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Research article

The origin of Baribis Fault and its relationship to the dynamics of Sunda Arc

Hanief Ajib Abdalla[1,2*], Nasywa Dhia Khalifa[1,3], Cyntia Adrian Lestari[1,3], M. Maruf Mukti[4], Akhmad Khahlil Gibran[2], Fadlin[2]

[1] MBKM Program, Geological Resources BRIN, Bandung 40135, Indonesia
[2] Geological Engineering, Jendral Soedirman University, Purwokerto, Indonesia
[3] Geological Engineering, Padjadjaran University, Jatinangor, Indonesia
[4] Geological Resources, BRIN, Bandung 40135, Indonesia

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Corresponding author:
Hanief Ajib Abdalla
Email address: hanief.abdalla@mhs.unsoed.ac.id

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ABSTRACT

Based on analyses of published geological cross sections along the Baribis Fault, we briefly review several possible mechanisms of this backarc thrust that developed behind the volcanic arc in western Java. There is no general agreement regarding the mechanisms of the backarc thrust. Therefore, the origin of this fault remains uncertain. Previous works proposed that the backarc thrust in western Java may have developed as deformation of paleo-accretionary wedge sediments behind a continental backstop, inverted normal fault, northward migrating thrust belt, and thrusting due to gravitational sliding of the volcanic arc. However, evidences supporting those mechanisms still need to be elucidated. Detailed examination of the available geological data might suggest that backarc thrusting in western Java may have formed due to stress transfer through rigid arc blocks. The far-field stress from the subduction zone is propagated through remnants and modern volcanic arcs and finally, deformed sediments in the Bogor Trough that nucleated as backarc thrust.

INTRODUCTION

In several locations of active margin, backarc thrusting with vergence away from the arc have been observed along backarc region, close and parallel to the arc (e.g., Bali-Wetar margin (Silver et al., 1983; Yang et al., 2020), Panama (Suárez et al., 1995), Vanuatu (Lagabrielle et al., 2003), Caribbean (ten Brink et al., 2009). Such backarc thrusting hosts several large earthquakes, such as the 1992 Mw 7.9 earthquake nucleated in the Flores backarc thrust and recorded as the largest event in the area, generating a large destructive tsunami (Beckers & Lay, 1995) (Figure 1a). In 1991, the Mw 7.7 Limon earthquake occurred along the Caribbean coast of Costa Rica and Panama. This earthquake caused widespread damage of infrastructures due to liquefaction by the shaking of the poorly consolidated coastal deposits (Suárez et al., 1995). In 2018, a Mw 6.4 broke the western part of the Flores backarc thrust, followed by four Mw >6 events and hundreds of aftershocks (Yang et al., 2020). The Flores backarc thrust has been interpreted to have continued farther west to the island of Java, distributed parallel to the axis of the island known as the Baribis-Kendeng backarc thrust (Koulali et al., 2016; Simandjuntak & Barber, 1996) (Figure 1b). The presence of backarc thrusting on the island of Java becomes a threatening potential hazard for residents of this densely populated island in Indonesia.

The origin of these backarc thrusts has been ascribed to several mechanisms: deformation behind a continental backstop (Simandjuntak & Barber, 1996) (Figure 1c); arc and continental collision (Silver et al., 1983); gravitational sliding (Hamilton, 1979; Satyana & Armandita, 2004; van Bemmelen, 1949); reversal of subduction polarity (Hamilton, 1979); inverted normal fault (Armandita et al., 2002); northward migrating fold-thrust belt (Martodjojo, 2003). Since there is no general agreement regarding the cause of this backarc thrusting, its origin remains to be elucidated. Here, we analyze several interpretations of the mechanism of backarc thrusting in the western part of Java proposed by earlier works to understand its origin, and further discuss its relationship to the dynamics of the Sunda arc. Furthermore, our understanding of the origin of the backthrust is an important input in earthquake disaster mitigation plans due to the activity of such faults in the near future.

GEOLOGIC SETTING

Indonesia is situated at the boundaries of three major plates: Eurasia, Indo-Australia, and Pacific-Philippine Sea. This tectonic setting makes Indonesia situated along an active plate margin due to the convergence of those plates. The interaction between the southeastern margin of the Eurasian plate (Sundaland) and the Indo-Australian plate formed the Sunda orogeny stretches between Sumatra in the west and Lesser Sunda Islands in the east (Simandjuntak & Barber, 1996). One of this subduction system results is the docking of the Mesozoic accretionary mélange complex (Simandjuntak & Barber, 1996) following the new subduction started since the Paleogene along the Sunda arc (Hall, 2012) (Figure 1c). In Java, this mélange complex plays as a basement for the sedimentary basin in the forearc and intra-arc area (Simandjuntak & Barber, 1996). To the north of the forearc basin, the modern volcanic arc chain occupied the axis of the island, overprinted the Late Miocene – Pliocene magmatic arc, whereas the Eocene – Oligocene magmatic arc stretches along the onshore forearc Java (Figure 1b) (Soeria-Atmadja et al., 1994). Farther north, the northern peneplain of Java is covered by Quaternary deposits. All these physiographic zones of Java extend along west-east trend, parallel to the axis of the island, that formed since the renewed subduction that elongated in west – direction in the south of Java since the Middle Eocene (Hall, 2012; Hall & Smyth, 2008).

The present-day subduction in the south of Java Island with a convergence rate of 58–65 mm/year from west to east (e.g., Koulali et al., 2016) causes seismogenic zone along the megathrust and earthquakes along active faults in the island (Figure 1) (Irsyam, 2017). The active faults include the transpressional left-lateral WSW-ENE-trending Cimandiri Fault (Arisbaya et al., 2019; Dardji et al., 1994; Handayani et al., 2017; Marliyani et al., 2016), the E-W-trending left-lateral Lembang Fault (Daryono et al., 2019), and the right-lateral WNW-trending Citanduy Fault (Simandjuntak & Barber, 1996). Another seismic activity cluster has also been reported recently, nucleated from the NE-SW trending Garsela Fault in the south of western Java (Arisbaya et al., 2023). Farther north, a major E-W trending Baribis Fault occurred near the toe of the modern volcanic arc (Aribowo et al., 2022; Simandjuntak & Barber, 1996) that extends farther east to the Kendeng, Flores, and Wetar faults (Koulali et al., 2016). The Baribis Fault exhibits a segmented northward-vergence backarc thrust that has been active since the Pliocene (Aribowo et al., 2022) (Figure 2). This fault extends farther east and merges with the Kendeng Fault in eastern Java, marking the presence of a major backarc thrusting in the boundary of the active continental margin. Farther east, crossing the boundary between active continental margin and island arc, the backarc thrust continued as the Flores-Wetar fault zone that hosted several large earthquakes nucleated from the backarc thrust system (Figure 1).

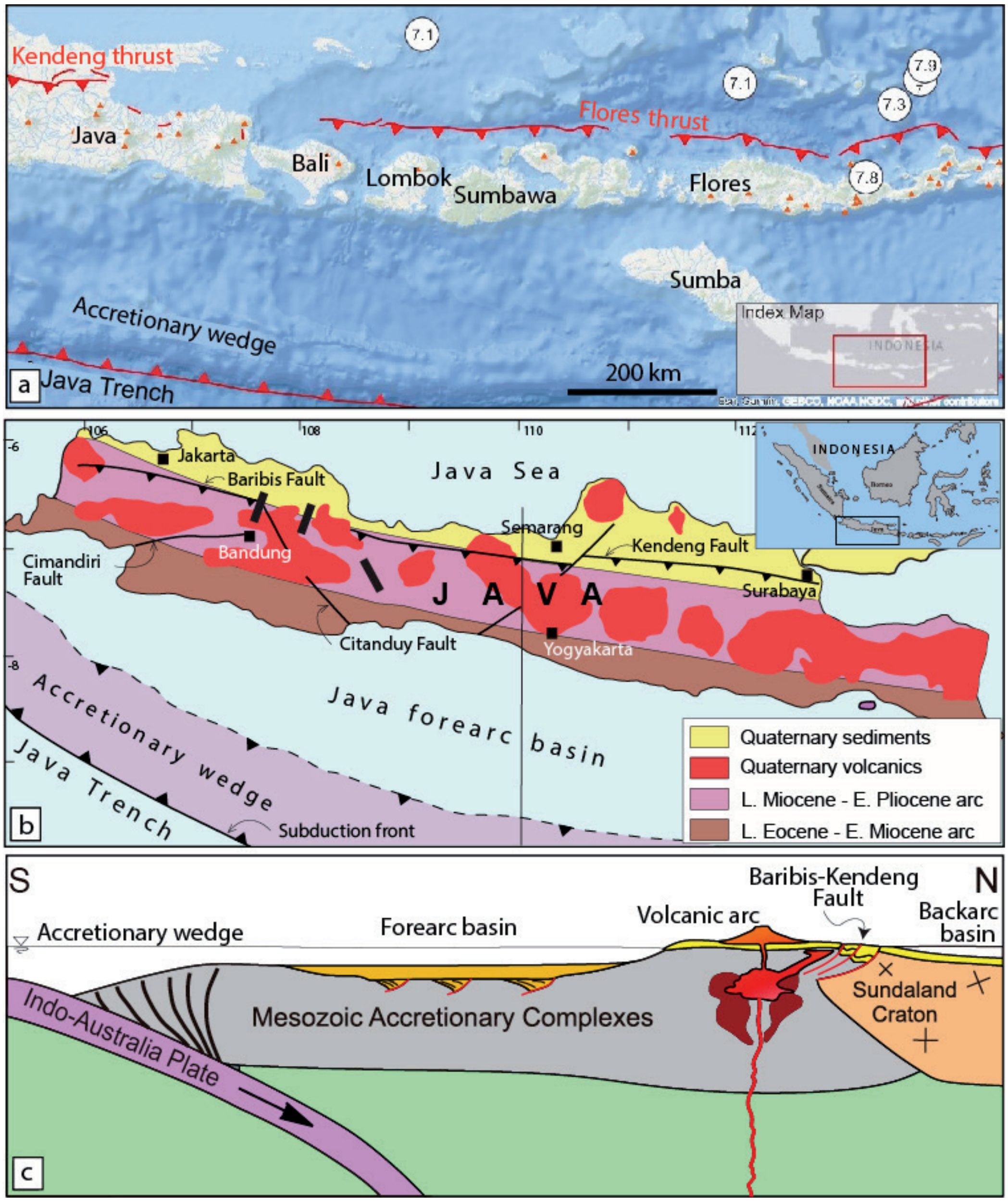

Figure 1. (a) Spatial distribution of large earthquakes (M > 7) close to Flores backarc thrust. (b) Map showing changing of remnant to modern volcanic arcs and in major faults in Java. Modified after Soeria-Atmadja et al. (1994), Simandjuntak & Barber (1996). (c) Schematic cross section across central Java showing convergence between the Indo-Australian and Sundaland craton, major structure from trench to backarc, including the Kendeng backarc thrust. See the location of the cross section in Figure 1b. Modified after Simandjuntak & Barber (1996).

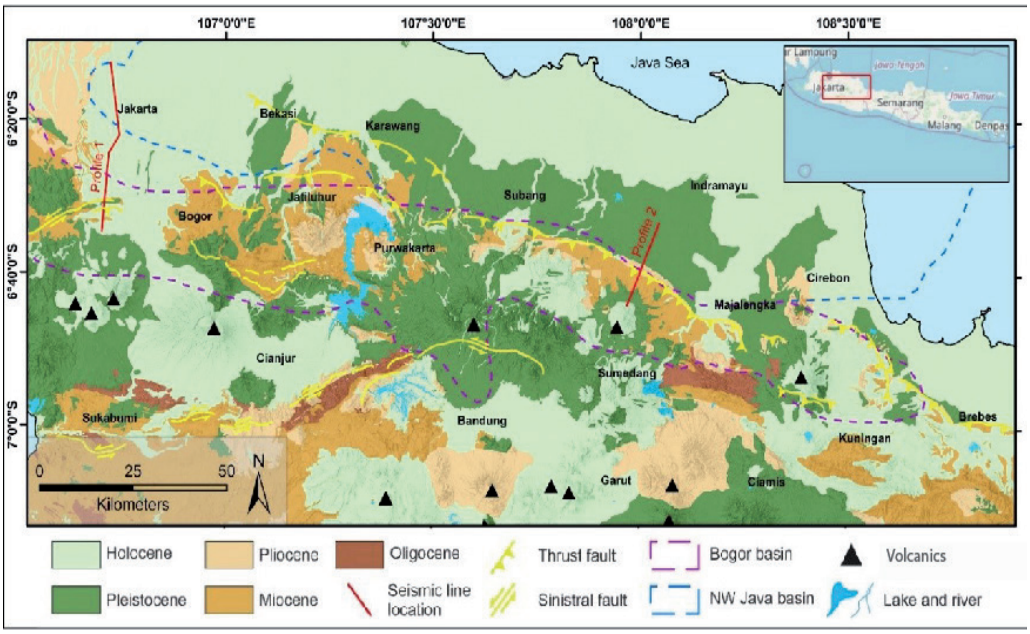

Figure 2. Simplified geological map of the northern part of West Java with the distribution of major active faults. Modified after Aribowo et al. (2022) and compiled from the Geological Survey Center-Indonesia (https://geoportal.esdm.go.id).

The stratigraphy of West Java is divided into three main areas: the Southern Mountains, Bogor Trough and Northern Java (Martodjojo, 2003) (Figure 3). In the basal part of the Bogor and Southern Mountain area the Eocene Ciletuh Formation shows mudstone, with quartz sandstone and graywacke. There are also occasionally observed polymict breccia with fragments of metamorphic rocks. The upper Eocene-Oligocene Jatibarang Formation is dominated by igneous and tuff, whereas the middle-upper Eocene Bayah Formation cropped out as sandstone-mudstone alternation. The upper Oligocene Batuasih Formation comprises mudstone and marlstone, interlayered with quartz sandstone calcareous sediments. The upper Oligocene-lower Miocene Rajamandala Formation consists of coral, clastic, and massive limestone.

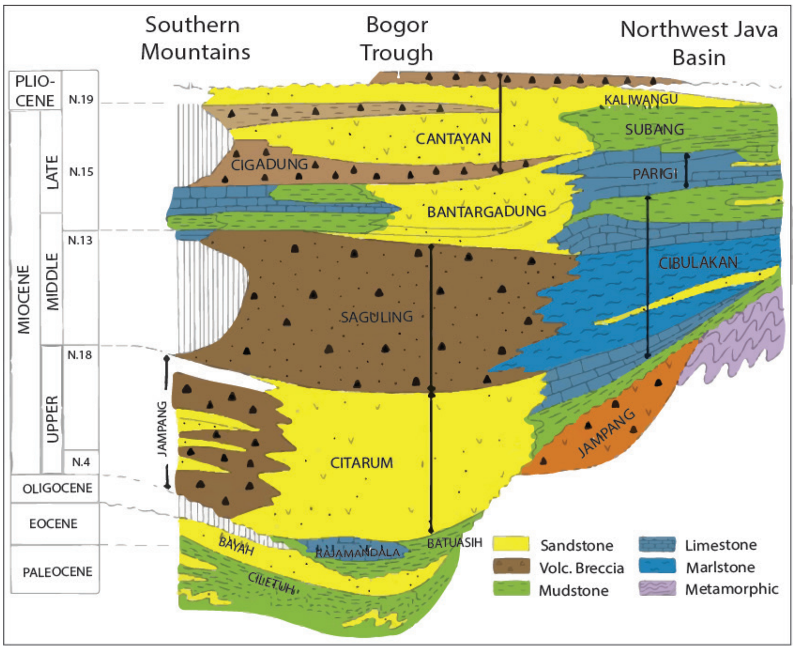

Figure 3. Cenozoic lithostratigraphic units in the Southern Mountains, Bogor Trough, and Northwest Java Basin. Modified after Martodjodjo (2003).

The Neogene strata in the Southern Mountains and Bogor Trough include the Lower Miocene Jampang Formation, which is dominated by volcano gravity-flow deposits and the Lower Miocene Citarum Formation (siltstone interbedded by sandy mudstone-siltstone and greywacke). The Middle Miocene Saguling Formation is dominated by breccia and mudstone, whereas the age-equivalent Cimandiri Formation comprises sandstone, sandy limestone, and conglomerate. The Middle-Upper Miocene series includes the Bantargadung Formation (mudstone interbed with greywacke and breccia) and Bojonglopang Formation (limestone). The upper Miocene strata comprise the Cigadung Formation (volcanic breccia) and the Cantayan Formation (breccia and tuffaceous sandstone). In the northern Java area, the middle-upper Miocene series includes the Cibulakan/Jatiluhur Formation (marl, sandy limestone, and limestone) and the Paragi/Klapanunggal Formation that is dominated by limestone. The upper Miocene and Pliocene rocks consist of Subang/Cisubuh Formation (marly sandstone and mudstone) and Kaliwangu Formation (sandstone, mudstone, and tuff interbedded with conglomerate), respectively. In the upper part, the early Pleistocene Tambakan Formation is dominated by laharic breccia.

STRUCTURAL OBSERVATIONS OF THE BACKARC THRUST

The available published geologic and geophysical data related to the backarc thrusting in Java and elsewhere were re-analyzed and reviewed in this paper. Several mechanisms for the growth of the backarc thrusting have been mentioned in the literature, in particular for the Java-Timor area, including deformation behind a continental backstop (Simandjuntak & Barber, 1996), inverted normal fault (Armandita et al., 2002), gravitational sliding (Hamilton, 1979; van Bemmelen, 1949), northward migrating fold-thrust belt (Martodjojo, 2003), arc and continental collision (Silver et al., 1983), and reversal of subduction polarity (Hamilton, 1979). However, in this paper, we exclude the mechanism of arc–continental collision and reversal of subduction polarity because they are only applicable for the collision of arc and continental margin and island arc subduction.

Deformation behind a backstop

A major backarc thrust extending along the island of Java is interpreted to have formed due to the deformation of the rear part of a Mesozoic accretionary wedge with the continental backstop in the north (Simandjuntak & Barber, 1996) (Figure 1). These authors interpret a change from extensional to compressional regime across the subduction zone due to a consequence of subducting features such as the Roo Rise on the Indo-Australian Plate. They further suggest that the compression behind the backstop may be due to magmatic intrusion and consequent uplift of the arc. This suggestion for the occurrence of a large backstop in north Java has been criticized as unclear (Clements et al., 2009). Furthermore, usually, the continental backstop occurs between the forearc basin and the continental margin (Chauhan et al., 2009; Kopp & Kukowski, 2003; Mukti et al., 2012). The concept of the basement of the forearc and arc of Java comprising a Mesozoic accretionary wedge can be excluded since recent works conclude that the basement is actually a continental fragment derived from Gondwana (Smyth et al., 2007). Moreover, recent geophysical investigation shows that accretion of remnant oceanic crust in the western part of Java is only observed in the offshore western Java forearc (Kopp et al., 2002).

Inverted normal fault

Armandita et al. (2002) proposed the mechanism of the Baribis Fault as an inverted normal fault based on the interpretation of contrasting bathymetry and stratigraphy between the area to the south of Baribis Fault (Bogor Trough) and the region farther north (Northwest Java Basin) from Oligocene to late Miocene (Figure 4a). These contrasting two adjacent basins are possibly bounded by a normal fault that inverted into a thrust fault during the Pleistocene. This argument was further supported by Satyana et al., (2002) by their observation of a geologic cross section interpreted from seismic reflection

(Supriyanto & Ibrahim, 1993) that showed a normal offset of Baribis Fault when crossing the Talangakar Formation at depth. In contrast, the offset of the fault crossing the shallower horizons from the Baturaja into the Cisubuh formations exhibits a reverse slip. We have looked at the original cross-section of Supriyanto & Ibrahim (1993) to verify the existence of the inverted normal fault and found that the occurrence of such fault is arguable. Furthermore, we do not observe any harpoon structure normally found in inversion tectonic (e.g., McClay, 1995).

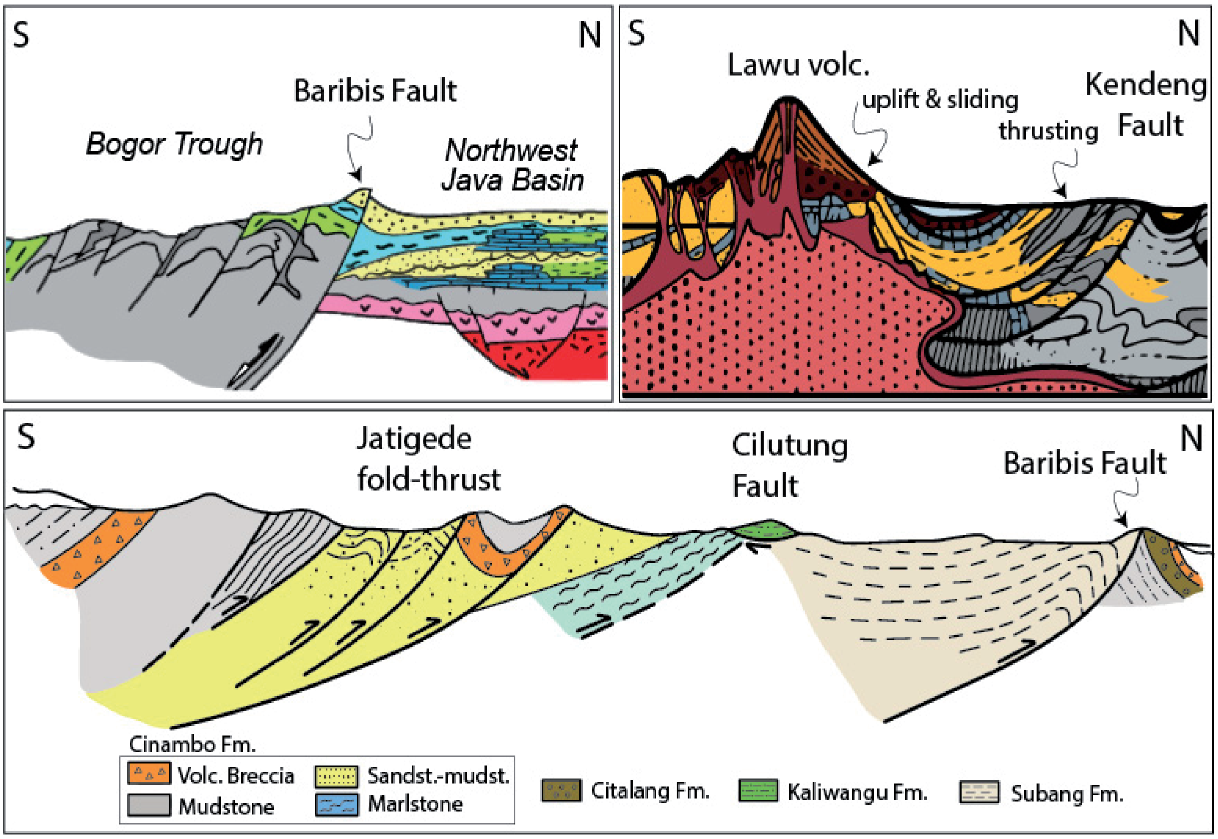

Figure 4. (a) Schematic geologic cross section showing the mechanism of inverted normal fault for the origin of Baribis Fault (Armandita et al., 2002). (b) Gravity sliding-induced thrust fault in the central Java (van Bemmelen, 1949). (c) Northward-migrating fold-thrust belt of the Baribis Fault in western Java (Martodjojo, 2003).

Figure 2 shows a detailed observation of the Baribis Fault along the northern area of western Java (Aribowo et al., 2022). They divided the Baribis Fault into 12 segments and proposed the recent activity of this fault zone. We show their interpretation of the Baribis Fault in two different areas, in the western and the easternmost segments (Figure 5). In general, in the footwall of the Baribis Fault, the seismic reflection shows several horizons interpreted as stacked sedimentary layers tilted and thickening to the southward. To the south of the Baribis Fault, the reflectors in the hanging-wall block are very chaotic. Therefore, it is difficult to correlate the horizons crossing the Baribis Fault or even identify any harpoon structures. Based on the distribution of these seismic reflection data, the Baribis Fault is formed north of the Quaternary volcanic (Figure 2).

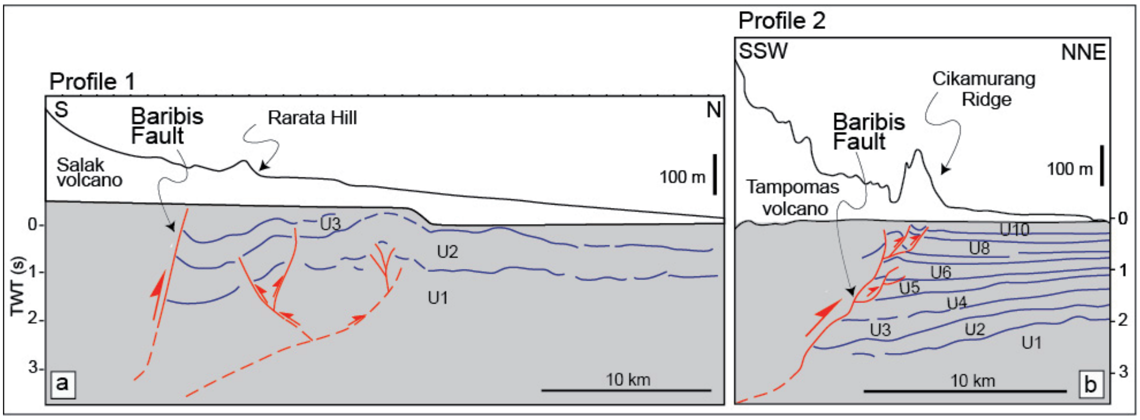

Figure 5. Interpretation of seismic profile crossing the Baribis Fault. (a) in the western part of Baribis Fault, and (b) in the eastern part. See Figure 2 for location of the profiles. Modified after Aribowo et al. (2022).

Gravitational sliding-induced thrust fault

Van Bemmelen (1949) proposed the origin of backarc thrusting due to the gravity sliding of the strata overlying the uplifted basement, which was followed by Hamilton (1979) and Satyana & Armandita (2004) for the growth of overthrusts in the backarc basin of central Java. (Figure 4b). This model explains the origin of the Baribis-Kendeng backarc thrusting in the northern margin of Kendeng Basin, which is the continuation of Bogor Trough farther east.

The mechanism of such a model suggests that large masses of strata overlying the basement rocks move down a slope under gravitational force due to the uplifted basement. The downward sliding of the sedimentary strata toward the north caused folding and overthrusting at the toe of the uplifted block. Furthermore, van Bemmelen (1949) suggested that the uplift of the basement also formed a spreading and tensional faulting at the top of the uplifted rocks. However, the folding and thrusting mechanism due to gravity sliding of the sedimentary cover of the basement requires a slope of the basement that tilted to the north that hosts a gliding plane or decollement zone, similar to that occurred in a gravity-driven toe-thrust belt in prograding delta (Maulin et al., 2019; McClay et al., 1998). Earlier investigations of such slopes underlying the area of the arc to the back arc basin in central Java revealed an adverse finding (de Genevraye & Samuel, 1972). Instead, a slope of the basement facing southward occurred in such an area based on analysis of the teleseismic receiver function (Anggono et al., 2020). Moreover, earlier observations showed that deformation in the Kendeng and Rembang zones occurred during volcanic quiescence and could not have been due to gravity sliding, as van Bemmelen proposed (Lunt et al., 1996).

Northward-migrating fold-thrust belt

Martodjojo (2003) proposes a northward-migrating fold-thrust belt to explain the Baribis Fault occurrence in the northern margin of Bogor Trough (Figure 4c). Based on fieldwork observation and seismic reflection interpretation, he concluded that the Baribis Fault was formed as a fault zone with several splays developed from the southern edge of Java to the present-day position of the Baribis Fault in the north. Figure 4c shows that the southern splay of the Baribis Fault deformed the early-upper Miocene sediments (Cinambo Formation). In contrast, in the northern part, the thrust displaced the upper Miocene-Pliocene strata. Furthermore, Armandita et al. (2002) observed a complex structure of Pliocene-Pleistocene rocks due to the activity of the Baribis Fault. However, we do not observe any folding and thrusting of Neogene strata in the area farther south between the southern coast of Java and the modern volcanic arc. Hence, the fold-thrust belts appear to have only formed in the area between the Quaternary volcanic arc and backarc basin. Therefore, evidence for the northward-migrating fold-thrust belt mechanism remains unclear.

DISCUSSION

The suit of evidence for the mechanisms of backarc thrusting in western Java discussed in the previous section is unconvincing. Therefore, we need to look more in detail at the mechanism of backarc thrusting elsewhere, including that formed in different geologic settings. Previous works attribute the occurrence of backarc thrusting to different phenomena, including the collision of continental margin with an island arc followed by subduction reversal (Byrne et al., 1985; Dewey & Bird, 1970), potential or incipient arc reversal (Hamilton, 1979; Yang et al., 2020), stress propagation from the collision in the forearc (Silver et al., 1983; ten Brink et al., 2009). Silver et al. (1983) further argued that the efficiency of stress propagation across the arc system also contributes to the growth of backarc thrust. They observed that backarc thrust is well developed in the area where the forearc crust is relatively thick. Based on laboratory sandbox modeling, ten Brink et al. (2009) proposed that the backarc thrust plays as a retrowedge thrust fault system. In contrast, the prowedge thrust system is represented by fold-thrust in the accretionary wedge near the trench, similar to that formed in the doubly-vergent accretionary wedge mechanism (McClay et al., 2004; Mukti et al., 2012; Willet et al., 1993). The concept of stress transfers through a rigid arc can explain why deformation in the backarc is dominated by a dip-slip thrust belt, whereas thrust faults are relatively rare within the arcs.

In the case of Java, the area between the present-day accretionary wedge in the south and the backarc thrust in the north comprises an amalgamation of volcanic arcs (Figure 1b). The southern part consists of the Late Eocene-Early Miocene volcanic arc, followed by the Late Miocene-Pliocene volcanic arc to the north. The Quaternary volcanic edifices overprint some parts of the Late Miocene-Pliocene volcanic arc. This observation leads to a suggestion that the area to the south of the backarc thrust is a rigid block comprising massive remnants and an active volcanic arc, similar to what was observed in the collision of arc and continental margin in Panama, the Caribbean, and Flores (e.g., Lagabrielle et al., 2003; Silver et al., 1983; Suárez et al., 1995; ten Brink et al., 2009). The stress generated from the subduction zone farther south off Java is transferred through the rigid arc blocks (Figure 6). Due to the rigidity of the massive arcs, the strain is only partly accommodated in the form of strike-slip faults (e.g., Cimandiri and Lembang faults in western Java (Daryono et al., 2019; Marliyani et al., 2016), Opak-Ngalang and Grindulu faults in eastern Java (Arisbaya et al., 2021; Librian et al., 2024). Farther north, the stress is transferred to the area behind the arcs and deformed thick sedimentary sequences in the form of backarc thrusting. Another factor that possibly controls the formation of intense deformation in the Bogor Trough in the form of backarc thrusting is the relatively much thicker basin fills than the adjacent basin (Mukti et al., 2009; Septama et al., 2021). Moreover, the basement in the Bogor Trough is much deeper than the area farther north (Anggono et al., 2020; Waltham et al., 2008). Furthermore, sandbox models generate backarc thrusting even in the absence of arc collision with a buoyant block, suggesting that the contribution of collision of arc and continental margin is not a necessity in the growth of backarc thrusting (ten Brink et al., 2009).

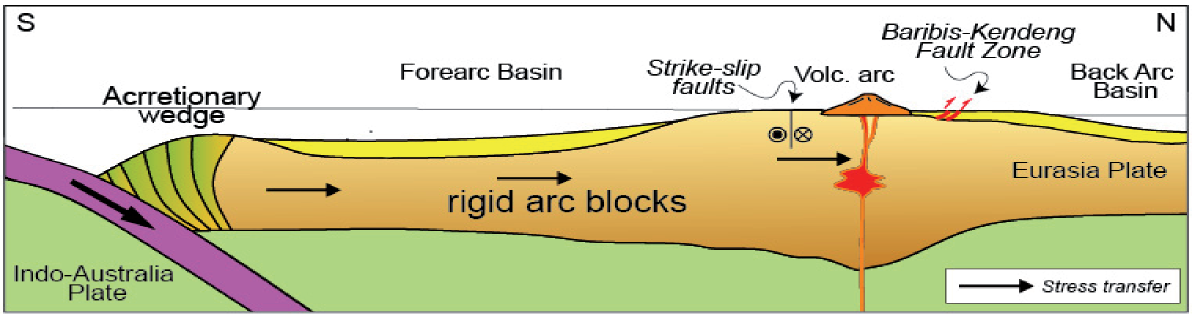

Figure 6. Conceptual cross section showing the possible role of rigid arc blocks that transfer the far-field stress from the subduction zone to the backarc, leading to the nucleation of backarc thrusting.

CONCLUSIONS

We reviewed several possible mechanisms of backarc thrust in the western Java so-called Baribis Fault, and we concluded that there is no general agreement regarding the mechanisms of this thrust system. Previous works proposed that the Baribis Fault may have formed as deformation of paleo-accretionary wedge sediments behind a continental backstop, inverted normal fault, northward migrating thrust belt, and thrusting due to gravitational sliding of the volcanic arc. We reanalyzed the evidence supporting those mechanisms and found that they are not unconvincing, yet they need to be more elucidated. Another possibility for the mechanism of the backarc thrusting in western Java is that such deformation may have accrued due to stress transfer through rigid arc blocks. The far-field stress from the subduction zone is propagated through remnants and active volcanic arcs and finally deformed thick sediments in the Bogor Trough that nucleated as backarc thrust.

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