pagerungan-5 cores are available in Ebanks et al. (1993).

The Ngimbang clastic sequence lies unconformably on the pre-Ngimbang Formation and is overlain by Ngimbang carbonates. The entire Ngimbang section was assigned to the Middle-Late Eocene age. A core of the pre-Ngimbang in the Pagerungan-5 was cut 25 feet at the base of the well. This is interpreted to have been

deposited on an alluvial or coastal floodplain. Formation age of the pre-Ngimbang is assigned to Paleocene to Early Eocene while the underlying basement is the pre-Tertiary (Late Cretaceous) metasediments (Phillips et al., 1991).

Phillips et al. (1991) suggested that the JS 53A-1 oil and Pagerungan gas were generated from mature coals and carbonaceous shales of the Eocene Ngimbang clastic and pre-Eocene Ngimbang source rocks in the kitchen nearby areas. TOCs of the Ngimbang clastic shales range from 0.2-17 % and 26-82 % for coals. The oil gravity in JS 53A-2 (1985) is 27.5° API suggesting waxy oil, while in the Pagerungan-1 the API gravity is 53.6° which is condensate. The pre-Ngimbang coals at Pagerungan-1 have a TOC of 77 % and S2 of 259 mg/g. Leroy et al (2000) suggested that the oils were generated from either lacustrine or fluvial/deltaic source rocks, however most of them including Pagerungan condensates were originated from fluvio-deltaic sources. Specifically, the hydrocarbons in the West Kangean-2 and Sepanjang Island-1 samples were exclusively derived from lacustrine source rocks.

However, Sutanto & Musu (2015) suggested that the Sepanjang oils originated from source rocks deposited in a marine environment. The oils have very low oleanane and sterane indexes of lower than 20 % (Sutanto et al., 2015) and the oils also showed high number of the triaromatic dinosteroid index suggesting Cretaceous source rocks (Sutanto et al., 2016). The L46-1 well, located southeast of the Sepanjang wells, encountered pre-Tertiary sediments and tested oil and gas in the pre-Ngimbang clastic area, which might also be sourced from Cretaceous source rocks. The location of the active pods of hydrocarbon source rocks in the region remains uncertain. The possible presence of Cretaceous source rocks has attracted companies to explore around greater Central High regions and to the east of the Masalima Trough and Doang Platform (Figs. 2, 3, & 6), which is currently still lack of exploration wells.

As discussed above, Phillips et al. (1991) indicated that the sedimentary clastic section with high GR readings was defined to be the pre-Ngimbang Formation, as shown in the Igangan-1, Pagerungan-1, and JS 53A-1 wells dated to be Paleocene to Early Eocene. Ebanks & Cook (1993) defined the same section in Pagerungan-5 to be the same age; however, Siemers et al. (1992) assigned the pre-Ngimbang section encountered by West Kangean-2 to be pre-Tertiary or Cretaceous in age. It consists of an interbed of claystones and siltstones with occasional coal stringers. A DST flowed 3968 MCFGPD and another one about 700 feet deeper tested 15 MCFGPD. It is possible that the source rocks are actually the pre-Ngimbang section with a long-range age from Paleocene to Early Eocene.

Another proven petroleum system is the Globigerinid sand carbonates present in the Terang (1982), Sirasun (1993), Batur (1995), and Kubu (1995) gas fields in the southwest of Kangean Island (Sutadiwiria & Prasetyo, 2006). The fields contain dry gas made up of over 99.5 % methane. The reservoirs are carbonates of the Upper Paciran (=Late Pliocene Madura) with Quaternary shales as the top seal. The overall porosity is very high, ranging from 40 to 55 %. The permeability is generally low controlled by depositional facies though it could be in the wide range of 1 mD to more than 1 Darcy (Hadiyanto et al., 2010).

CONCLUSIONS AND DISCUSSIONS

1. The 2D seismic interpretation suggests that the Cepu inverted graben extends further to the east in a west-east orientation to the Central High graben, crossing the southern Masalima Trough, and finally terminating in the southwestern part of the Doang Platform. The Cepu-to-Madura graben is interpreted to have initiated in the Middle Eocene; however, the Central High syn-rift deposition occurred slightly earlier in the Paleocene. Early structural uplift occurred in the Late Oligocene, followed by strong uplift in the Early Pliocene. The Cepu-to-Central High inversion is a result of the orthogonal convergence of the Australian Oceanic Plate to the Java Trench strike.

2. The Cepu-to-Central High inverted graben is a prominent Cenozoic prolific structure with a proven petroleum system since Dutch exploration drilling in pre-World War II. Repeated oil and gas discoveries have been continuous until recently. Two proven petroleum systems are present which are Eocene-to-Miocene thermogenic and Pliocene-to-Pleistocene biogenic plays. There are numerous regions still under-explored both onshore and offshore of the East Java Basin.

3. The 2D seismic interpretation and SRTM topographic and bathymetric images indicate that the onshore Baribis-Kendeng back-thrust fault is obviously continuous eastwards to merge with the offshore Bali-Lombok-Flores-Wetar back-thrust fault segments to form a mega-regional back-thrust fault in NNW-SSE orientation. The back-thrusts commenced during the Pliocene to Early Pleistocene, when the Baribis-Kendeng segment might have taken place in the Early Pliocene.

4. The lithospheric crust changes from west to east, starting with a continental crust offshore north Lombok to the west, to transitional with a narrow oceanic crust over offshore north Sumbawa, and to the east to be well-developed oceanic crust in the offshore north Flores. The KBTF impact to the east together with the northward compressional stress from the Sunda subduction and Timor collision in the south resulted in an intra-oceanic subduction initiation in the form of a Flores “nascent” trench stage.

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