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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 (*c*. 23 Ma–present) Australia–SE Asia collision, but no model explicitly accounts for how the Weber Deep achieved its anomalous depth. Here we propose 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 back-arc 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.

TECTONIC CONTEXT

The Banda Arc (Fig. 1, 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 since the rolling-back subduction zone has collided with the Australian continental margin. It has been proposed that the shape of this margin from the Jurassic approximated 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 towards 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 c. 16 Ma (Pownall et al., 2014), opening the North Banda Basin (Fig. 2) 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 beneath the easternmost Banda Sea to subside to its present depth of 7.2 km. Some authors have suggested it 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 the Weber Deep as an extensional basin (Charlton et al., 1991; Hinschberger et al., 2005; Spakman and Hall, 2010; Hall, 2011, 2012), attributed E–W extension either directly to N–S 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 sub-parallel (within 10°) with consistent NW–SE orientations across the entire basin floor (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, 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 to comprise 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 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

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 *c*. 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 (130.46°E, 3.62°S), and on the small Banda Arc islands of Tioor, Kasiui, Kur, and Fadol SE, 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

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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 comprise 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 (*c*. 16 Ma U–Pb zircon and ^{40}Ar/^{39}Ar biotite ages; Pownall et al., 2013) and on Kur (*c*. 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 the KSZ must have functioned as a right-lateral continental transform east of 129.5ºE in order to have separated NW–SE 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 migration of the Banda subduction zone over the last 10 myr. 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 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, 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 *c*. 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, 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 western USA’s Basin-and-Range Province (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.

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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FIGURE CAPTIONS

Figure 1. Bathymetric map of the Weber Deep and Aru Trough, showing the location of the Banda Detachment and its relationship to the Kawa Shear Zone on Seram. Purple areas mark approximate exposures of exhumed upper-mantle/lower-crustal (Kobipoto Complex) rocks. MULTIBEAM data (15 m resolution) courtesy of TGS and GeoData Ventures. See Fig. 2 for location map; Figs. 3, DR1, and DR2 for enlargements of yellow boxes; Fig. 4 for photos of the Banda Detachment; Fig. 5 for cross section X–X′; and Fig. DR4 for a 3D visualization.

Figure 2. Map of eastern Indonesia showing the location of the Banda Arc, and the extent of MULTIBEAM bathymetry data used in Fig. 1.

Figure 3. A, B: Enlargements of bathymetric map (marked by yellow boxes in Fig. 1) showing grooved normal fault surfaces comprising the fluted Banda Detachment footwall, analogous to the ‘turtlebacks’ of Death Valley (Wright et al., 1974). Note the consistent 130–310° orientations, which are parallel to the inferred slip direction and also

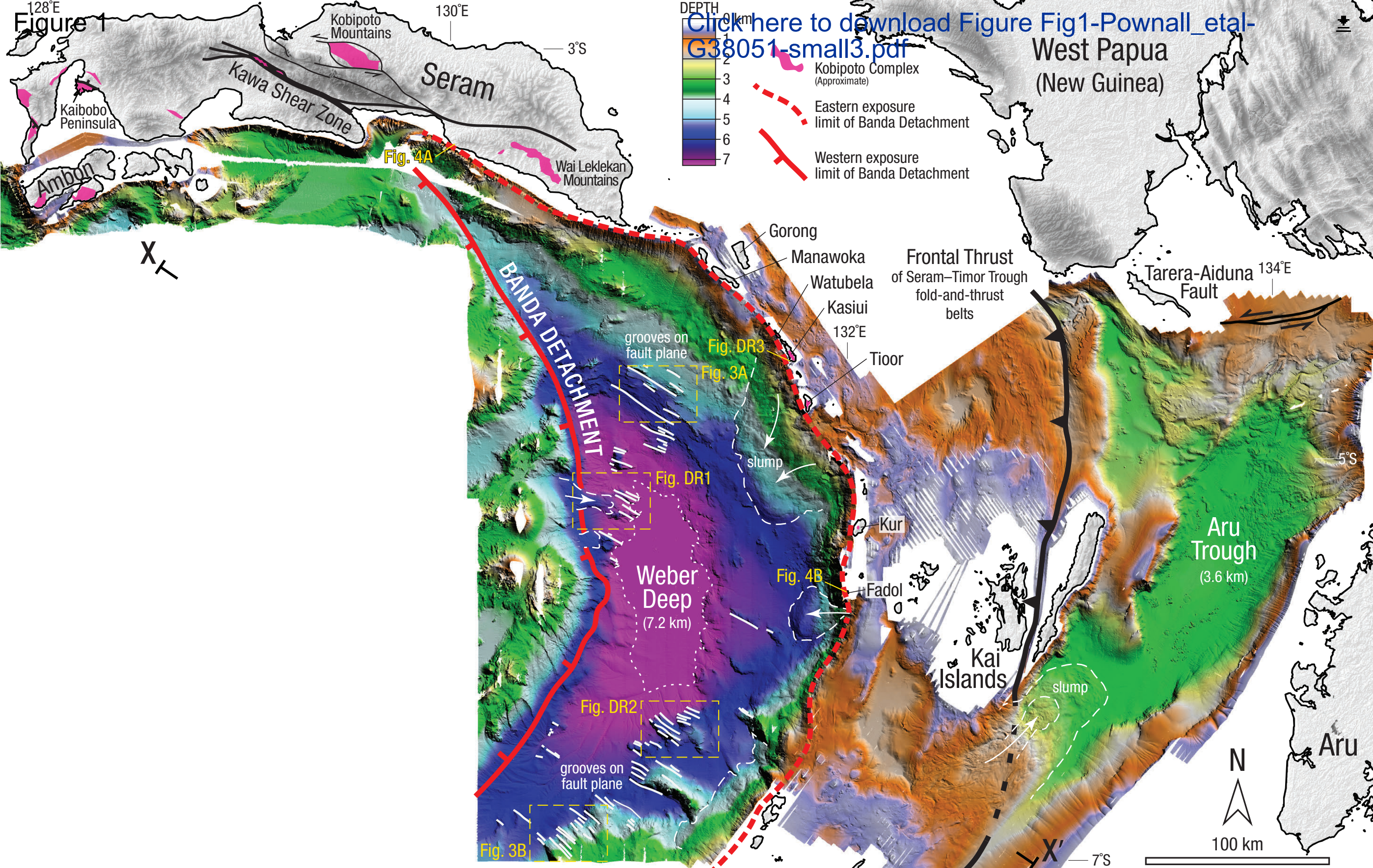
to the trend of the Kawa Shear Zone on Seram. Further examples are shown in Figs. DR1 and DR2.

Figure 4. The Banda Detachment, exposed on land in A: Eastern Seram (130.03°E, 3.46°S), and B: the island of Fadol (131.94°E, 5.67°S). Both fault planes dip towards the Banda Sea at 12° – identical to the dip inferred from Fig. 1.

Figure 5. A: Cross section X–X′ (located in Figure 1; no vertical exaggeration) through the eastern Banda Arc, cut parallel to the grooves on fault surfaces and the proposed direction of rollback (130°SE). The geometry of the Proto-Banda Sea Slab is inferred from earthquake hypocenter locations catalogued by the International Seismological Centre Online Bulletin (isc.ac.uk). KSZ—Kawa Shear Zone. B: Enlargement of the Banda Detachment (2 × vertical exaggeration) showing schematically the configuration of over-riding continental allochthons (dark red).

[1]GSA Data Repository item xxxxxx, additional examples of grooved normal fault scarps flooring the Weber Deep (Fig. DR1 and DR2) a low-angle extensional shear zone on Kasiui (Fig. DR3), and a 3D visualization of the Weber Deep (Fig. DR4), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org.

Figure 1



128°E
130°E
132°E
134°E
3°S
5°S
7°S
Kobipoto Mountains
Seram
Kawa Shear Zone
Kaibobo Peninsula
Ambon
Wai Leklekan Mountains
Fig. 4A
DEPTH
0 km
1
2
3
4
5
6
7
Kobipoto Complex
(Approximate)
Eastern exposure limit of Banda Detachment
Western exposure limit of Banda Detachment
West Papua
(New Guinea)
Gorong
Manawoka
Watubela
Kasiui
Tioor
Frontal Thrust
of Seram–Timor Trough fold-and-thrust belts
Tarera-Aiduna Fault
X
X'
BANDA DETACHMENT
grooves on fault plane
Fig. DR3
Fig. 3A
slump
Fig. DR1
Kur
Weber Deep
(7.2 km)
Fig. 4B
Fadol
Kai Islands
Aru Trough
(3.6 km)
Fig. DR2
grooves on fault plane
Fig. 3B
Aru
N
100 km

Figure 2

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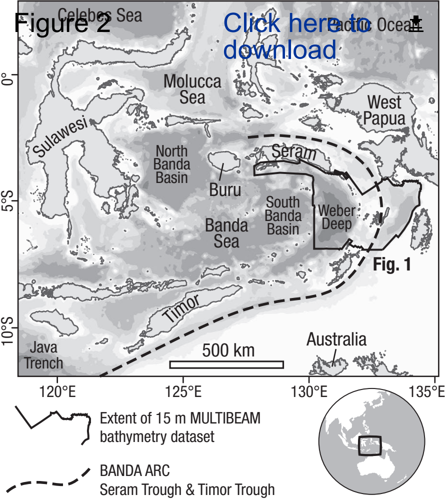

Figure 3

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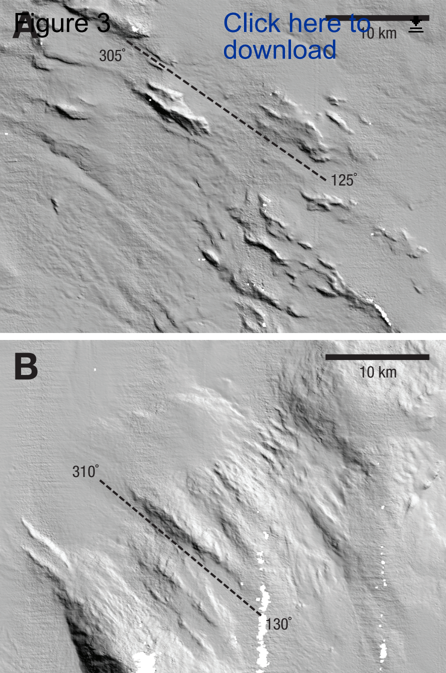

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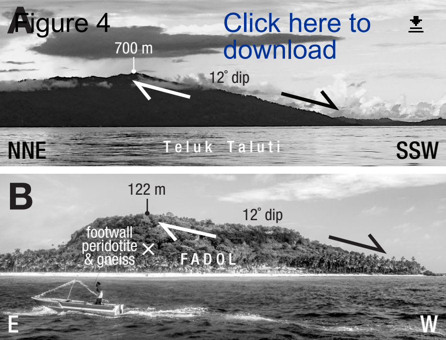

Figure 5

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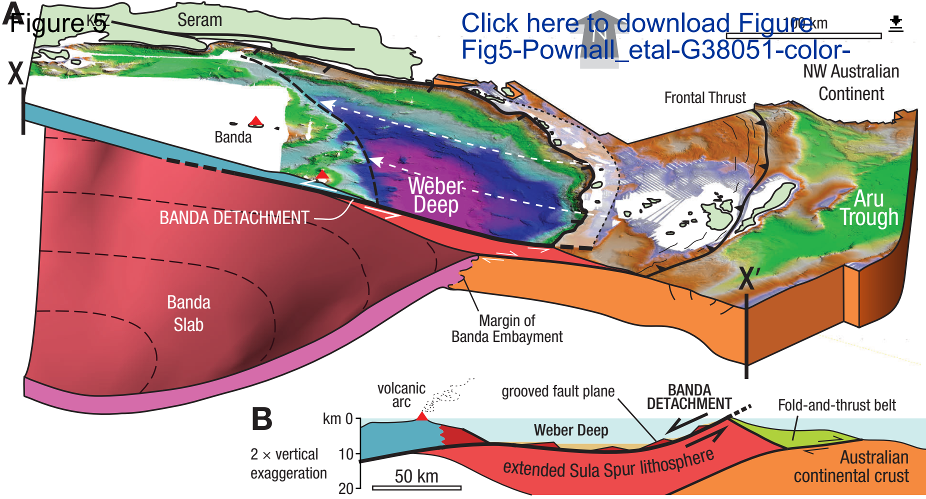

Pownall et al.

Rolling open Earth's deepest forearc basin

DATA REPOSITORY ITEMS

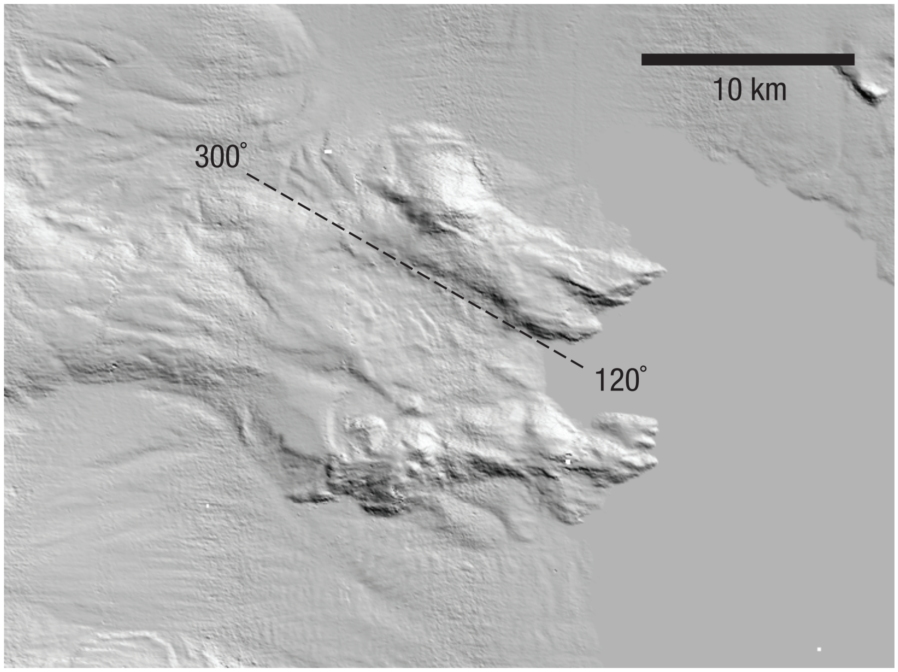

Figure DR1. Enlargement of yellow box 'DR1' in Figure 1. Normal fault scarp grooves have 300–120˚ orientation.

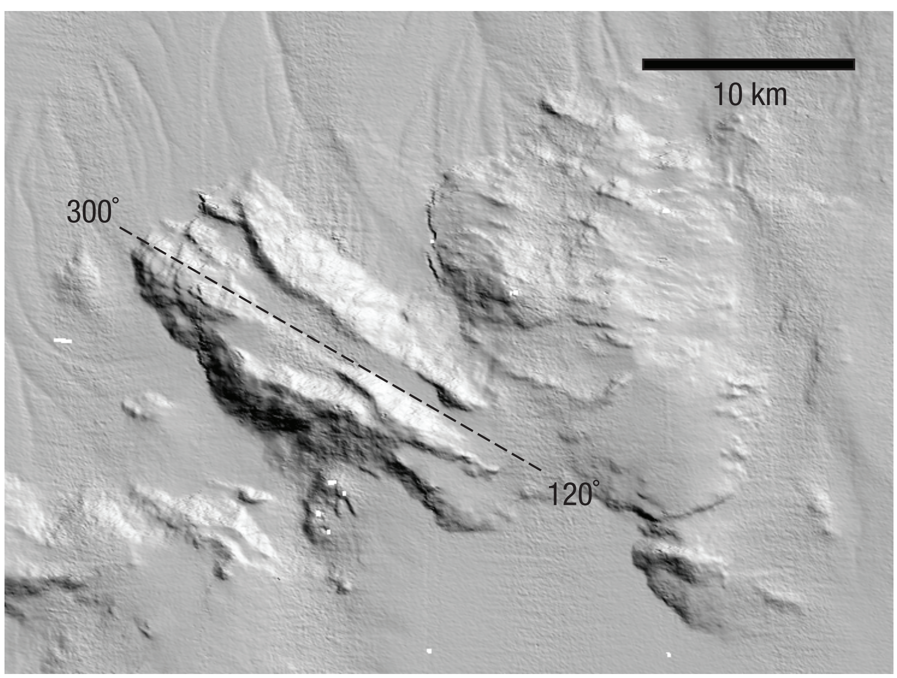

Figure DR2. Enlargement of yellow box 'DR2' in Figure 1. Normal fault scarp grooves have 300–120˚ orientation.

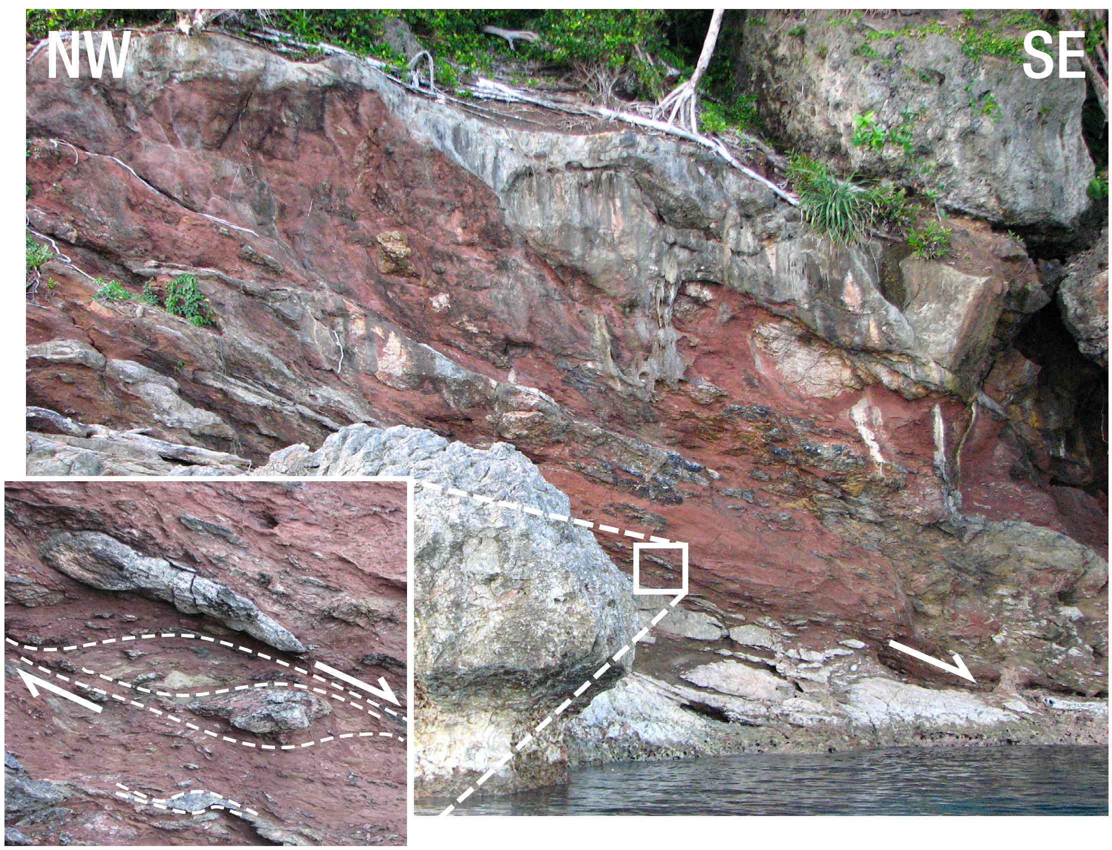

Figure DR3. Low-angle extensional normal shear zone, south Kasiui (131.6776˚E, 4.5394˚S), dipping 20˚ to 345˚NNW. Enlarged box is 0.6 m wide.

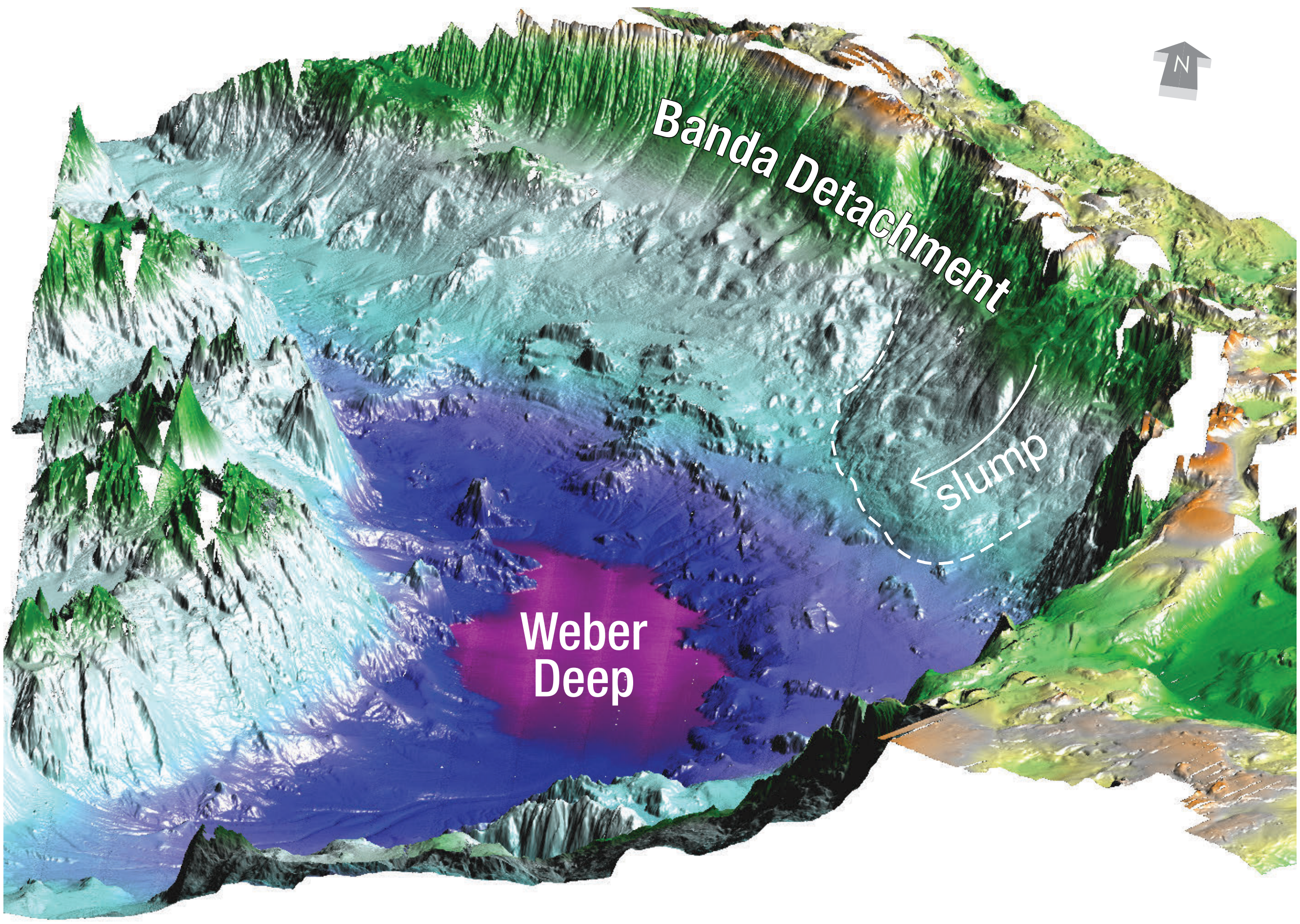

Figure DR4. 3D visualization of the Weber Deep, produced from the MULTIBEAM data used also in Fig. 1.