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# Geological aspects of Banda Sea ecosystems and how they shape the oceanographical profile

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**Abstract.** The Banda Sea is a collage of young oceanic basins and fragmented Australian continental crust located at the heart of the Australia–SE Asia collision zone where Australian and Asian biogeographic regions converge. The formation of the sea was governed by the southeastward rollback of the Banda Slab since *c.* 16 Ma, which in its wake opened new oceanic basins and extended and fragmented Australian crust. These Australian crustal fragments are today either stranded within the Banda Sea where they form the prominent submarine 'Banda Ridges', or now reside as thrust-sheets on the NW Australian shelf after being transported all the way to the southern Banda Arc. The deepest part of the Banda Sea, the 7.2 km Weber Deep, was formed by extreme lithospheric extension that occured in the latter stages of Banda Slab rollback. This extension was accommodated by the vast low-angle 'Banda Detachment', which operated above the subducted fringes of the Australian continental margin.

## 1. Introduction

The Banda Sea is one of several seas located within the Indonesian archipelago between Australia and mainland SE Asia. Together, these seas comprise the route for the Indonesian 'Throughflow' between the Indian and Pacific oceans – a crucial gateway for ocean circulation and regulation of global climate [1, 2, 3]. These seas also mark the boundary for important biological separations. Wallace's line passes through the Celebes Sea and west of Sulawesi, while Weber's line and Lydekker's line both pass through the Banda Sea its self. These observations can all be explained when considering the region's changing tectonics. The formation of narrow seaways, and the juxtaposition of different flora and fauna, are both side-effects of the collision of Australia with SE Asia and the closure of the Tethys Ocean that once separated them [4] (Fig. 1).

One hundred and eighty million years ago (Ma), Australia and India both separated from Antarctica during breakup of the supercontinent Gondwana, later heading north. India collided with central Asia at around 50 Ma, ahead of the slower continent of Australia that collided with SE Asia at around 23 Ma [5]. Whereas India–Asia collision commenced early enough to have today produced the Himalaya, Australia–Asia collision is still in its infancy. In the place of 8000-metre peaks and an elevated continental plateau is a complex array of oceanic basins, continental fragments, volcanic arcs, and carbonate platforms. The infancy of the Australia–SE Asia collision zone accounts for why the geography and ecosystems of the Indonesian archipelago and its intervening seaways are so intricate and diverse.

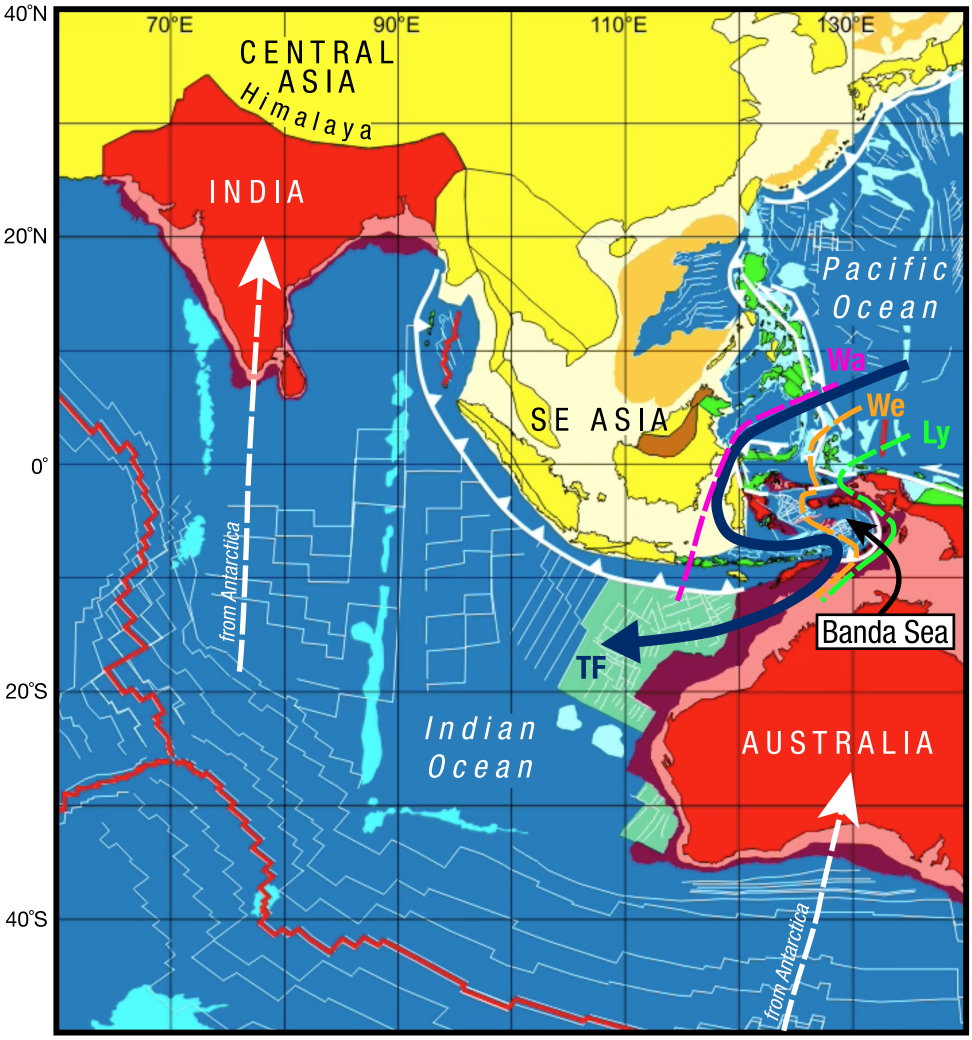

**Figure 1.** Map of India, SE Asia, and Australia. The Banda Sea is located within the SE Asia–Australia collision zone. India and Australia (Gondwanan; red), which both rifted from Antarctica at *c.* 160 Ma, collided with Asia (yellow) at *c.* 50 Ma and *c.* 23 Ma, respectively. Note the course of the Indonesian Troughflow (TF) oceanic current connecting the Indian and Pacific oceans, and the positions of Wallace's (Wa), Weber's (We), and Lydekker's (Ly) faunal boundary lines within the SE Asia–Australian collision zone. Figure adapted from Hall (2012) [4].

## 2. How did the Banda Sea form?

The Banda Sea has a complex and varied oceanographic profile due to the composite nature of the crust it overlies [6]. Young oceanic crust (12.5–3.5 Ma [7, 8]) contains numerous continental fragments such as those forming the Banda Ridges, and features the very deep oceanic basins of the North Banda Basin and Weber Deep (Fig. 2). The Banda Sea lies mainly within the curved island chain of the Banda Arc, from Timor to Tanimbar to Kai to Seram to Buru. An active inner volcanic arc from Damar volcano to Banda Api [9, 10] forms an eastward extension to the more mature volcanic islands of Flores, Alor, and Wetar. The 7.2 km deep Weber Deep [11, 12] is the forearc basin between the inner volcanic and outer non-volcanic arcs.

So, why is the Banda Arc so tightly curved? It's shape was dicated by the geometry of the underlying subducted slab, shown by the location of earthquakes produced within it to have assumed a highly

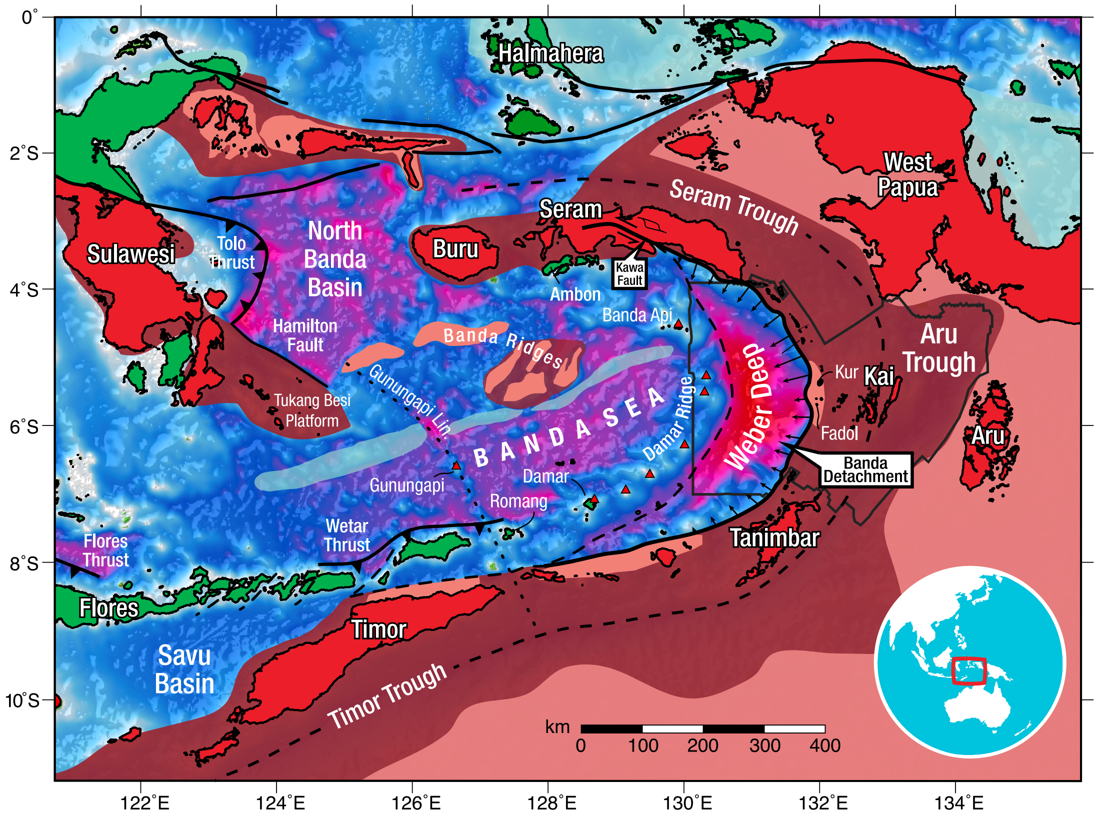

**Figure 2.** Present-day configuration of the Banda Sea, showing the location of the Banda Detachment flooring the Weber Deep [11]. As in Fig. 4, submarine arcs and oceanic plateaus are shown in pale blue; volcanic island arcs, ophiolites and material accreted along plate margins are shown in green; and Australian-affinity continental crust is shown in red.

concave spoon- or half-bathtub-shaped geometry [13, 14, 15] (Fig. 3). This slab, an eastward extension to the Java and Sumatra slabs, was once located adjacent to southern Sulawesi – a few thousand kilometres further west of its present location (Fig. 4a). As depicted by the tectonic reconstuctions in Figure 4, the location of the subduction trench has migrated gradually to the southeast, driven by the sinking of the slab—the Proto-Banda Sea—into the mantle through a process of ‘slab rollback’ [13].

The Proto-Banda Sea, Jurassic in age, once occupied a ‘Banda Embayment’ within the Australian continental margin not too disimilar in shape to the modern Banda Sea [5, 13]. As this old, cold, and dense oceanic lithosphere rolled back into the embayment (Fig. 3b,c), extension of the lithosphere behind the arc drove oceanic spreading, and the formation of new oceanic crust beneath the modern Banda Sea. The North Banda Basin and South Banda Basin spread open at different times behind this rolling-back arc, between 12.5–7.15 Ma [7], and 6.5–3.5 Ma [8], respectively. In addition to forming new oceanic crust, extension behind the rolling-back slab thinned and rifted apart Australian continental crust that once enclosed the northern extent of the Banda Embayment. This caused continental slivers to be standed within the Banda Sea in the form of the Banda Ridges (Fig. 2), as discovered by dredging [17]. Continental slivers may also have been transported immediately behind the rolling-back Banda Trench right up until the point of arc–continent collision between the Banda Arc and the southern Banda margin, causing Australian-affinity blocks from north of the Banda Sea to have been accreted onto a different part of the Australian continental margin in the vicinity of Timor and Babar [3, 6].

Extreme lithospheric extension driven by Banda Slab rollback (Fig. 4) also affected islands in the

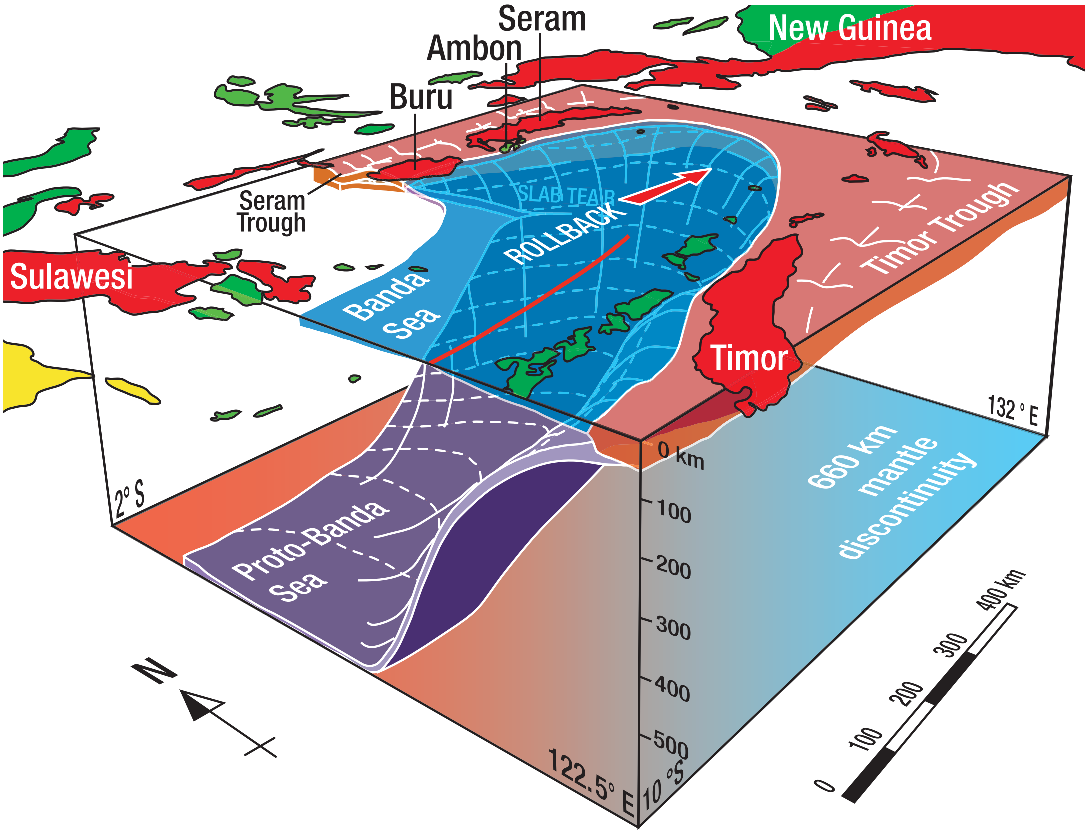

**Figure 3.** Present-day configuration of the Banda Sea, overlying the curved Banda Slab (the Proto-Banda Sea), modified from Pownall *et al.* (2014) [16]. Note the horizontal tear in the Banda Slab beneath Buru and western Seram.

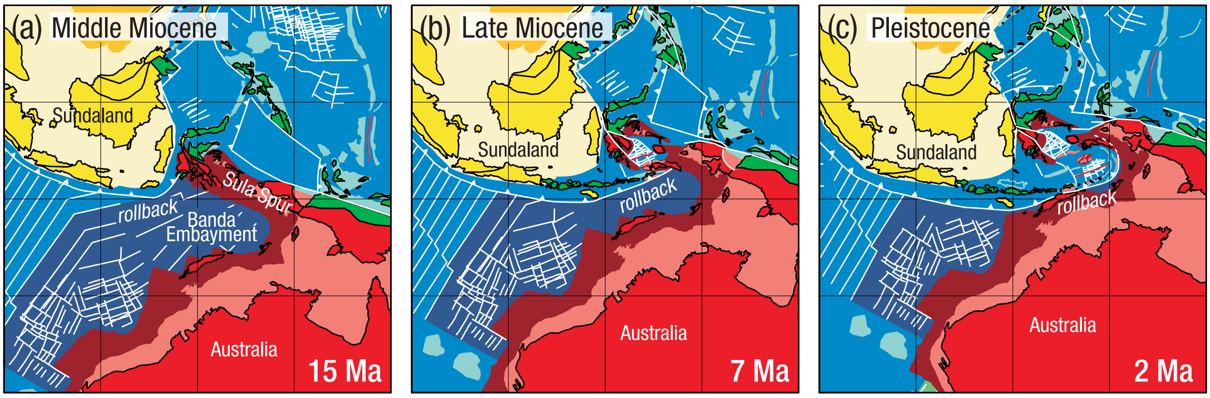

**Figure 4.** Tectonic reconstruction of eastern Indonesia, depicting formation of the modern Banda Sea during rollback of the Banda Arc, at (**a**) 15 Ma, (**b**) 7 Ma, and (**c**) 2 Ma (adapted from Hall, 2012 [4]). Oceanic crust is shown in dark blue (older than 120 Ma) and mid-blue (younger than 120 Ma); submarine arcs and oceanic plateaus are shown in pale blue; volcanic island arcs, ophiolites and material accreted along plate margins are shown in green.

northern Banda Arc. Hot mantle rocks were exhumed to the shallow sub-surface [11, 16, 18, 19, 20], driving crustal metamorphism of adjacent rocks under ultrahigh-temperature (UHT; $>$ 900°C) conditions [16, 21]. Volcanic rocks comprising the island of Ambon are shown to be derived primarily from the melting of these stretched continental crustal rocks [20], and so are disctinct from the volcanic products of the rest of the arc. However, volcanoes from Banda Api to Damar also record elevated continental input due to the subduction of continental material from the Australian margin [9, 10].

Exhumation of mantle rocks and HT–UHT metamorphic rocks in the northern Banda Arc was faciliated, in part, by strike slip faults such as the Kawa Fault of Seram (Fig. 2), and the associated Kobipoto Mountains pop-up structure [18, 21, 12]. The Kawa Fault is a major structure that has been fundamental in enabling the Banda Arc to roll back eastwards with respect to the northern Banda Embayment margin. The fault also forms part of a larger structure, the Seram–Kumawa Shear Zone, which may have developed in the Jurassic when continental blocks were rifted from the Banda Embayment [12].

## 3. SE Asia–Australia collision and the Indonesian Throughflow

Collision of SE Asia with Australia at *c.* 23 Ma [5] closed the deepwater passageway that existed between the Indian and Pacific oceans [1, 22]. The Indonesian 'Throughflow' describes the resulting oceanic current that follows a winding and anastomosing course through the narrow and shallow Indonesian seaways from the SW Pacific to the Indian Ocean (net flow rate: 15 Sverdrups [23]). The primary route follows the Makassar Strait, Flores Sea, South Banda Sea, and Timor Trench (Fig. 1), although weaker currents also pass through the Lombok and Ombai straits. Throughflow transport is governed seasonally by El Niño–Southern Oscillation and over millennial timescales by sealevel flucuations [22, 24]. Over geological time, the configuration and strength of the Throughflow has undoubtedly been controlled by the evolving tectonic configuration, with the uplift of mountain belts on, for instance, Sulawesi restricting the flow. Due to uncertainties of reconstructing exact palaeogeographies, it is not know exactly how the passageways of the Indonesian Throughflow evolved through time [22]. However, it is thought that the passageways were especially restricted between 12 and 3 Ma, with the narrowest gaps occuring at around 10 Ma [22].

## 4. Isostatic controls on the Banda Sea profile

Structures within slabs beneath the Banda Sea (Fig. 5), and the mechanism by which they were subducted, have been highly influential in controling on the oceanographic profile through their isostatic response:

- Within the northern limb of the slab beneath Buru, an aseismic zone is interpreted as a tear that has caused the slab to peel away from its northern margin [13, 14, 15] (Fig. 3), shown also by tomographic models [13, 15]. Propagation of this horizontal tear may have contributed to the rapid uplift rates recorded around the northern Banda Arc [25, 26] as the upper plate rebounded.
- The southern limb of the slab features a band of intense seismicity—the Damar Zone [27]—at 100–200 km depth, which extends westwards from the Aru Trough and terminates sharply just west of Romang at the plane of intersection with the 'Gunungapi Lineament' (Fig. 2) passing from the Timor Trough to the North Banda Basin via Gunungapi Volcano. We interpret this ridge to be the surface expression of a major subvertical slab tear that delineates the actively-rupturing slab on its eastern side, and which potentially accounts for the positive increase in mean topographic elevation identified by Sandiford (2008) [27] moving west from Romang to Wetar.
- There is a shallow-dipping section of slab extending to beneath the Weber Deep [11], which likely is the down-flexed and over-thrust outermost Australian continental margin (Fig. 5). Beneath the Weber Deep is the location of the continental–ocean transition, at which point the slab steepens abruptly. As discussed by Pownall *et al.* (2016) [11], the incredible depth of the 7.2 km Weber Deep forearc basin floor (Fig. 6) is likely supported by this shallow-dipping slab segment.

As discussed in the next section, the Weber Deep was created by the development of a low-angle detachment system during the final stages of extension behind the rolling-back Banda Slab [5, 11, 12].

## 5. The Weber Deep

The floor of the Weber Deep (Fig. 6, 7), beneath 7.2 km water depth, is the deepest part of Earth's oceans that does not occur in a trench. So why is this forearc basin so deep? It has been suggested that the Weber Deep formed as a flexural response to a tightening of the Banda arc's curvature [6], or in response to the thrusting of the Banda Sea over the surrounding Australian continental margin [28]. Alternatively, some authors by interpreting the feature as an extensional basin attributed east-west extension either directly to north-south shortening caused by the northward advance of Australia [29] or to eastward slab rollback [13]. The extreme depth of the basin has also been explained simply as the result of sinking of the underlying Banda slab [6, 30] without requiring rollback.

New high-resolution (15 m) bathymetry [11] has revealed in incredible detail intricate features of the eastern Banda Sea, including the Weber Deep and Aru Trough [11, 12]. Most notably, the entire Weber Deep forearc features a set of parallel striations or grooves oriented at 120–300 ± 10° (Fig. 6), which have been generated within a single low-angle detachment fault zone, the 'Banda Detachment' [11]. The detachment has a listric geometry, curving from a 12° dip adjacent to the eastern rim of the basin, becoming horizontal then slightly backrotated (by 1°) approaching the volcanic arc (Fig. 5b). The grooves' orientation and length demonstrate a southeasterly slip direction of 120–130°, along which the

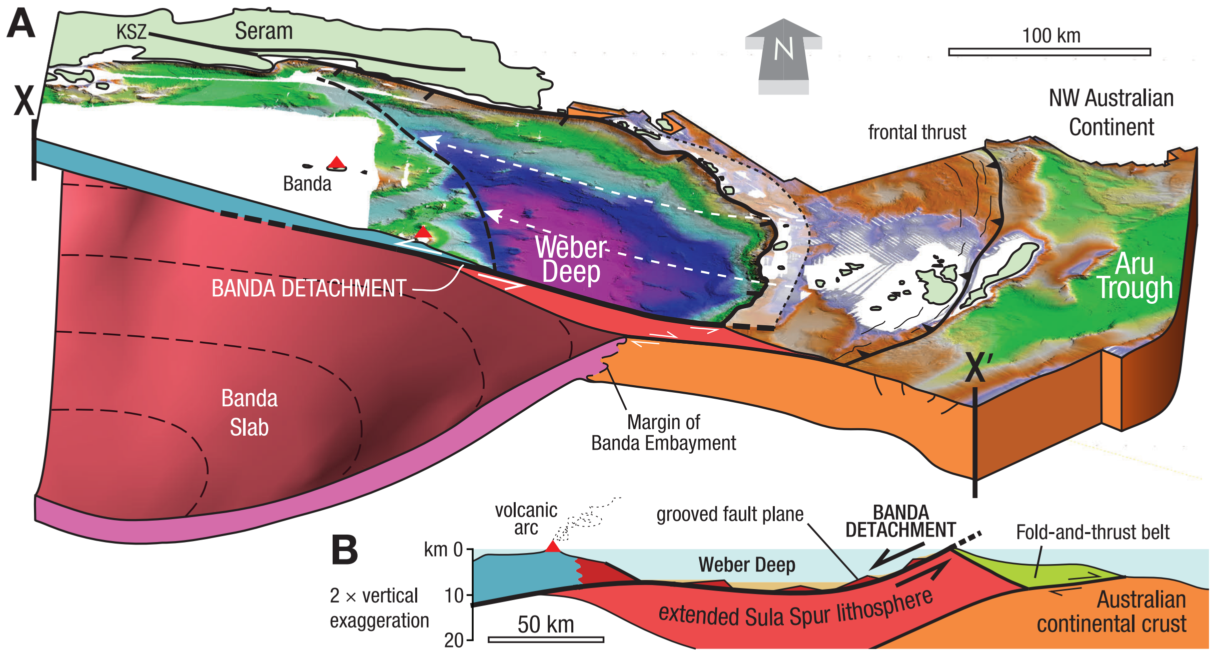

**Figure 5.** (**A**) Arc–continent collision in the Banda Region. Note how the continent–ocean boundary between the continental margin of the Banda Embayment (orange) and the Jurassic Proto-Banda Sea (pink) has been over-thrust by the modern Banda Sea (red and blue). Extreme lithospheric extension along the Banda Detachment has opened the Weber Deep above the Banda Slab. The location of this cut-away is shown in Fig. 6 by the line X–X′. (**B**) An enlargement of the Banda Detachment cross-section (2× vertical exaggeration) with the highly-extended Sula Spur lithosphere shown in red. Figure from Pownall *et al.* (2016) [11].

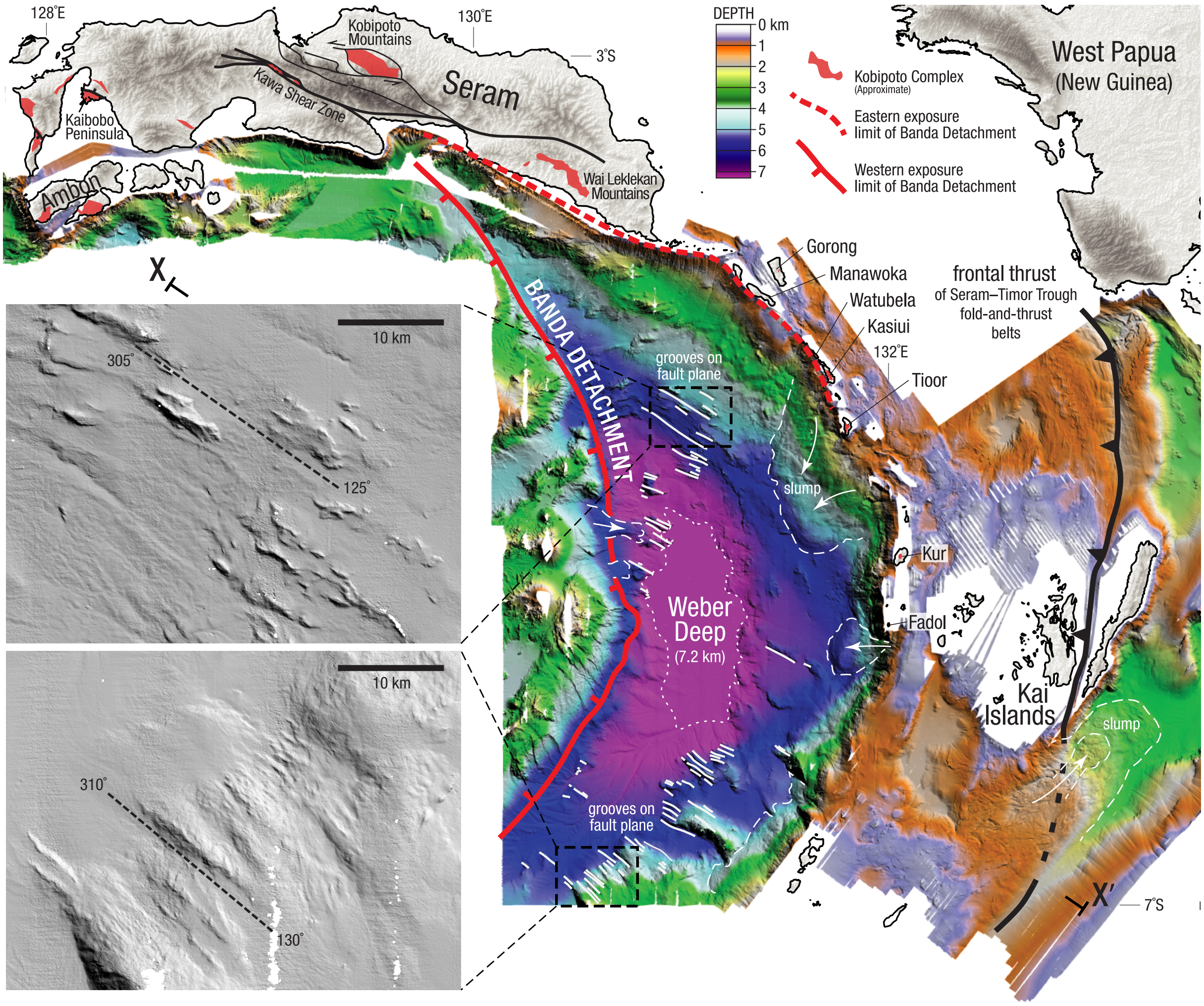

**Figure 6.** Bathymetric map of Weber Deep and Aru Trough (eastern Indonesia), showing the location of Banda detachment and its relationship to Kawa shear zone on Seram, after Pownall *et al.* (2016) [11]. The red areas mark approximate exposures of exhumed upper-mantle–lower-crustal (Kobipoto Complex) rocks. Multibeam data (15 m resolution) courtesy of TGS (www.tgs.com) and GeoData Ventures (Singapore). The enlargements, bottom–left, show the parallel lineations present on the Banda Detachment scarp. Note how the grooved fault scarps exposed in the Weber Deep are parallel also to the Kawa Shear Zone on Seram.

450 km-long detachment must have slipped > 120 km during a massive extensional phase in the arc's evolution. The Banda Detachment is the largest identified normal fault system exposed anywhere in the world's oceans [11].

Ultramafic rocks and high-temperature metamorphic rocks (diatexites, gneisses, high-grade amphibolites) are exposed all around the northeastern rim of the Weber Deep, from the Wai Leklekan Mountains of eastern Seram, to the small islands of Kur and Fadol (Fig. 8) in the east of the arc. Offset along a major normal fault is the only plausible way of explaining how these lower-crustal–upper-mantle rocks are exposed adjecent to a 7 km-deep basin [11]. Furthermore, the Banda Detachment fault scarp—dipping into the Weber Deep at a consistent 12°—has been observed on Fadol (Fig. 8) and in eastern Seram [11]. There is also a connection between the Banda Detachment and the Kawa Fault Zone, described previously. Both the Kawa Fault and the grooves on the Banda Detachment fault scarps are

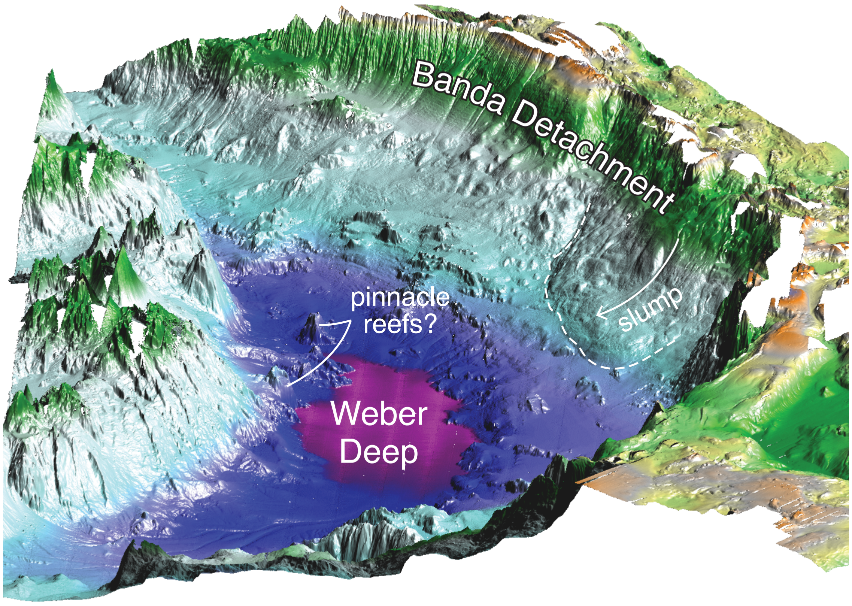

**Figure 7.** Perspective view of the Weber Deep (large vertical exaggeration; looking north) showing the large submarine landslides and submerged pinnacle reefs.

**Figure 8.** Sailing south to the island of Fadol in the eastern Banda Arc. The Banda Detachment bounds the gently-dipping western side of the island (right side in the photo). On Fadol, high-temperature metamorphic rocks and ultramafic rocks are exposed, capped by uplifted carbonate terraces.

parallel, thereby demonstrating the two structures are in some way coupled; and so likely acted together to facilitate southeastward slab rollback plus extreme forearc extension.

The oceanographical profile of the Weber Deep has been also influenced by submerged pinacle reef structures (alternatively mud volcanoes?; Fig. 7), and by large submarine debris flows that blanket much of the eastern rise (Fig. 6,7). These flows, some continuous over 100 km, demonstrate the mass transport of unstable material from the shallow shelf into the abyss. They also provide evidence that the Banda Detachment is either active, or only recently ceased.

From a geohazards perspective, these mass debris flows may pose a greater tsunami risk than earthquakes produced by the vast Banda Detachment. As the Banda Detachment is now exposed at the seabed, it can no longer generate earthquakes other than beneath the volcanic arc, which comprises its hanging wall (Fig. 5b). Nevertheless, frequent low-magnitude ($< 5$) shallow ($< 60$ km) earthquakes recorded in the eastern Banda Sea suggest that steeper-angle faults beneath the Banda Detachment, and dominantly strike-slip faults at the Weber Deep's northern and southern extents, faciliate continued extension.

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