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Rolling open Earth's deepest forearc basin

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ABSTRACT

The Weber Deep—a 7.2-km-deep forearc basin within the tightly curved Banda arc of eastern Indonesia—is the deepest point of the Earth's oceans not within a trench. Several models have been proposed to explain the tectonic evolution of the Banda arc in the context of the ongoing (ca. 23 Ma–present) Australia–Southeast Asia collision, but no model explicitly accounts for how the Weber Deep achieved its anomalous depth. Here we propose that the Weber Deep formed by forearc extension driven by eastward subduction rollback. Substantial lithospheric extension in the upper plate was accommodated by a major, previously unidentified, low-angle normal fault system we name the "Banda detachment." High-resolution bathymetry data reveal that the Banda detachment is exposed underwater over much of its 120 km down-dip and 450 km lateral extent, having produced the largest bathymetric expression of any fault discernable in the world's oceans. The Banda arc is a modern analogue for highly extended terranes preserved in the many regions that may similarly have "rolled open" behind migrating subduction zones.

INTRODUCTION

A subducting slab will sweep backward through the mantle if its negative buoyancy overcomes the mantle's viscous drag. This action—slab rollback—will drive a trench to migrate in the opposite direction to that of subduction, thereby enabling an arc to travel considerable distances and continually adjust its curvature (Dewey, 1980; Royden, 1993). Rollback may cause an adjacent mountain belt to switch between periods of shortening and extension (Lister and Forster, 2009), drive the extension of backarc and forearc basins (e.g., D'Agostino et al., 2011; Maffione et al., 2015; Do Couto et al., 2016), exhume metamorphic core complexes (e.g., Lister et al., 1984; Dewey, 1988), and/or cause oroclinal bending (e.g., Schellart and Lister, 2004). These first-order tectonic processes are intrinsic to the evolution of many, if not all, mountain belts; however, they are typically very difficult to identify once active deformation ceases. Consequently, the influence of slab rollback on the formation of mature and ancient mountain belts and basins is poorly understood. Here we demonstrate how slab rollback was fundamental to basin formation within the tightly curved Banda arc of eastern Indonesia (Fig. 1)—importantly, one of very few places where active subduction can be related to geological observations of modern orogenesis.

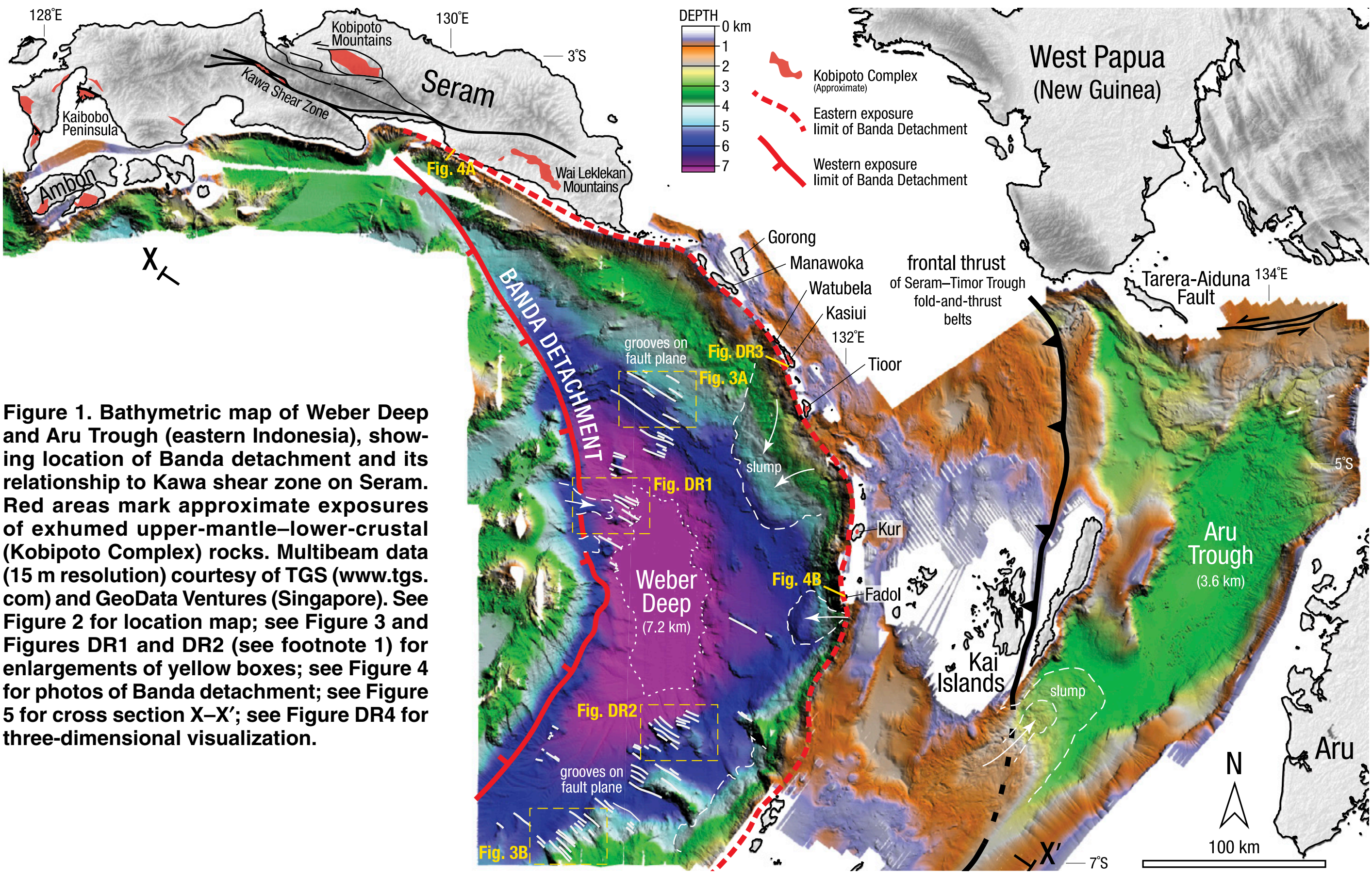

Figure 1. Bathymetric map of Weber Deep and Aru Trough (eastern Indonesia), showing location of Banda detachment and its relationship to Kawa shear zone on Seram. Red areas mark approximate exposures of exhumed upper-mantle–lower-crustal (Kobipoto Complex) rocks. Multibeam data (15 m resolution) courtesy of TGS (www.tgs.com) and GeoData Ventures (Singapore). See Figure 2 for location map; see Figure 3 and Figures DR1 and DR2 (see footnote 1) for enlargements of yellow boxes; see Figure 4 for photos of Banda detachment; see Figure 5 for cross section X–X′; see Figure DR4 for three-dimensional visualization.

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TECTONIC CONTEXT

The Banda arc (Figs. 1 and 2), due to its extreme 180° curvature, is often cited as a classic example of a modern orocline (e.g., Schellart and Lister, 2004). Jurassic oceanic lithosphere was subducted at the trench, beneath the Neogene Banda Sea, to form a highly concave westward-plunging synform that, at present, reaches the 660-km-depth mantle discontinuity (Spakman and Hall, 2010; Hall and Spakman, 2015). Although some authors have argued that this highly concave slab geometry was created by two independent subduction zones with opposite polarities (e.g., Cardwell and Isacks, 1978), there is now considerable evidence that it once comprised a single slab, deformed during slab rollback (e.g., Hamilton, 1979; Hall and Wilson, 2000; Milsom, 2001; Spakman and Hall, 2010; Hall, 2011, 2012; Pownall et al., 2013).

Unlike most modern arcs, the Banda arc does not preserve an oceanic trench because the rolling-back subduction zone has since collided with the Australian continental margin. It has been proposed that the shape of this margin from the Jurassic approximated that of the modern Banda arc (Hall, 2011), enclosing a D-shaped “Banda Embayment” of dense Jurassic oceanic crust (the proto–Banda Sea) that was readily subducted on arrival at the eastward-migrating trench (Spakman and Hall, 2010). Upon arc-continent collision, some buoyant continental crust of the Banda embayment margin may have entered the upper mantle in the final stages of subduction (Royden and Husson, 2009; Tate et al., 2015). During this time, there was thrusting toward the Australian continental margin to form the Seram Trough, the Timor Trough, and their adjacent fold-and-thrust belts.

Banda slab rollback has driven upper-plate extension since ca. 16 Ma (Pownall et al., 2014), opening the North Banda Basin (Fig. 2)

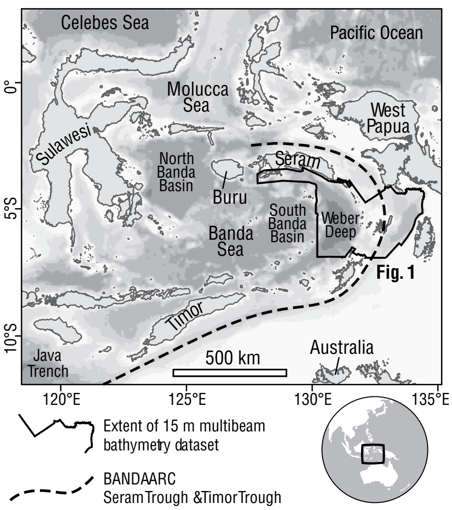

Figure 2. Map of eastern Indonesia showing location of Banda arc and extent of multibeam bathymetry data used in Figure 1.

between 12.5 and 7.2 Ma and the South Banda Basin between 6.5 and 3.5 Ma (Hinschberger et al., 2005). However, it remains unclear what caused the lithosphere within the Banda forearc to subside to depths >7.2 km below sea level and form the Weber Deep. Some authors have suggested that the Weber Deep formed as a flexural response to a tightening of the Banda arc’s curvature (Bowin et al., 1980) or the thrusting of the Banda Sea over the surrounding buoyant Australian continental margin (Hamilton, 1979). Others, who instead interpreted it as an extensional basin (Charlton et al., 1991; Hinschberger et al., 2005; Spakman and Hall, 2010; Hall, 2011, 2012), attributed east-west extension either directly to north-south shortening driven by the northward advance of Australia (Charlton et al., 1991) or to eastward slab rollback (Spakman and Hall, 2010; Hall, 2011, 2012) as discussed previously. The Weber Deep has also been explained as simply the result of sinking of the underlying Banda slab (Bowin et al., 1980; McCaffrey, 1988) without the requirement of rollback.

Here, we propose that basin extension and subsidence were driven by the final stages of Banda slab rollback and accommodated by extension along a vast but previously undocumented low-angle normal fault system—the Banda detachment—whose scarps form the eastern wall and floor of the Weber Deep.

EVIDENCE FOR THE BANDA DETACHMENT

Bathymetric Analysis

Figures 1 and 3 are images derived from 15-m-resolution multibeam bathymetry data of the eastern Banda arc, which cover the Weber Deep and the Aru Trough. Significantly, these data show corrugated landforms on inliers within the abyssal sedimentary infill. The ridges and grooves of these features are straight and are subparallel (within 10°) with consistent northwest-southeast orientations across the entire floor of the Weber Deep (Fig. 1). The grooves are most pronounced in the northern (Fig. 3A), western (Fig. DR1 in the GSA Data Repository[1]), and southern (Fig. 3B; Fig. DR2) parts of the Weber Deep, below 3 km depth. Large submarine slumps have blanketed much of the eastern rise.

We interpret these lineated surfaces as defining the footwall of a low-angle normal fault system (following Spencer [2010]) that closely approximates the morphology of the entire floor and outer wall of the easternmost Banda Sea. The grooved surfaces could belong to a single

[1]GSA Data Repository item 2016324, additional examples of grooved normal fault scarps flooring the Weber Deep (Figs. DR1 and DR2), a low-angle extensional shear zone on Kasiui (Fig. DR3), and a three-dimensional visualization of the Weber Deep (Fig. DR4), is available online at www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

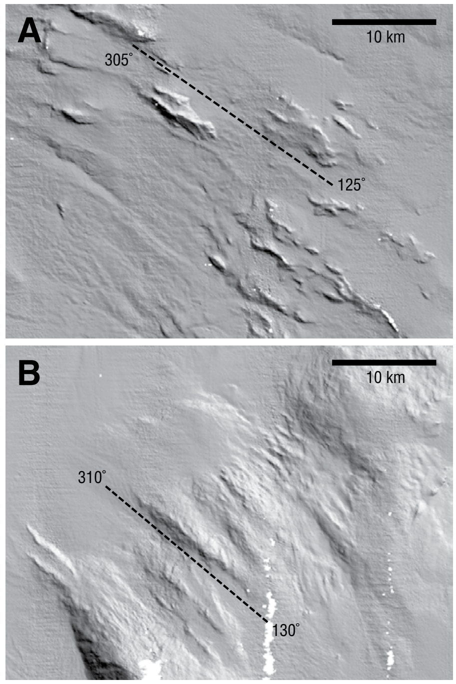

Figure 3. Enlargements of bathymetric map (marked by yellow boxes in Fig. 1) showing grooved normal fault surfaces composing fluted Banda detachment footwall, analogous to “turtlebacks” of Death Valley (California, USA) (Wright et al., 1974). Note consistent 130°–310° orientations, which are parallel to inferred slip direction and also to trend of Kawa shear zone on Seram. Further examples are shown in Figures DR1 and DR2 (see footnote 1).

low-angle fault, although they could alternatively mark subsidiary normal faults that shallow into a master detachment at slightly greater depth. The Banda detachment has a listric geometry, curving from a 12° dip adjacent to the eastern rim of the basin, to horizontal beneath the abyssal sedimentary infill, and becoming slightly back-rotated (by 1°) adjacent to the volcanic arc. We also interpret the grooves’ orientation and collective length to record a southeasterly slip direction of 120°–130°, along which the 450-km-long detachment must have slipped >120 km. To our knowledge, this is the largest normal fault system exposed anywhere in the world’s oceans.

Geological Evidence

The islands of Seram and Ambon (Fig. 1) have undergone considerable lithospheric extension throughout much of the Neogene (Pownall et al., 2013, 2014), attributed to their eastward movement above the rolling-back Banda slab (Spakman and Hall, 2010; Hall, 2011, 2012). Initially, this extension exhumed hot, predominantly lherzolitic mantle rocks to shallow depths (~30 km), inducing melting and granulite-facies metamorphism of adjacent crust under ultrahigh-temperature (UHT; >900 °C) conditions (Pownall et al., 2014; Pownall, 2015). Since ca. 6.5 Ma, peridotites and

high-temperature migmatites of the resulting Kobipoto Complex (Pownall, 2015) have been exhumed beneath low-angle detachment faults to the present-day exposure level across Seram (Pownall et al., 2013).

Our new field observations in the Wai Leklekan Mountains of eastern Seram (3.62°S, 130.46°E), and on the small Banda arc islands of Tioor, Kasiui, Kur, and Fadol, southeast of Seram (see Fig. 1), corroborate reports by Hamilton (1979), Bowin et al. (1980), Charlton et al. (1991), and Honthaas et al. (1997) of ultramafic rock and migmatite outcrops. In addition, we identified low-angle (12°) fault scarps in southeast Seram (Fig. 4A) and on Fadol (Fig. 4B) that we interpret as surface expressions of the Banda detachment (Fig. 1). Low-angle extensional shear zones were also observed on the south coast of Kasiui (Fig. DR3). On Fadol, where ultramafic rocks and felsic gneisses compose the footwall (Fig. 4B), a normal-shear-sense fault is the only way to account for the exhumation of upper-mantle–lower-crustal rocks (plus overlying Quaternary reefs) immediately adjacent to the 7 km Weber Deep.

We therefore propose that peridotites exposed around the eastern Banda arc, like the ultramafic rocks in western Seram, must have been exhumed from the shallow mantle and are not fragments of ophiolites. The similarity in ages of gneisses on Seram (ca. 16 Ma U-Pb zircon and ^{40}Ar/^{39}Ar biotite ages; Pownall et al., 2013) and on Kur (ca. 17 Ma K-Ar ages; Honthaas et al., 1997) further support a similar origin for exhumed lower-crustal–upper-mantle complexes around the northern and eastern Banda arc.

A final piece of evidence is that the grooves on the fault surfaces of the Weber Deep run parallel to strike-slip faults within the Kawa Shear Zone (KSZ) on Seram (Fig. 1)—a major lithospheric fault zone incorporating slivers of exhumed mantle (Pownall et al., 2013). The Banda detachment converges with the KSZ, and we interpret them as part of the same system. We infer that the KSZ must have functioned as a right-lateral continental transform east of 129.5°E in order to have separated northwest-southeast extension on the Banda detachment from contraction on land in northern Seram and offshore. Although the current geomorphological expression of the KSZ indicates a left-lateral shear sense, there is microstructural evidence for a complex history of both left- and right-lateral motions (Pownall et al., 2013).

"ROLLING OPEN" THE WEBER DEEP

To account for extension of the Weber Deep in a 130°–310° direction, we interpret the driving force—rollback of the Banda slab—to have followed the same southeastward trajectory. This inference is consistent with previous reconstructions by Spakman and Hall (2010) and Hall (2011, 2012), which depict southeastward

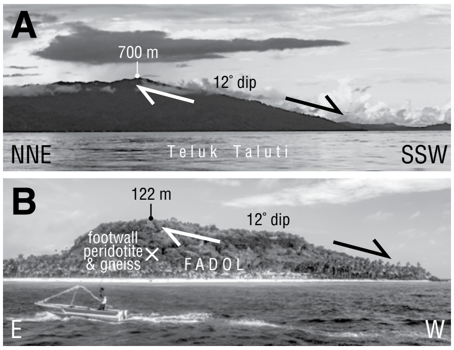

Figure 4. Banda detachment, exposed on land on eastern Seram (A; 3.46°S, 130.03°E) and on island of Fadol (B; 5.67°S, 131.94°E). Both fault planes dip toward Banda Sea at 12°, identical to dip inferred from Figure 1. Elevations of slope tops are marked in meters above sea level.

migration of the Banda subduction zone over the last 10 m.y. These plate reconstructions further suggest that the Weber Deep began to extend at 2 Ma (Hall, 2011, 2012), or alternatively 3 Ma (Hinschberger et al., 2005), during the final stages of rollback, synchronous with arc-continent collision. The relatively thin cover of basin-floor sediments (Hamilton, 1979; Bowin et al., 1980) is indicative of young and rapid subsidence of the Weber Deep. The depth of the basin may also have been enhanced by downward flexure of the underlying (gently dipping) Australian continental margin in response to the downward pull of the connected oceanic slab, as suggested for the shallower Western Alboran Basin (western Mediterranean Sea) which formed in a similar rollback setting in the Betic-Rif arc (Do Couto et al., 2016).

As illustrated in Figure 5, the Banda detachment must bound the upper surface of a lithospheric wedge, likely derived from the fragmented Sula Spur (Bowin et al., 1980; Hall, 2011, 2012), that was transported southeast and thrust over the Banda embayment continental margin. There is a terrane stack (cf. Lister and Forster, 2009, 2016) of Australian crust and lithospheric mantle slices sandwiched between the Banda detachment and the frontal thrust (labeled in Fig. 5). As observed, this stack includes lherzolites and high-temperature migmatites of the Kobipoto Complex (Pownall, 2015) and a number of core complexes which crop out across Seram and Ambon and around the eastern archipelago.

There is no evidence from recent seismicity that the Banda detachment is currently active. However, slip along the low-angle fault could feasibly operate through aseismic creep (e.g., Hreinsdóttir and Bennett, 2009) or may occur infrequently during catastrophic large-magnitude earthquakes (Wernicke, 1995). If the detachment is no longer active, its prominent topographic expression (Fig. 4) would suggest that its operation has only recently ceased.

CONCLUSIONS AND WIDER IMPLICATIONS

We conclude that southeastward rollback of the Banda slab since ca. 2 Ma (Hall, 2011, 2012) drove substantial extension of its forearc, accommodated principally by the 450-km-long Banda detachment, to form the 7.2 km Weber Deep (Fig. 5). Before this (16–2 Ma), the rolling-back Banda slab was forced by the resistance of the D-shaped Australian continental margin to adopt its extreme curvature, which in turn drove the lithospheric extension, mantle exhumation, crustal melting,

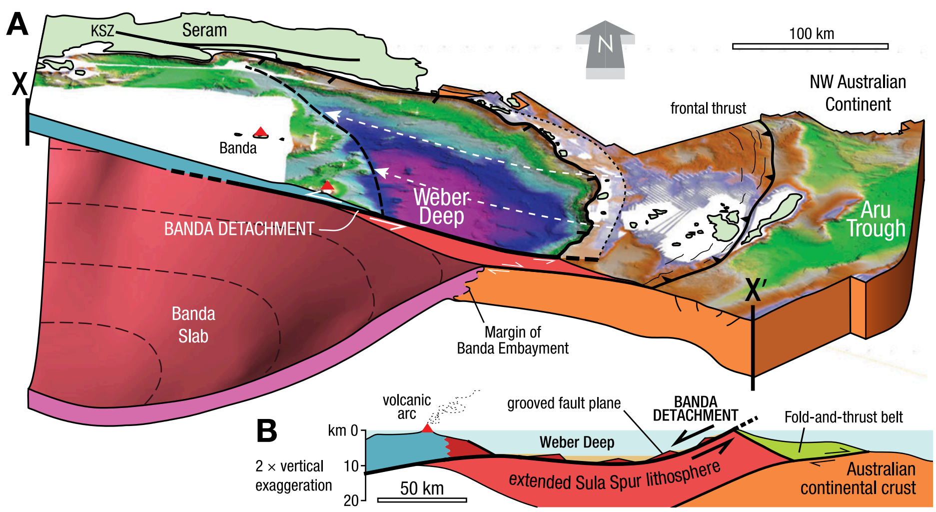

Figure 5. A: Cross section X–X′ (located in Figure 1; no vertical exaggeration) through eastern Banda arc, cut parallel to grooves on fault surfaces and proposed direction of rollback (southeast, 130°). Geometry of proto–Banda Sea slab is inferred from earthquake hypocenter locations catalogued by International Seismological Centre Online Bulletin (isc.ac.uk). KSZ—Kawa shear zone. B: Enlargement of Banda detachment (2× vertical exaggeration) showing schematically the configuration of over-riding continental allochthons (dark red). Red triangles represent volcanoes.

and high-temperature metamorphism across the northern and eastern arc. The Banda arc illustrates how slab rollback in the modern Earth may drive oroclinal bending and substantial extension of outer arc and forearc regions.

The Banda detachment and Weber Deep may be amongst the largest of their kind in the modern Earth, but they are similar in scale to many "fossil" examples preserved in older terranes. For instance, the Banda detachment's listric geometry, "upwarping" toward the volcanic arc (cf. Spencer, 1984), and size are all analogous to detachment faults characterizing the Basin and Range province in the western United States (e.g., Lister and Davis, 1989). Furthermore, the grooved fault surfaces in the Weber Deep are similar in morphology and scale to the "turtlebacks" (Wright et al., 1974) of California and Nevada (western United States). It is a distinct possibility that several older highly extended terranes, such as the Basin and Range, may have also formed in response to major rollback events (cf. Dewey, 1980, 1988; Lister et al., 1984; Royden, 1993) for which eastern Indonesia is a rare modern analogue.

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