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REVIEW ARTICLE

STRUCTURAL CONFIGURATION AND DEPOSITIONAL HISTORY OF THE SEMANGKO PULL-APART BASIN IN THE SOUTHEASTERN SEGMENT OF SUMATRA FAULT ZONE

KONFIGURASI STRUKTUR DAN SEJARAH PENGENDAPAN DI CEKUNGAN PULL-APART SEMANGKO DI SEGMEN TENGGARA ZONA SESAR SUMATRA

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ABSTRACT Re-examination of published seismic data in the southeasternmost segment of the active Sumatra Fault Zone (SFZ) reveals the characteristics of structural style and depositional history of Semangko pull apart basin (SPB). The SPB have been developed as a transtensional pull-apart basin resulted from stepping over of the Semangko to Ujung Kulon segments of the SFZ. The geometry of SPB is of rhomboidal shape characterized by dual depocenters separated by a discrete structural high in the center of SPB. Based on the determination of pre- and syn-kinematic strata related to the formation of SPB, sedimentary units prior to deposition of Unit 3 can be regarded as pre-kinematic strata, whereas the syn-kinematic strata is represented by Unit 3. The basin sidewall faults of the SPB are likely to have been developed as en-echelon side wall faults and identified as the East Semangko Fault (ESF) and Kota Agung–South Panaitan Faults (KAF-SPF) in the western and eastern margin of the SPB, respectively. The development of discrete highs along the center of the SPB may relate to the formation of en-echelon cross-basin faults that are now overprinted by volcanic activity or magmatic intrusion.

Keywords: Pull apart basin, strike-slip fault, Sumatra Fault, Semangko, Sunda Strait.

ABSTRAK *Analisa ulang data seismik yang telah dipublikasikan di daerah segmen paling tenggara dari zona sesar aktif Sumatra (SFZ) mengungkapkan karakteristik struktur dan sejarah pengendapan dari cekungan pull-apart Semangko (SPB). SPB terbentuk sebagai cekungan transtensional pull-apart yang dihasilkan dari step over segmen Semangko dan segmen Ujung Kulon. Geometri SPB adalah bentuk rhomboidal yang dicirikan oleh dua depocenter yang dipisahkan oleh struktur tinggian yang tidak menerus di bagian tengah SPB. Berdasarkan penentuan unit pre- dan syn-kinematic strata yang terkait dengan pembentukan SPB, unit sedimen yang terbentuk sebelum pengendapan Unit 3 dapat dianggap sebagai pre-kinematic strata, sedangkan syn-kinematic strata diwakili oleh Unit 3. Sesar side-wall dari SPB kemungkinan telah berkembang sebagai sesar yang bersifat en-echelon dan diidentifikasi sebagai Sesar Semangko Timur (ESF) dan Sesar Kota Agung-Panaitan Selatan (KAF-SPF) di tepian barat dan timur SPB. Pembentukan tinggian yang tidak menerus di sepanjang bagian tengah SPB berhubungan dengan pembentukan sesar-sesar cross-basin yang bersifat en-echelon yang sekarang telah tertutupi jejaknya oleh aktivitas gunung api atau intrusi magmatik.*

Kata Kunci: *cekungan pull-apart, sesar geser, Sesar Sumatra, Semangko, Selat Sunda.*

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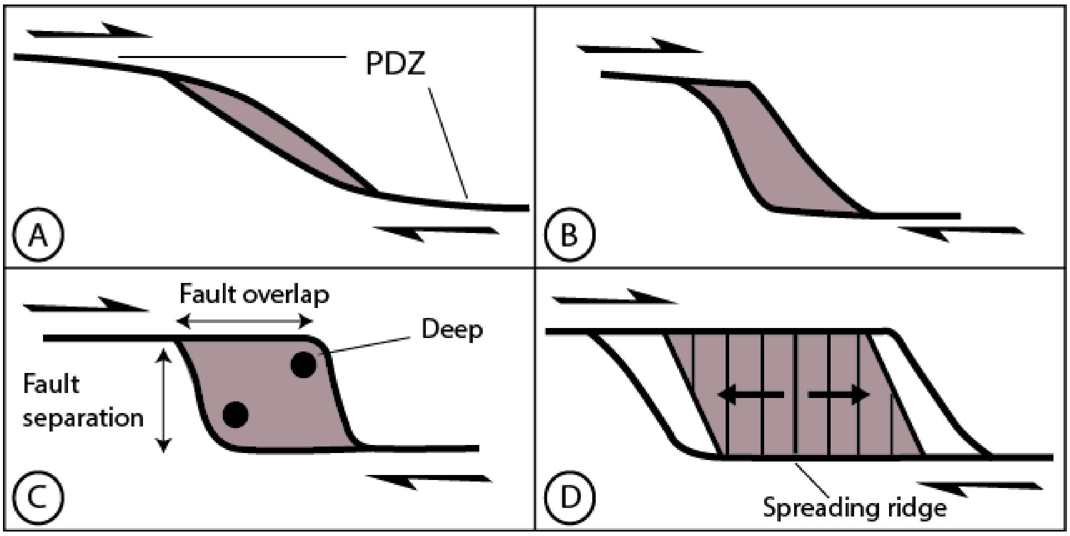

Figure 1. Model for pull-apart basin nucleation as (A) a spindle-shaped pull-apart and growth through (B) lazy-Z, (C) rhomboidal with dual depocenters, and (D) extreme pull-apart, with increased displacement on the master fault system. PDZ = Principal Displacement Zone. Modified after Mann (2007).

INTRODUCTION

Pull apart basin, a distinct feature in a trench-linked strike-slip fault system (e.g. Sumatran Fault (Bellier and Sébrier, 1994; Sieh and Natawidjaja, 2000)) or along continental transform faults (e.g. San Andreas Fault and Dead Sea Fault (Aydin and Nur, 1982; Christie-Blick and Biddle, 1985; Smit et al., 2008)) records history of strike-slip faults development (Smit et al., 2008). Pull-apart depressions of a variety of sizes form major discontinuities along straight segments of the main ‘principal displacement zone’ (PDZ) (Mann, 2007; Tchalenko and Ambraseys, 1970) (Figure 1). Furthermore, a close relationship between pull apart and magmatic activity have been well documented (Girard and van Wyk de Vries, 2005). Active pull-apart basins are easily recognizable along active strike-slip faults based on the occurrence topographic lows and fault-bounded depressions on land (Mann, 2007; Sieh and Natawidjaja, 2000). Whereas, observation of pull-apart depression in offshore areas (Lelgemann et al., 2000; Susilohadi et al., 2009) is challenging due to its thick sea-water column.

The Semangko pull-apart basin (SPB), the southern end of the Sumatran Fault zone (SFZ) (Sieh and Natawidjaja, 2000), is located in a transitional area between the frontal subduction zones in southern Java and the oblique subduction system in Sumatra. This transition area exhibits unique characteristics, including the disappearance of the forearc basin and the formation of horst and graben structures in this region (e.g. Lelgemann et al., 2000; Malod et al., 1995; Susilohadi et al., 2009) (Figure 2). Horsts and grabens formed in the SPB are the products of transtensional movement between the forearc Sumatra sliver plate and the main Sundaland (Lelgemann et al., 2000; Malod et al., 1995; Susilohadi et al., 2009). Two relatively north-south trending grabens are separated by a lineament of NW-SE basement highs (Lelgemann et al., 2000; Malod et al., 1995; Susilohadi et al., 2005). Graben formation and crustal thinning allow 6-km-thick graben fills as indicated on seismic reflection and refraction data (Lelgemann et al., 2000).

The vast thickness of the graben fills in the SPB raised questions on how this thick graben deposits have been formed and so the sediment source. Initiation of this graben had been proposed since 5 myr ago (Lelgemann et al., 2000; Susilohadi et al., 2009, 2005). While based on field geological observation along onland Sumatra, the formation of the active SFZ started 2 Ma, (Sieh and Natawidjaja, 2000). Assuming no compaction, the sediment thickness in the Sunda Strait graben indicates exceptionally high sedimentation rate. In contrast, part of the Sunda Strait graben situated in the present-day forearc basin is characterized by

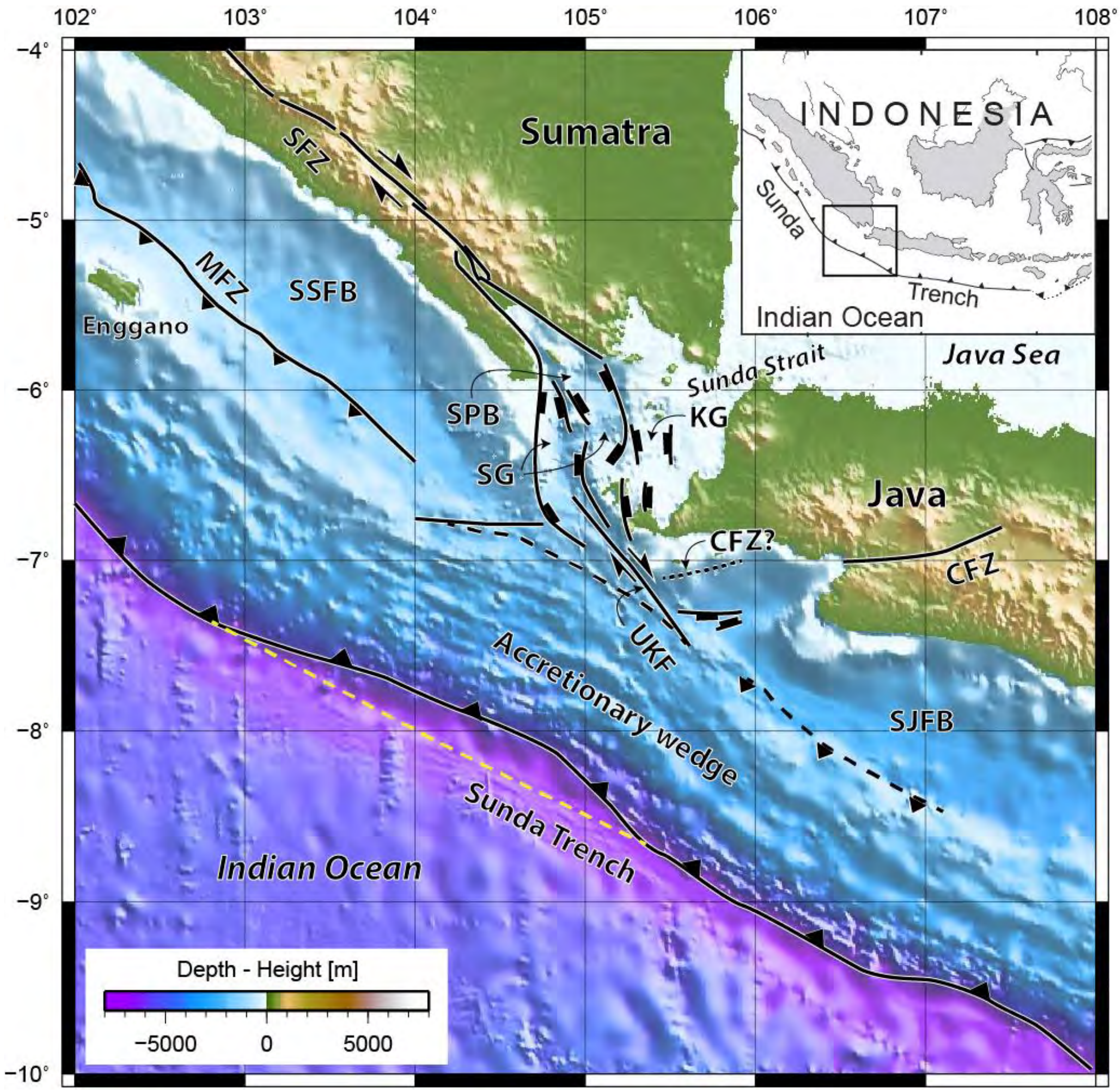

Figure 2. Tectonic setting of the Semangko pull-apart basin (SPB). The deep forearc basin to the south of SPB appears to be less developed as indicated by the termination of the South Sumatra forearc basin (SSFB) and the south Java forearc basins (SJFB). SG = Semangko Graben, KG = Krakatau Graben (Susilohadi et al., 2009); SFZ = Sumatra Fault Zone (Natawidjaja, 2018; Sieh and Natawidjaja, 2000); UKF = Ujung Kulon Fault (Arisbaya et al., 2016b; Malod et al., 1995); MFZ = Mentawai Fault Zone (Mukti et al., 2011, 2012a, 2012b); Backthrust in the south Java forearc is from Kopp et al., (2009); CFZ = Cimandiri Fault (Dardji et al., 1994; Handayani et al., 2017). Yellow dashed line marked the indentation of deformation front in the Sunda trench (Mukti et al., 2016).

thin sediments. This paper reviews the contrasting sediment depositions within parts of the graben related to structural styles developed in the SPB in order to understand the formation processes of the basin.

Geological Setting

The Semangko pull-apart basin is the southeasternmost segment of the SFZ, which extends 1900 km as a sinusoidal and segmented fault zone (Bellier and Sébrier, 1994; Lelgemann et al., 2000; Pramumijoyo and Sebrier, 1991; Sieh and Natawidjaja, 2000). In its northwesternmost part, the SFZ is terminated in an extreme rhomboidal pull-apart basin floored by oceanic crust in the Andaman Sea (Curray, 2005). Based on bathymetry and seismic data, the SPB may have been bounded by the SFZ and UKF (Malod and Kemal, 1996), suggesting that the SFZ extends farther southeast. A sliver plate occupies the space between the Sumatran trench and the SFZ (Jarrard, 1986; Malod and Kemal, 1996). The overall shape of the SFZ is sinusoidal that mimicked the sinusoidal trace of the Sumatran deformation front (Sieh and Natawidjaja, 2000). This observation indicates a close genetic link between the subduction process and the geometry of major fault zone (Mann, 2007).

The area around the Sunda Strait, which lies between Sumatra and Java exhibits morphology of high and low structures (Figure 2). This area has a maximum width of 125 km, covering a shallow part (<200 m) in the east of the strait and to a depth of more than 1600 m in the Semangko Graben. An active volcanic complex, Krakatau, is situated to the northeast of the graben. The internal structure of the Semangko Graben forms a north-south trending structure (Susilohadi et al., 2009). However, in some parts, southwest-trending structures are also observed (Lelgemann et al., 2000).

The forearc basin in the south of Sunda Strait is very narrow compared to the adjacent forearc basins, either south Sumatra or south Java (Malod et al., 1995; Schlüter et al., 2002). The accretionary prism complex formed relatively farther northeast and marked by a concave shape in the deformation front (Figure 2). Furthermore, the forearc basin appears to be less developed compared to that in the southwest Sumatra and south Java. The peculiar shape of the accretionary wedge and the disappearance of the deepest part of the forearc basin had been related to the movement of the Sumatra sliver-plate to the northwest, thus forming an extensional basin in the Sunda Strait (Huchon and Le Pichon, 1984; Lelgemann et al., 2000; Malod et al., 1995).

The formation of the Sunda Strait has also been suggested to have associated with the clockwise rotation of Sumatra to Java during Pliocene (Ninkovich, 1976; Nishimura et al., 1986). This rotation is believed to have accelerated the transtensional process in the Semangko Graben and transpressional regime in the Krakatau Graben (Schlüter et al., 2002). Furthermore, continental crust thinning has been observed from seismic reflection and refraction data that enhance graben formation in the Sunda Strait since 5 Ma (Lelgemann et al., 2000).

Based on new seismic data, details on the grabens formation and their basinal fills have been revealed by Susilohadi *et al.* (2009). These new data also described the occurrence of Krakatau Graben that is located to the east of the Semangko Graben (Schlüter et al., 2002). The Semangko and Krakatau grabens have been proposed to have initiated by the releasing stepover between the Sumatran Fault and its southeastern segment near Ujung Kulon (Susilohadi et al., 2009). Based on morphology and age of the pull apart basins, the Semangko Graben has been classified as recently nucleated and relatively young spindle-shaped pull-aparts (Mann, 2007), and as interpreted in the basin evolutionary model of Mann et al., (1983).

Pull-Apart Basin

A continuum model of pull-apart basin development had been proposed based on structural, sedimentary, and thermal characteristics of mapped active and ancient basins (Mann, 2007; Mann et al., 1983) that includes: (a) nucleation of spindle-shape pull apart on releasing bend, (b) continued offset forms "lazy S" geometry, (c) further continuation of offset produces rhomboidal or "rhomb graben" geometry, and with steady offset, rhomboidal basins can develop into (d) long narrow troughs which at some point develop a short spreading ridge and are floored by oceanic crust (Figure 1). In analogue modeling, both pure strike-slip and transtensional setting produce similar elongate rhomboidal to sigmoidal basins with arcuate oblique-extensional sidewall faults in plan view (Dooley and McClay, 1997; Rahe et al., 1998; Wu et al., 2009). This geometry is similar to many active and ancient pull-apart basins (Aydin and Nur, 1982; Christie-Blick and Biddle, 1985; Mann et al., 1983).

In a pull apart basin, there are at least two elements that commonly develop during the formation of the basin: basin sidewall fault (BSF) and cross-basin strike-slip fault (CSF). In a transtensional setting, the occurrence of en-echelon BSF in a pull-apart basin has been proposed as the primary character of the basin (Wu et al., 2009), whereas in pure strike-slip system, the en-echelon BSFs do not developed as evidenced in physical (Dooley and McClay, 1997; Rahe et al., 1998) and numerical modeling (ten Brink et al., 1996) (Figure 3). The Vienna transtensional pull-apart basin appears to have bounded by en-echelon oblique-extensional faults similar to that observed in analog model (Royden, 1985; Wu et al., 2009).

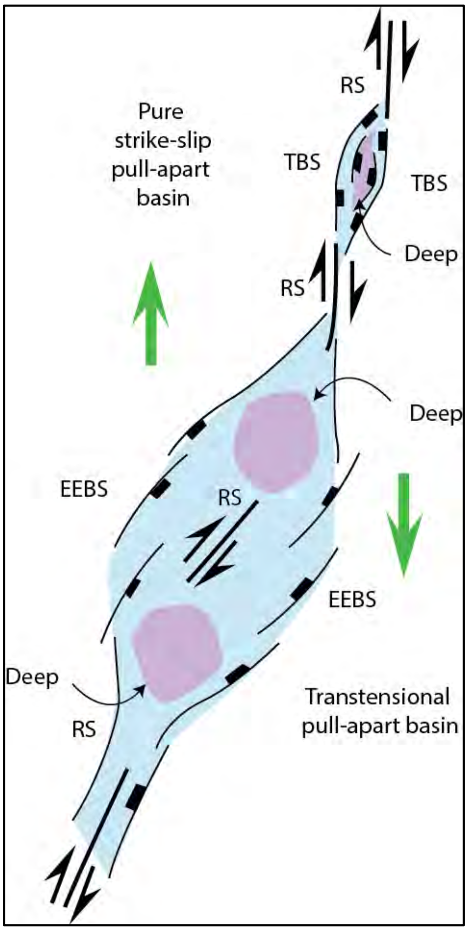

Figure 3. Plan view of structural configuration in a dextral pure strike-slip and transtensional pull-apart basins system. RS = Riedel shear; TBS = Terraced basin sidewall; EEBS = En-echelon basin sidewall. Modified after Wu et al. (2009).

Other field example of transtensional pull-apart basin with en-echelon marginal fault systems includes the Central Marmara Basin, Turkey (Armijo et al., 2002).

Another physical feature that exhibits during development of pull apart basin is dual depocenters separated by an intra-basinal high. Dual depocenters developed in both transtensional and pure strike slip pull-apart basin models (Sims et al., 1999; Wu et al., 2009). This feature is also observed in numerical models of pure strike-slip pull-apart basins (Katzman et al., 1995). Furthermore, development of a dual depocenter pull apart basin appears to be greatly enhanced in a transtensional pull-apart basin setting (Wu et al., 2009) (Figure 3). This morphology of dual depocenters might have developed because the area of maximum extension occurred at the junction of the PDZ with the stepover (Bertoluzza and Perotti, 1997). Field example of such transtensional pull apart basins is the Dead Sea basin that exhibits dual depocenter morphology (Smit et al., 2008).

A through going cross-basin strike-slip fault zone had been suggested to have formed a 'shortcut' across strike-slip releasing bends as the basin widen (McClay and Dooley, 1995; Wu et al., 2009). The development of this fault system had been observed in both pure strike-slip and transtensional pull-apart systems analogue (Dooley and McClay, 1997; Dooley and Schreurs, 2012; Rahe et al., 1998). Natural examples of transtensional pull-apart basin in the Vienna Basin revealed that continued strike-slip motion caused extinction of one PDZ, and strike-slip motion transfers via a linear cross-basin strike-slip fault across the remaining PDZ (Decker et al., 2005).

METHODS

This paper re-analyzes several published seismic reflection data acquired during SONNE-137 cruise (Reichert et al., 1999; Schlüter et al., 2002; Susilohadi et al., 2009, 2005). The seismic reflection data were acquired by using a 3 km long streamer, 14 second recording length, with a total track length of 4,138 km. For the background map, GEBCO one arc minute bathymetric data (British Oceanographic Data Center, 2003) is used. Determination of several key stratigraphic surface is referred to previous work of Susilohadi et al. (2009) with some modifications. The absence of well data that can be correlated to the seismic sections led to the uncertainty of age determination. The determination of pre-, syn-, and post-structural sequence related to the formation of the graben is referred to several published works of Dooley and McClay (1997), Dooley and Schreurs (2012), Rahe et al., (1998), and Wu et al., (2009).

RESULTS AND DISCUSSION

Basin Geometry and Depocenters

Based on the geometry of the Semangko pull-apart basin in Lelgemann et al., (2000), Mann (2007) categorized this basin to as active lazy-Z pull apart that known to have a single depocenter. However, based on maps of previous works, the SPB had been described as rhomboidal basin with several highs and lows (Malod et al., 1995; Malod and Kemal, 1996). The basinal lows appear as triangular shapes separated by a nearly NNW trending localized highs (Malod et al., 1995). None have been mentioned regarding the origin of these highs and lows. The UKF zone relays the Sumatra Fault to the south of the Sunda Strait pull-apart basin (Malod and Kemal, 1996). Lelgemann et al., (2000) had proposed the Tabuan – Panaitan highs as possibly a continuous N-trending ridge that subsequently stretched and sheared and thus broke into several distinct blocks.

Observation on the global bathymetric map suggested that the SPB consists of two depocenters separated by some localized highs along the center of the basin (Figure 4). The subaerial Tabuan Ridge (Susilohadi et al., 2009) is situated to the south of Semangko bay and elevated ~400 m above sea level. This ridge consists of volcanic edifices of breccias, lava and andesitic-basaltic tuff of the Lower Miocene Hulusimpang Formation, that locally covered by

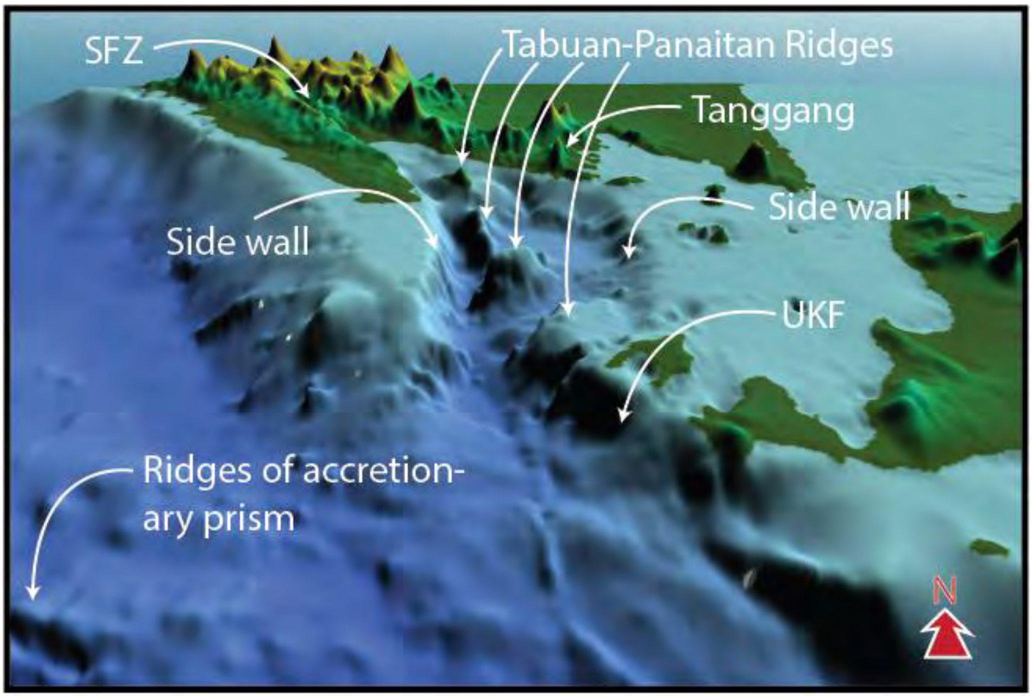

Figure 4. 3D perspective of bathymetry of the SPB showing the rhomboidal geometry bounded by basin side wall faults. Two depocenters in the basin are separated by discrete highs of Tabuan-Panaitan Ridges. Bathymetry is courtesy of GEBCO (British Oceanographic Data Center, 2003). Note the highly exaggerated vertical scale.

Quaternary coralline limestones in the northern most part of the ridge (Amin et al., 1993). To the south, a nearly linear submarine ridge is observed on the bathymetry with elevation ~1 km above sea floor of the deep basin. This ridge, the Central Tabuan Ridge, forms an 18-km-long prominent feature in the center of the basin. Further south, an almost circular submarine ridge is observed showing ~1450 m distinct high above the sea floor of the graben. Further south, near the Panaitan Island, a larger high is observed on the bathymetry and referred to as the Panaitan High. Bathymetric expression of the Panaitan High indicated that it may extend farther southeast to the westernmost part of Ujung Kulon area (Figure 4). No previous works have explained the origin of these Tabuan–Panaitan Highs. However, based on seismogram data deployed during the KRAKMON project, a cluster of seismicity had been observed around the Central Tabuan Ridge, approximately in the southern flank of the ridge (Arisbaya et al., 2016a, 2016b; Jaxybulatov et al., 2011). This cluster, which forms a vertical pattern with NWW-dipping column occur in a high-velocity area that may represent rifting processes in the lithosphere (Jaxybulatov et al., 2011) and transtensional in the Semangko pull-apart basin. The axial hinge of the Tabuan–Panaitan Highs appear to have develop in en-echelon system, sub parallel to the main trend of the highs (Figure 4). Based on geological field work in the Panaitan Island, the occurrence of volcanic edifices in the island may continue at depth through a magmatic dyke-like in the westernmost tip of Ujung Kulon (Atmawinata and Abidin, 1991). These volcanic units referred to as the Quaternary Payung volcanics that comprise andesitic-basaltic lavas, pumiceous tuff, and laharic breccia (Atmawinata and Abidin, 1991). Furthermore, Atmawinata and Abidin (1991) also revealed the occurrence of these Quaternary volcanics as localized highs in the southeastern part of Panaitan Island deposited above early Miocene volcanics of Cinangka Formation.

Structural Elements in the SPB

Basin sidewall faults

A single basin sidewall fault and terraced basin margin fault style have been proposed by previous works in the SPB (Lelgemann et al., 2000; Malod et al., 1995; Malod and Kemal, 1996; Susilohadi et al., 2009, 2005) (Figure 5). Those interpretation were probably the best that can be proposed for the margin of the SPB due to the wide spacing of the 2D seismic data set. Re-interpretation of two seismic lines crossing the northern and southern parts of the SPB has been carried out. These two lines reveal the structural styles on the basin sidewall, cross-basin strike-slip faults, and the kinematic strata during the development of SPB. Re-examination of the structural interpretation of the East Semangko Fault (ESF) by Susilohadi et al. (2009), found that this fault zone is actually characterized by a set of 4-7 normal faults (Figure 6). A similar character is also observed along the South Tanggang Fault (STF) which is regarded as the eastern basin side wall fault of the SPB. This fault zone comprised of 1 to 5 fault strands spread along the margin of the basin. Detail observation on the seismic section from the southeastern part of SPB found that a fault zone similar to STF is observed along eastern margin of the SPB (Figure 7). Further south, the South Panaitan Fault (SPF) have been interpreted as eastern margin of the West Semangko Graben (WSG) (Susilohadi et al., 2009). However, the characteristic of this fault is not similar with the fault zone in the north, along the eastern margin of WSG. Instead, the character of SPF is actually similar to STF, which acted as the basin sidewall fault of the SPB. Therefore, the eastern basin sidewall fault of the SPB may have developed farther south as compared to that interpreted by Susilohadi et al. (2009). Based on these analyses the ESF and STF may have developed as en-echelon basin sidewall faults as commonly found in a transtensional pull-apart basin (Armijo et al., 2002; Wu et al., 2009). Indeed, there are no narrow-grid 2D or even 3D data set available to verify this interpretation. However, the features observed on the available data set suggested that en-echelon basin sidewall faults may have likely been developed.

Cross-basin strike-slip faults

Based on the interpreted seismic data (Susilohadi et al., 2009), no indication of NE-SW structures that offset the Tabuan–Panaitan highs as proposed by Lelgemann et al., (2000). Moreover, the central Tabuan High exhibits radial features instead of a discrete block separated by faults. Beneath the top of the Tabuan– Panaitan High updoming reflectors are observed (Figure 6). Furthermore, an area dominated by blur reflectors with a vertical pattern is observed beneath the updoming reflectors. Seismogram data networks in the Sunda Strait suggest a cluster of epicenters occur around the

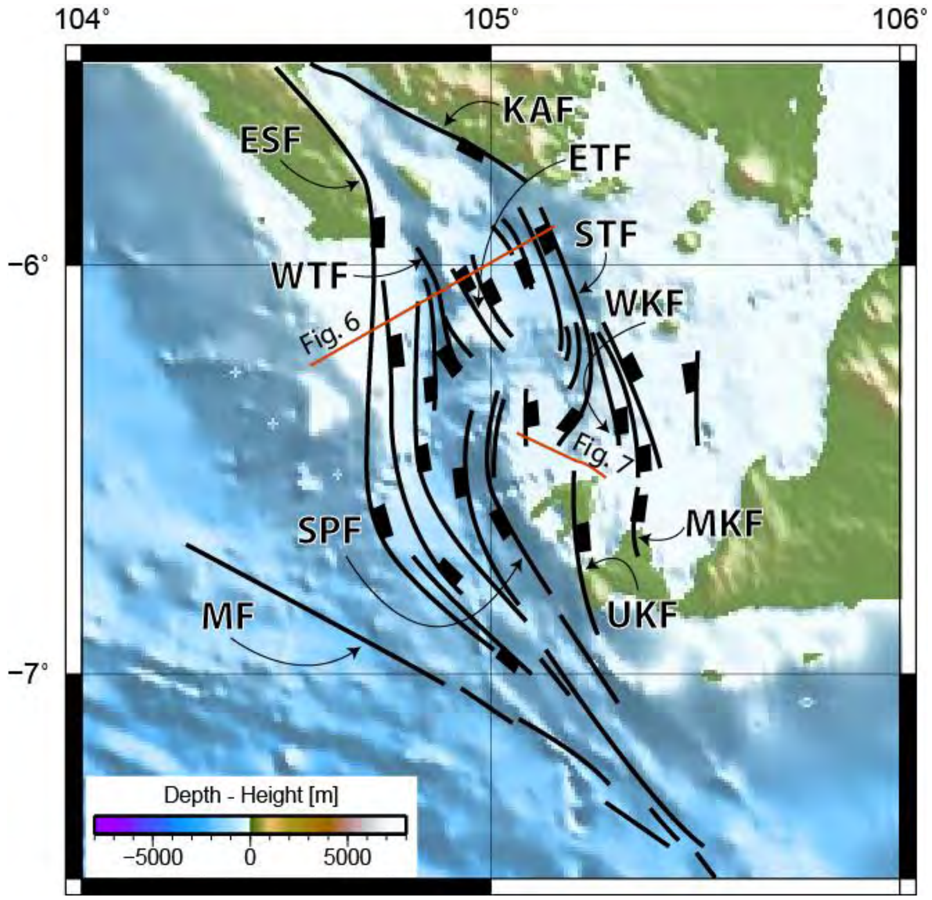

Figure 5. Structural configuration of the SPB (Semangko Pull-apart Basin) based on (Susilohadi et al., 2009). Note that some of the fault locations do not match with their bathymetric expression (i.e. the southern ESF located to the west of the basin side wall, the STF, the basin side wall does not observe farther south). ESF = East Semangko Fault; WTF = West Tabuan Fault; ETF = East Tabuan Fault; SPF = South Panaitan Fault; UKF = Ujung Kulon Fault; MKF = Mid Krakatau Fault; WKF = West Krakatau Fault; STF = South Tanggang Fault; KAF = Kota Agung Fault. Bathymetry is courtesy of British Oceanographic Data Center (2003).

central part of the Tabuan-Panaitan Highs, which shows a vertical distribution pattern (Arisbaya et al., 2016a; Jaxybulatov et al., 2011). This epicenters cluster forms a NWW-dipping column occur in a high-velocity area that may represent rifting processes in the lithosphere (Jaxybulatov et al., 2011). A NW trending anticline is observed in the southwesternmost of Ujung Kulon Peninsula, along the possible extension of the cross-basin fault farther southeast (Atmawinata and Abidin, 1991). Therefore, based on these observations, structures developed in Tabuan–Panaitan Highs may relate to a volcanic-magmatic activity. This volcanic-magmatic activity occurs through a weak zone created by en-echelon cross basin strike-slip faults. A strike-slip motion still can be observed beneath the Panaitan Ridge (Figure 7), suggesting the presence of cross-basin strike-slip fault along the axis of SPB. Such close relationship between pull apart basin and volcano-magmatic activity had been suggested in other areas (Girard and van Wyk de Vries, 2005).

Kinematic strata of the SPB

Susilohadi et al., (2009) divided the basin fill of the Semangko Graben into Unit 1–3 (Figure 6). Age determination of these seismic units were based on correlations with previous stratigraphic frameworks in the south of Java and west of Sumatra (Beaudry and Moore, 1985; Bolliger and Ruiter, 1975; Susilohadi et al., 2005). Unit 1, 2, and 3 represent Upper Miocene, Pliocene, and Pliocene–Pleistocene sediments, respectively. Units 1 and 2 appear to have deformed by normal

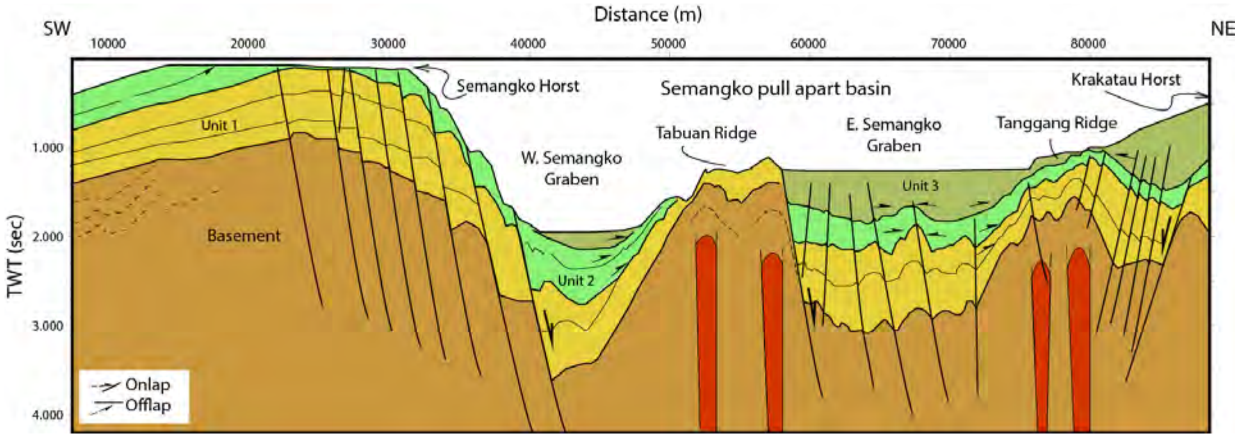

Figure 6. Re-interpretation of stratigraphy and structural styles in the SPB based on seismic section in Susilohadi et al. (2009). Dual depocenters marked by the West Semangko Graben (WSG) and East Semangko Graben (ESG). Tabuan Ridge developed in the center of the SPB, whereas a less prominence Tanggang Ridge formed near the eastern margin ESG. Stratigraphic unit is based on Susilohadi et al. (2009). See Figure 5 for the location of the line.

faults that bounded the Semangko pull apart basin. Unit 3 (Pliocene-Pleistocene) exhibits thicker layers in the East Semangko Graben as compared to that in the West Semangko Graben. Detail seismic characters and lithological interpretation of the basement and sedimentary rock units have been explained by Susilohadi et al., (2009). The following discusses the relationship between sedimentary units and the development of the pull apart basin.

Unit 1 is observed overlying the basement on the line that crosses the northern part of the SPB (Figure 6). Thickness of this unit appears to be relatively constant in the Semangko horst and thins near the Tabuan Ridge. Further east, Unit 1 appears to be thinly deposited over the Tanggang Ridge. Thickness of this unit is similar both in the hanging wall and foot wall of the main basin. However, the upper part of Unit 1 thins toward the tilted lower Unit 1 near Tanggang Ridge, suggesting that the ridge was uplifted prior to deposition of upper Unit 1. Unit 2 exhibits similar pattern with Unit 1, it is observed along the line with relatively uniform thickness. However, Unit 2 thins near the Tanggang Ridge, as indicated by onlap reflectors within this unit to the tilted Unit 1 (Figure 6). Unit 3 is deposited in the WSG and ESG where the thickness of this unit thickens in the eastern part of the SPB. Based on these observation, Unit 1 and Unit 2 may have been deposited as pre-kinematic strata in relation with the development of the pull apart basin, whereas Unit 3 formed as syn-kinematic basin fills. Similar pattern of sedimentary units is also shown in the southeastern part of SPB, where the basin sidewall fault deformed sediments up to Unit 2, suggesting that sedimentary unit below Unit 3 has been developed as pre-kinematic strata and Unit 3 as the pull-apart basin fill (Figure 7).

The Development of the SPB

Based on the re-interpretation of structural styles and stratigraphic units formed in the Semangko Pull-apart Basin, tentative development of the SPB related with the evolution of the SFZ is proposed. The development of discrete highs along the center of the SPB may have related with the formation of en-echelon cross-basin faults which then created a weak zone to allow volcanic activity or magmatic intrusion overprinted the structures as described in section 5.2.2. These cross-basin strike-slip faults may have initiated at least after the deposition of the lower Unit 1 or middle Late Miocene as indicated by onlap termination of upper Unit 1 on the tilted lower unit (Figure 6). Some of the strike-slip fault in these highs still can be observed in the seismic profile further south of Tanggang High (Figure 7). The subsequent phase of the Tabuan-Panaitan ridges uplift is identified by onlap termination upper part of Unit 3, suggesting recent activity of these ridges. This activity could be due to either the cross-basin strike-slip faulting or magmatic activities or even both of them.

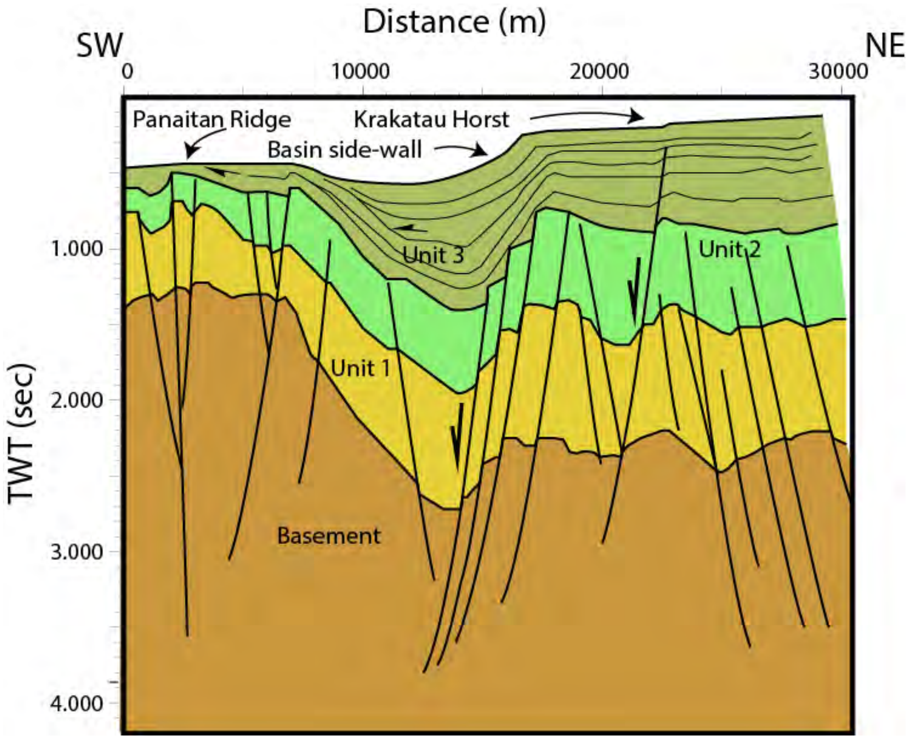

Figure 7. Re-interpretation of stratigraphy and structural styles in the southeastern part of SPB based on seismic section in Susilohadi et al. (2009). An unnamed fault zone may have correlated with the basin side-wall fault, the South Tanggang Fault (STF). This basin side-wall fault zone deformed the sediments up to unit 2, similar to that in the northern SPB. Deformation of basin fills up to the lower part of Unit 3 in the Panaitan Ridge suggest that the later episode after the initiation of pull-apart were responsible for the uplift of Panaitan Ridge. See Figure 5 for the location of the line.

The formation of the cross-basin strike-faults may initiate stepping over between the Sumatra Fault and Ujung Kulon Fault. This initiation phase induced by extension- of the crust (e.g. Wu et al., 2009) as evidenced by extensional events along the axes of SPB (Harjono, 1991). The initiation of the SFZ commenced in Middle Miocene based on the timing of Bukit Barisan uplift along the axis of the SFZ (McCarthy and Elders, 1997) and field work in the southeastern Sumatra by Pramumijoyo and Sebrier (1991). However, based on the results of active fault mapping, the SFZ was formed since 2 Ma (Natawidjaja, 2018; Sieh and Natawidjaja, 2000). Based on my observation on the growth strata, the initiation of the SFZ should be earlier than 2 Ma, at least since middle Late Miocene. Indeed, the correlation between seismic horizon with well data is tenuous, hence this conclusion can be changed with the addition of new data.

Based on the characteristics of the pre-kinematic strata, the basin sidewall fault of the SPB is likely to have developed after the deposition of Unit 2 or since late Pliocene (~2 Ma), or contemporaneously with the initiation of the active SFZ (Natawidjaja, 2018; Sieh and Natawidjaja, 2000). The formation of the SPB had also been proposed to have related with the development of Krakatau Graben to the east (Susilohadi et al., 2009). However, there is no direct evidence to support this hypothesis. The basin sidewall fault of the SPB is marked by the ESF in the northern segment that continued farther south and formed the western margin of the WSG. In the eastern part of the SPB, the ESG is bounded by Kotaagung Fault in the northern segment that extent farther south to the STF and acted as basin sidewall faults with possibly en-echelon configuration. These results revised the previous proposal for the development of terraced basin sidewall faults type in the SPB (Malod and Kemal, 1996; Natawidjaja, 2018; Susilohadi et al., 2009, 2005).

The SPB is developed as a transtensional pull-apart basin due to the step over of the Semangko and the Ujung Kulon segments of the SFZ. The name of Ujung Kulon Fault has been proposed for the southeastern segment of Sumatra fault zone (Malod and Kemal, 1996), and for the east dipping fault crossing the Ujung Kulon Peninsula that may related with the margin of the Krakatau Graben (Susilohadi et al., 2009). Here, I referred the Ujung Kulon Fault as the southeastern segment of SFZ but with revised location validated with bathymetry and seismicity data (Arisbaya et al., 2016b) suggesting the activity of this southeasternmost segment of the SFZ. The continuation of the SFZ can be traced farther southeast crossing the Sunda accretionary wedge complex.

Based on the interpretation of kinematic strata, the basin fill of the SPB are actually thinner as compared to the results of previous works (Lelgemann et al., 2000; Malod and Kemal, 1996; Susilohadi et al., 2009). In the north, the syn-kinematic strata of the SPB is up to ~0.8 sec thick in the ESG, and ~0.3 s in the WSG. Farther south, Unit 3 reaches ~0.8 s thick in the ESG. Similar thickness is also observed in the Krakatau horst, suggesting that the activity of basin sidewall fault (STF) is waning. However, a normal fault to the east of STF deformed sediments up to the upperpart of Unit 3, suggesting that the activity of the basin sidewall fault may have jumped outward of the SPB. I speculated this activity may be related with the recent growth of the SPB.

CONCLUSIONS

Based on the interpretation of the structural styles and stratigraphic units formed in the Semangko Pull apart Basin using published seismic and bathymetry data I proposed SPB have formed as a transtensional pull apart basin due to the step over between the Semangko and Ujung Kulon segments of the SFZ. The geometry of the SPB reveal a rhomboidal shape with dual depocenetrs separated by a discrete structural high in the center of the SPB. Based on the determination of pre- and syn-kinematic strata related to the formation of SPB, sedimentary units prior to deposition of Unit 3 is acted as pre-kinematic strata. The syn-kinematic package is represented by Unit 3. The basin sidewall fault of the SPB is likely to have developed as en-echelon side wall fault after the deposition of Unit 2 or since late Pliocene (~2 Ma). These basin side wall faults are marked by the ESF and KAF-SPF in the western and eastern margin of the SPB, respectively. The development of discrete highs along the center of the SPB may have related with the formation of en-echelon cross-basin faults that now may have overprinted by volcanic activity or magmatic intrusion. These cross-basin strike-slip faults appear to have initiated at least after the deposition of the lower Unit 1 or middle Late Miocene. Furthermore, recent activity of the cross-basin strike-slip fault may have related with the uplift of the Tabuan-Panaitan ridges. Outward development of the basin sidewall faults could represent the recent growth the SPB.

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