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REVIEW ARTICLE

Review: Geological Structure Impacts to Hydrocarbon Potential and Active Faults in the East Java Basin, Indonesia

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Abstract

Review of the geological structure patterns in the East Java Basin (EJB) to understand the geodynamics has implicated to the hydrocarbon potential and active faults. However, the impact of those structures on hydrocarbon potential and active faults is unclear. This study reviewed structure patterns using surface and subsurface data, GPS, seismicity and tremors in the East Java Basin, Indonesia and Nankai Trough, Japan. In EJB, Indonesia, the tectonic setting is constrained by the Rembang Fault. The north of the Rembang Fault, the pattern exhibits NE-SW structures, while to the south, it shows W-E structures. The results indicate that the upper crust (including ophiolitic basement) has greater density to the north than to the south. Thus, vertical motion of the crust is more dominant than lateral motion to the north of the Rembang Fault. This vertical motion may trigger the reactivation of the Meratus Fault (weak zone or as active fault) located on the northern platform (e.g., the Bawean earthquake on March 22, 2023). Conversely, to the south of the Rembang Fault, there is a significant hydrocarbon potential associated with W-E structures. Those structures could form by subduction and collision tectonic. Similary, tectonic backstop may account for presence of structures in Nankai Trough, Japan.

Keywords: Ophiolitic Basement, W-E Structures, Hydrocarbon, Active Fault.

1. Introduction

The East Java Basin (EJB) is a hydrocarbon-producing basin with seismic activity from the Rembang Fault and Kendeng Fault. Geographically and tectonically, the basin is a back and forearc basin with current volcanic boundaries (e.g., Mount Merapi, Mount Lawu, Mount Wilis, and Mount Arjuna). The tectonic framework began with the collision between Sundaland and the Australian continental crust since the Cretaceous period (Hall et al., 2007). This process involved basement rocks and sediment with varied structural patterns. However, the impact of EJB's tectonic evolution on the formation of geological structures and its implications for hydrocarbon potential and active faults are still debated.

The EJB is classified into four main structural groups from north to south, namely the Northern Platform (NE-SW), Central High (En-echelon fold belt of Rembang zone), Southern Basin/Central Deep (fold thrust belt of Kendeng Zone), and Southern Uplift (Fig. 1) (Satyana et al., 2004; Sribudiyani et al., 2003; Prasetyadi dkk., 2020). The movement of the main basement structures is influenced by two microcontinents (Satyana et al., 2004), which differ based on the block model by Koulali et al., (2017). The both blocks are bounded by the Rembang Fault. The southern block underlying the Southern Uplift is the Gondwana microcontinent originating from Australia based on U-Pb SHRIMP dating studies of zircon minerals (Smyth et al., 2005). The collision between the Gondwana microcontinent and Sundaland occurs at the active boundary of the convergent zone.

The subduction-collision process that generates major structures primarily above the ophiolitic basement (transition zone between the Sundaland continent and the Gondwana microcontinent) (Fig. 3; Smyth et al., 2005; Wakita et al., 1998), namely the Rembang fault, Kendeng fault, and Meratus fault (Satyana et al., 2004). Laterally, weak zones manifest as fault zones or boundaries between plates (such as a shear zone in Fig. 4) or two different or similar rock rheologies, while vertically, they appear as faults or fault zones. Fossen and Cavalcante, (2017) described shear zones as tabular zones that develop in noncoaxial and coaxial manners, ranging from small outcrop sizes to large structures (i.e., faults). The Rembang Fault and Kendeng Fault are segmented active faults (Koulali et al., 2017). The Rembang Fault forms an en-echelon fold belt (strike-slip faults) originating from the foreland basin, whereas the Kendeng Fault constitutes a fold thrust belt (thrust faults) as part of the back-arc basin (Prasetyadi dkk., 2020). Additionally, the Meratus fault is a normal fault (Lunt, 2019).

The collision also occurs between the backstop intrusion and the young accretion prism, in the Kii Peninsula, Japan (Tsuji et al., 2015), leading to subsidence processes. The subsidence processes occurring in the forearc basin of Japan serve as an analog for subsidence processes in the EJB because observation technologies of geological features on the seafloor surface up to a depth of 8 km can be observed. Fahrudin et al. (2022) argued that strike-slip faults (e.g., strain partitioning) control the thickness of shear zones and the distribution of tremors (or equivalent to small earthquakes < 4 M) with high pore pressure at the plate interface. Fluid migration from the plate interface results in cold seeps (methane gas), and the dynamics of the present forearc basin are influenced by shear zones acting as weak zones. Weak zones represent the boundary between two different or similar rock rheologies and serve as a seismic source.

In this study, we review the geological structures in the EJB that could have implications for hydrocarbon potential and active faults. These geological dynamics are compared to the tectonic activities of the backstop in the Nankai Trough, where shear zones can represent weak zones influencing the dynamics of sedimentary basins and active tectonics.

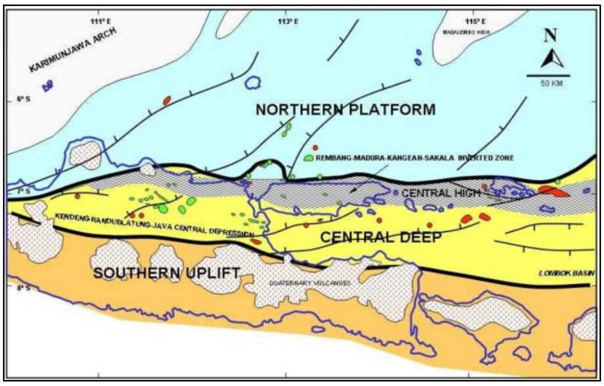

Fig. 1. The geological setting in the East Java Basin shows three configurations of platform (Satyana et al., 2004).

2. Methods

The research method involves a literature review of the structural geology in EJB that could have implications for hydrocarbon potential and active faults. The relevant literature on hydrocarbon potential includes: Clements and Hall, 2007; Hall et al., 2007; Luan and Lunt, 2022; Novianto et al., 2020; Satyana et al., 2004; Smyth et al., 2005, 2008; Sribudiyani et al., 2003, while the literatures on hydrocarbon potential includes: Fahrudin et al., 2022; Harris and Major, 2016; Koulali et al., 2017; Simandjuntak and Barber, 1996; Wölbern and Rümpker, 2016.

3. Geological setting

Clements and Hall, (2007) and Sribudiyani et al., (2003) divided the formation of the EJB into three tectonic phases. They argued that the EJB resulted from the collision between the Sundaland continent and the Gondwana microcontinent originating from the south (Australia) (70-35 Ma; subduction-collision phase [1]). The original structure of the basin was the Sundaland continent with the Meratus structures and the Gondwana microcontinent with the Rembang Fault. After the collision during the Cretaceous period between the Gondwana microcontinent and the subduction system of the Sundaland continent, the subduction of the Meratus direction ceased, and the Southern part of Java became a passive margin until the Eocene period (Hall et al., 2007).

During the Late Eocene to Early Miocene, the continent underwent rifting, and the basin was subsequently filled with quartz-rich clastic deposits carried by rivers flowing from the Sunda Shelf in Central Java, as well as volcanic sediments originating from volcanoes. Since rifting phase [2] on 35 to 20 Ma, east-west trending highs and lows were formed by extension processes with local transtension (Luan and Lunt, 2022). Because Simandjuntak and Barber, (1996) and Sribudiyani et al., (2003) suggested that Rembang and Kendeng Fault with W-E trending are older than Meratus Fault, the formed basin is oriented W-E.

The subduction phase [3] since the Early Miocene and Pliocene (20 - 2 Ma), the Indian plate pushed northward, leading to the reactivation of the Rembang Fault and anticlockwise crustal movements at present (Koulali et al., 2017).

4. Results

4.1 Weak zones (faults) act as active tectonic boundaries and hydrocarbon migration pathways.

The age of the crust beneath Java Island, which is subducting, is relatively older (120-130 Ma) compared to the crust beneath Sumatra Island, resulting in fewer seismic events in terms of frequency and magnitude. However, the occurrence of significant earthquakes in 1994 (Abercrombie et al., 2001) and 2006 (Ammon et al., 2006; Fujii and Satake, 2006) in Java Island is likely due to locked patches caused by the subduction of the seamount (Abercrombie et al., 2001). The Indian Ocean crust subducts with a NE-SW convergence rate of 7 cm/year (Simandjuntak and Barber, 1996). Then, the change in deformation velocity decreases from ~65 ± 0.4 mm/year in the Java Trench to ~2.3 ± 0.7 mm/year in the Kendeng Fault (Koulali et al., 2017), and the strain rate of <1 microstrain/year indicates active faults (Gunawan and Widiyantoro, 2019). Active faults are indicated in Figure 2, and earthquake events are listed in Table 1 (Gunawan and Widiyantoro, 2019; Harris and Major, 2016; Tim Pusat Studi Gempa Nasional, 2017). Therefore, active faults in north of the volcanic arc, acting as tectonic boundaries, undergo segmentation with a system of uplift faults (Kendeng Fault) and strike-slip faults (Rembang Fault).

Table 1 The occurrence of earthquakes in EJB (Harris and Major, 2016)

Location	Date			Intensity
	Year	Month/day	Time	(MMI)
Semarang	1773	21-Apr	12:00 PM	7
Surabaya	1815	22-Nov	11:00 AM	8
Pasuruan	1818	8-Nov	11:15 PM	8
Pacitan	1840	5-Jan	1:15 PM	
East Java, north Bali	1848	17-Feb	10:00 AM	7
Central Java	1856	19-Jan	6:00 AM	
Pacitan	1859	20-Oct	5:30 PM	7
Central and East Java	1865	17-May	7:00 PM	8
Ambarawa	1865	18-Jul	2:27 AM	7
Ambarawa	1866	22-Apr	6:30 PM	7
Central and East Java	1866	30-Sep	9:18 AM	6
Djogjakarta	1867	11-Jun	4:30 AM	9

Based on biomarker plots and carbon-13 isotopes of source rocks, hydrocarbon sources in offshore exhibits more terrestrial characteristics compared to hydrocarbon sources from onshore (e.g., Lower Ngimbang Shale) (Devi et al., 2018; Satyana and Purwaningsih, 2003). The hydrocarbon potential lies within the sandstone of the Ngimbang Formation, limestone of the Kujung/Tuban Formation, sandstone of the Ngrayong Formation, and limestone-sandstone of the Mundu-Tawun Formation (Fahrudin et al., 2018; Satyana and Purwaningsih, 2003; Sribudiyani et al., 2003). The distribution of hydrocarbon potential in Cepu-Bojonegoro and Surabaya-Madura (yellow polygon in Figure 2) is controlled by two main structural trends, namely the NE-SW of strike-slip faults and the W-E of normal faults (Satyana and Purwaningsih, 2003). Therefore, those faults may serve as important conduits for hydrocarbon migration.

4.2 Dynamic of faults in ophiolitic basements

The geological structure map illustrates that the orientation of geological structures in the basement predominantly has the NE-SW pattern, while the geological structures in sedimentary rocks obtain the NE-SW and W-E trends (Sribudiyani et al., 2003). The W-E structures develop around the Kendeng Fault zone, whereas the NE-SW structures develop to the north of that zone. Sedimentary rocks exhibit increasing thickness towards the south (yellow and green colors in Figure 3; Prasetyadi dkk., 2020). However, the basement undergoes thinning towards the south from 39 km in the form of continental crust (Sundaland) to 30 km in the form of ophiolitic basement beneath the Kendeng zone (Figure 3) based on the Vp/Vs ratio calculation (Clements and Hall, 2007; Sribudiyani et al., 2003; Wölbern and Rümpker, 2016). This thinning indicates varying basement depths, thus shifting sediment deposition environments from terrestrial to marine towards the south (Devi et al., 2018; Satyana and Purwaningsih, 2003).

The basement composition described in the preceding paragraph indicates that the ophiolitic basement is a transitional basement resulting from the collision between Sundaland and the Gondwana microcontinent (Figure 3). However, according to (Satyana et al., 2004), the basement in north of the Rembang Fault consists of the Paternoster-Kangean microcontinent. This is based on differences in structural patterns to the north and south of the Rembang Fault. The basement has the same composition (oceanic ophiolite origin; (Clements and Hall, 2007; Sribudiyani et al., 2003) with two geological structure patterns (i.e., NE-SW and W-E). The extension process in phase 2 caused the basement structures to extend, forming highs and lows with boundaries of the Kendeng and Rembang Fault. The NE-SW structure is influenced by extensional forces from the Makassar Strait, while the W-E structure is influenced by extension at the edge of the Java Island (Lunt, 2019). Therefore, both faults may experience reactivation in the future with the ophiolitic basement as the underlying foundation displaced in rifting phase.

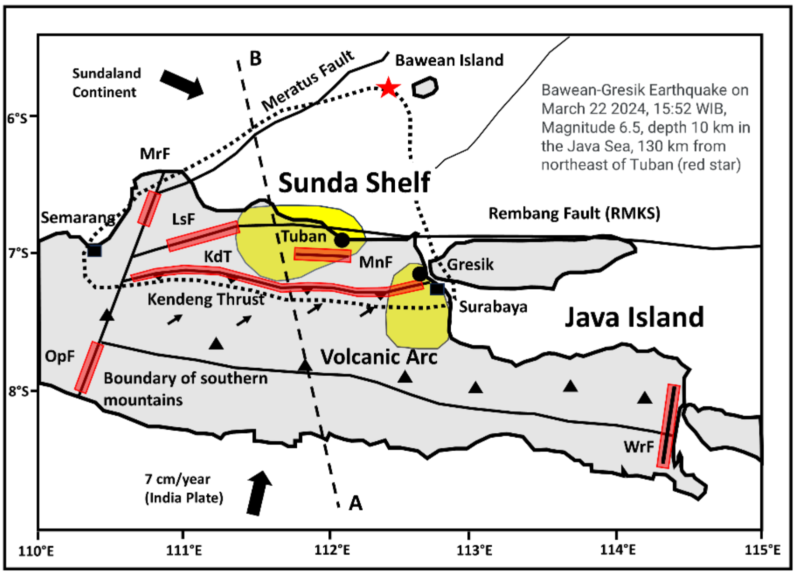

Fig. 2. The association of hydrocarbon potential and active faults on the Kendeng and Rembang faults, where the crust in south of the Kendeng fault moves anticlockwise (black arrow) (Koulali et al., 2017). The yellow polygons represent hydrocarbon accumulations (Satyana and Purwaningsih, 2003). The red polygons indicate active faults (MrF = Muria Fault; LsF = Lasem Fault; KdT = Kendeng Thrust; OpF = Opak Fault; MnF = Montong Fault; WrF = Wongoserojo Fault; Gunawan and Widiyantoro, 2019; Tim Pusat Studi Gempa Nasional, 2017). The dashed line AB represents a cross-section (Figure 3). The red star and dashed lines denote earthquake locations and the vibration paths of Bawean earthquake.

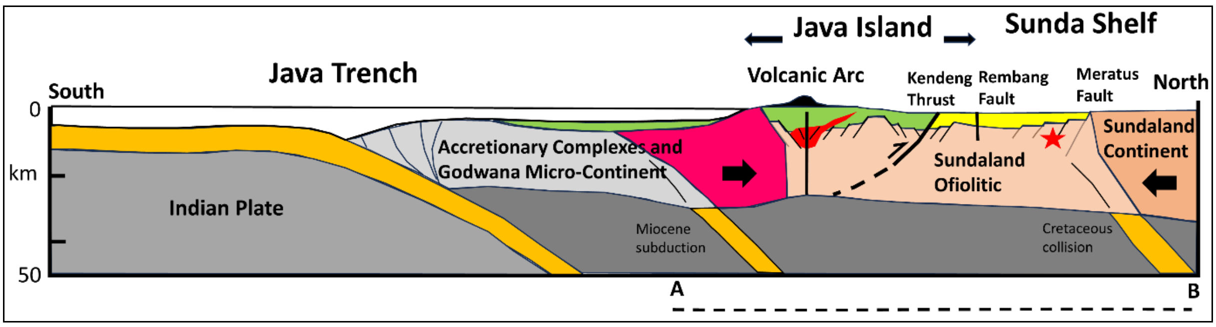

Fig. 3. A cross-section cutting across the island of Java, where the continental crust is composed of various rock formations forming a basement. The Kendeng and Rembang faults are located in the transitional zone due to the subduction-collision between the Gondwana microcontinent and the Sundaland continent (Modified from Clements and Hall, 2007; Simandjuntak and Barber, 1996; Smyth et al., 2005).

5. Discussion

5.1 The inheritance of basement influences hydrocarbon potential and facilitates active faults.

The segmentation of active faults along fault lines in the Rembang and Kendeng fault zone, and the occurrence of a 6.5 M earthquake in Bawean at a depth of 10 km on March 22, 2024, approximately 130 km northeast of Tuban city(red star in Figures 2 and 3) indicates that fault segmentation and earthquake events occur in ophiolitic basement (Clements and Hall, 2007; Smyth et al., 2005). Meanwhile, hydrocarbon migration occurs in sedimentary basins along fault zone at depths < 5 km in the same basement. The hydrocarbon migration pathway and crack propagation due to shallow earthquakes (10 km) may occur along the same path. Zaputlyaeva et al., (2020) have reported that in the EJB, hydrocarbon migration in the Lusi mud volcano is caused by current magmatism in the Arjuno-Welirang Mountain at a depth of 6 km.

The tectonic of rifting is resulted by the crustal thinning in the W-E direction at the EJB depocenter with ophiolitic basement. However, the thicker crust to the north of the Rembang Fault run into the extension of crust to NE-SW direction. Furthermore, the NE-SW pattern is younger than the W-E direction (Lunt, 2019; Wölbern and Rümpker, 2016). The crustal uplift to the north led to changes in deposition environments, resulting in deeper deposition environments to the south of the Rembang fault (Devi et al., 2018). In contrast, deposition environments to the north of the Rembang Fault are shallower, where the Bawean earthquake occurred at a depth of 10 km (Figure 3). These tectonic results indicate that the upper crust to the north (including the basement) has greater density than to the south (Figure 3). Therefore, in the southern part of Java Island, the inheritance of passive margin basement (Hall et al., 2007) in the form of ophiolite may influence hydrocarbon potential and seismic activity.

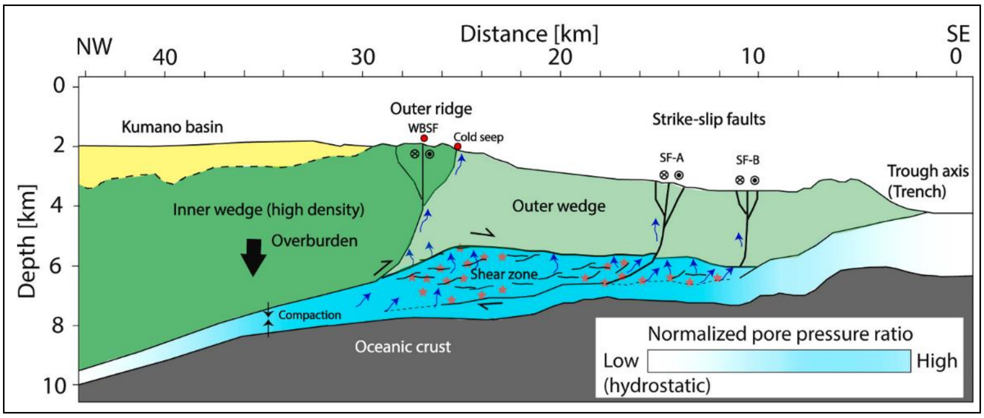

Fig. 4. A cross-section of the forearc basin model in Japan that illustrates the cause of tremors at the plate interface or shear zone (Fahrudin et al., 2022).

5.2 Model of structures controls the basement

The forearc basin in Japan shows that the Off Mie earthquake occurred at the plate interface at a depth of 11 km with a magnitude of 6.0 (Tsuji et al., 2017). The high-density crust has triggered this earthquake, leading to increased tremors in the thick shear zone before and after the earthquake (Figure 4) with fault slip partitioning (Fahrudin et al., 2022). Thus, Fahrudin et al., (2022) concluded that the shear zone and tremors are controlled by the strike-slip fault in the upper plate.

The subduction phase where the Indian oceanic crust subducts to northeastward beneath the Sundaland (Figure 2) within the upper plate of ophiolitic basement (Figure 3). However, the oblique movement between these crusts is very small (~2.3 ± 0.7 mm/year; Koulali et al., 2017), which is approximately ~170 km from the earthquake center (Figure 2). Because the upper crust has greater density to the north than to the south, it causes vertical motion to be more dominant than lateral motion. This may trigger the reactivation of the Meratus Fault located in the back arc basin. The cause of the earthquake is similar to the cause of the Off Mie earthquake in the forearc basin area in Japan (Fahrudin et al., 2022; Tsuji et al., 2017).

6. Conclusion

Inheritance of basement with the Rembang Fault boundary originated from Godwana. Furthermore, the northern side of the fault has a higher seismic potential than the southern side. Conversely, high hydrocarbon potential is located to the south. This is because the density factor of the upper plate influences seismicity and migration paths affect hydrocarbon potential.

Reactivation of the Meratus Fault may be influenced by vertical motion because the crust density in the northern part of the fault is greater than in the southern part. Although the crust density is lower in the southern part, seismic potential still exists, marked by active faults.

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