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Surface deformation and slab–mantle interaction during Banda arc subduction rollback

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The spectacularly curved Banda arc comprises young oceanic crust[1,2] enclosed by a volcanic inner arc, outer arc islands and a trough parallel to the Australian continental margin[3–5]. Strong seismic activity in the upper mantle defines a folded surface[6,7], for which there are two contrasting explanations: deformation of a single slab[5,8] or two separate slabs subducting from the north and south[6,9]. Here we combine seismic tomography with the plate tectonic evolution of the region to infer that the Banda arc results from subduction of a single slab. Our palaeogeographic reconstruction shows that a Jurassic embayment, which consisted of dense oceanic lithosphere enclosed by continental crust, once existed within the Australian plate. Banda subduction began about 15 million years ago when active Java subduction tore eastwards into the embayment. The present morphology of the subducting slab is only partially controlled by the shape of the embayment. As the Australian plate moved northward at a high speed of about 7 cm yr^{-1}, the Banda oceanic slab rolled back towards the south–southeast accompanied by active delamination separating the crust from the denser mantle. Increasing resistance of the mantle to plate motion progressively folded the slab and caused strong deformation of the crust. The Banda arc represents an outstanding example of large-scale deformation of the Earth's crust in response to coupling between the crust, slab and surrounding mantle.

The Banda arc (see Fig. 1) is famous for its 180° curvature and is, in Timor, generally agreed to be the product of collision between a volcanic arc and the Australian continental margin[3–5]. The arc is the subject of important controversies[10] about how it acquired its shape, and the origin and the direction of subduction. Some have interpreted it as the result of subduction of a single oceanic slab[4,5] at the Timor–Aru trough and others have suggested that it formed by subduction of two slabs[6,9], the second subducting southwest from the Seram trough. Two-slab models are mainly based on interpretations of seismicity patterns and earthquake mechanisms[6,7,9], magmatism[11] and geodetic evidence of active contraction across the Banda region[12,13]. They explain the shape of subducted lithosphere but require prior existence of oceanic crust between the Bird's Head and Seram for which there is no evidence. Single-slab models, however, must explain the origin of the exceptionally strong curvature within the entire upper mantle. Hypotheses[14] have proposed either deformation of an east-trending arc through 180° or deformation of the slab in the mantle[5] by some form of rollback[8,15]. Two-slab models have been favoured in several recent publications[7,11]. Here, by combining mantle tomography with tectonic evolution and active surface deformation, we propose a model based on rollback of a single slab resolving important issues regarding the origin of the slab, its unusual morphology and subduction evolution.

Several key observations point to slab rollback during evolution of Banda subduction. Tomographic images of the Banda slab[16], (see Supplementary Movies S1 and S2) show that it is confined to the upper mantle (see Fig. 2). In contrast, evidence for deep subduction is found in the lower mantle directly west of Sulawesi[16] (see Supplementary Movies S1 and S2), suggesting a different evolution of Sunda (Java) and Banda subduction. This contrast is also indicated by a marked change in the age of the volcanic arc from Java (∼45 Myr, ref. 17) and eastward from Flores (<16 Myr, refs 18,19). The age (<12.5 Myr) of the backarc basins[1,2] within the Banda region also indicates a young subduction history and their opening history provides support for slab rollback[8]. Independently, strong tomography support for rollback is found beneath the western Banda region, south of Sulawesi, where a ∼300-km-wide flat-lying portion of the Banda slab is found at the bottom of the upper mantle (see Supplementary Movies S1 and S2 and Fig. 2).

A critical issue is the origin of the lithosphere that constitutes the Banda slab. A widely recognized and key geological observation is the stratigraphic and structural continuity of the Australian continental margin[3,8,15,20,21] surrounding the present-day Banda arc from Seram to Timor implying that the strongly curved margin existed before subduction started. Plate tectonic reconstructions[8] (see Supplementary Movie S3) demonstrate that the margin enclosed an oceanic embayment within the Australian plate. This formed in the Late Jurassic south of the Australian continental promontory of the Sula spur[22] and its last remnant is the Argo abyssal plain[23,24] southwest of Timor (see Fig. 1). Below, we show that most of the Banda slab corresponds to subducted embayment lithosphere but part must have been subducted continental lithosphere from north of the embayment.

Our model of the detailed Cenozoic tectonic evolution of the region[8,25] uses an Indo-Atlantic hotspot reference frame[26] in which the Eurasian plate, Sunda arc and Java trench remain broadly stationary since 45 Myr ago (see Supplementary Movie S3). From about 45 Myr ago, Australia moved north, and ocean crust was consumed at north-dipping subduction zones stretching from Sumatra in the west to Halmahera in the east. At about 23 Myr ago, the leading part of continental Australia, the Sula spur directly north of the Banda embayment, began to collide with the Southeast Asian margin forming the east Sulawesi orogen. This collision broke and detached the subducting slab north of the Sula spur and the transform fault east of Sumba changed into a west-dipping subduction fault as Sundaland commenced anticlockwise rotation. This trench advanced ∼500 km east until 15 Myr ago. The relative motion between west Sulawesi and the Sula spur led to ∼250 km east–west subduction. At the Java trench there was ∼660 km subduction in the west to ∼330 km in the east, parallel to Australia motion, contributing to the Sunda slab observed beneath present-day Java and Sumba (see Fig. 2a).

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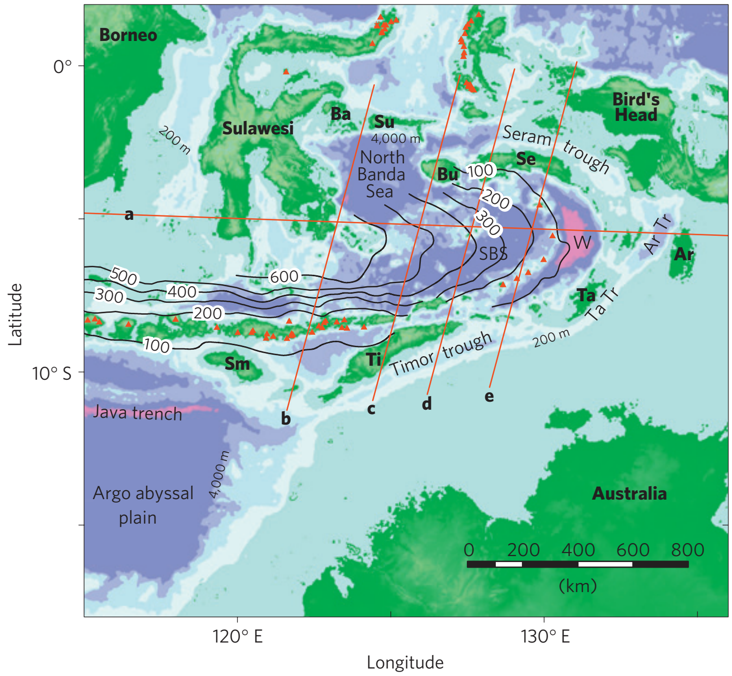

Figure 1 | The Banda arc and surrounding region. 200 m and 4,000 m bathymetric contours are indicated. The numbered black lines are Benioff zone contours in kilometres. The red triangles are Holocene volcanoes (http://www.volcano.si.edu/world/). Ar = Aru, Ar Tr = Aru trough, Ba = Banggai Islands, Bu = Buru, SBS = South Banda Sea, Se = Seram, Sm = Sumba, Su = Sula Islands, Ta = Tanimbar, Ta Tr = Tanimbar trough, Ti = Timor, W = Weber Deep. The red lines are the locations of the tomography sections in Fig. 2.

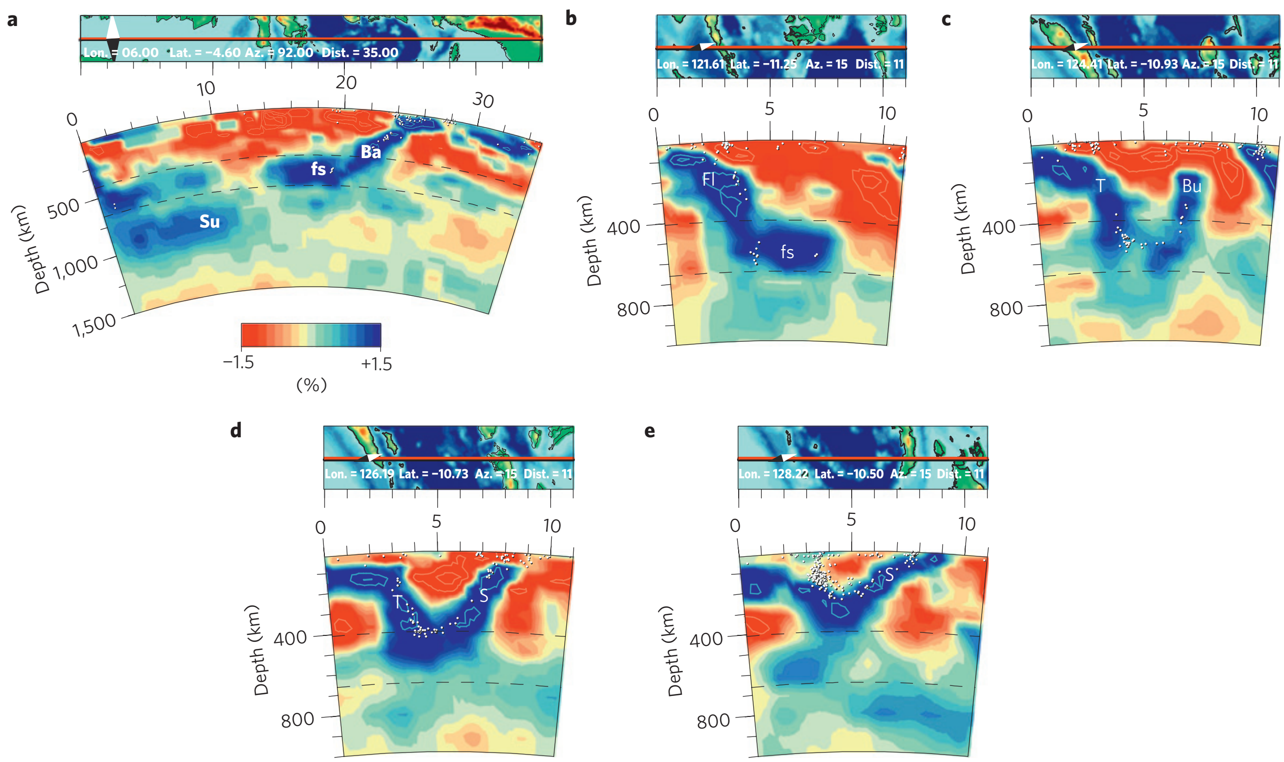

Figure 2 | Tomographic images of the Banda slab. Vertical sections through the tomography model along the lines shown in Fig. 1. Colours: P-wave anomalies with reference to velocity model ak135 (ref. 30). Dots: earthquake hypocentres within 12 km of the section. The dashed lines are phase changes at ~410 km and ~660 km. The sections are plotted without vertical exaggeration; the horizontal axis is in degrees. The labelled positive anomalies are the Sunda (Su) and Banda (Ba) slabs: Bu = detached slab under Buru, Fl = slab under Flores, S = slab under Seram, T = slab under Timor. **a**, The Sunda slab enters the lower mantle whereas the Banda embayment slab is entirely in the upper mantle with the change under Sulawesi. **b**–**e**, Banda slab morphology in sections parallel to Australia plate motion shows a transition from a steep slab with a flat section (fs) (**b**) to a spoon shape shallowing eastward (**c**–**e**). See details in Supplementary Movie S2.

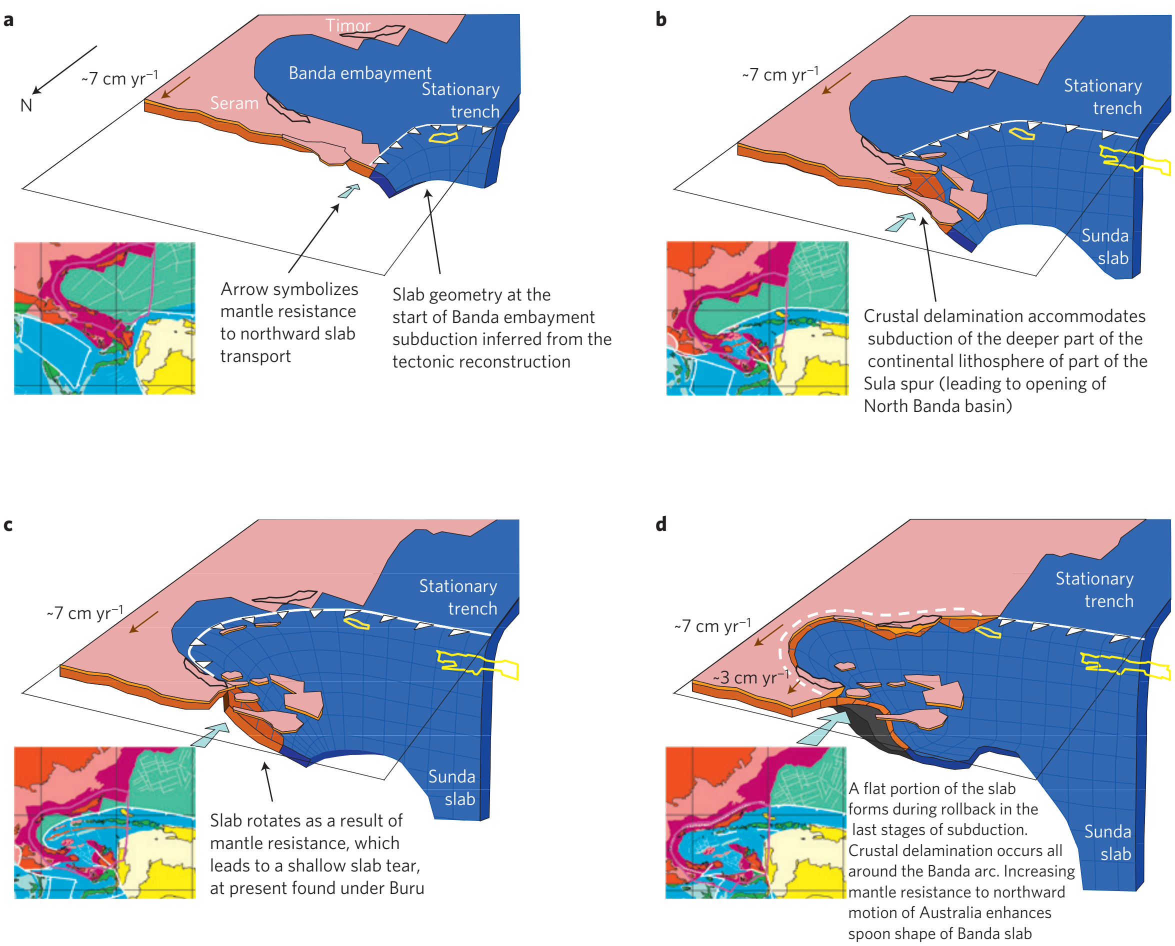

Figure 3 | Evolution of Banda subduction in the absolute plate motion frame. a–d, The situation at 15 (**a**), 7 (**b**), 4 (**c**) and 0 (**d**) Myr ago, with insets from the tectonic reconstruction (see Supplementary Movie S3). The magenta lines in the insets show the estimated area of subducted lithosphere reconstructed back to the surface. The Sunda slab was stationary in the mantle while the Australian plate, including the Banda embayment, moved north at ∼7 cm yr^{-1}. Between 15 and 0 Myr ago, the Sunda trench was stationary and the subducted slab entered the lower mantle under Java. Rollback into the Banda embayment from (**a**) ∼15 Myr ago led to (**b**) delamination of lithosphere (brown) of the Sula spur leaving crustal fragments in parts of Sulawesi and around the North and South Banda basins. These therefore remained stationary (**c**,**d**) in the reference frame. The shape of the Banda embayment initially determined slab morphology and (**c**,**d**) further sinking and folding was the response to increased mantle resistance (blue vectors in **a**–**d**) since 4 Myr ago. This rotated and tore the slab (**c**) under Buru and caused north–south contraction (**d**) between Seram and Timor. Australian plate motion slowed to ∼3 cm yr^{-1} at the latitude of Seram, diminishing to zero further north. The Timor–Seram trough (dashed) is now the locus (**d**) of active delamination. Rollback produced a flat slab (**d**) that rests on the upper–lower mantle discontinuity at ∼660 km.

Banda embayment subduction initiated around 15 Myr ago as the Java trench aligned with the northern margin of the embayment and the old thick Jurassic embayment lithosphere entered the Sunda trench (see Supplementary Movie S3 and Fig. 3a). As the trench propagated into the embayment, the lithosphere sank rapidly by its own negative buoyancy while Australia continued to advance northward. This early development coincides with the gradual break-up of the western Sula spur and opening of the North Banda basin. From reconstruction of the imaged Banda slab to the surface (see Fig. 3), we infer that part of the continental lithosphere underlying the western Sula spur must have been incorporated in the subducted slab (see Fig. 3). We explain the geologically inferred break-up of the Sula spur to be a result of delamination of the crustal part of the lithosphere from its lower mantle part as the Banda slab rollback occurred (see Fig. 3b).

Our detailed reconstruction of the region (see Supplementary Movie S3) incorporates the timing and opening directions of young oceanic basins in the Banda region. As the trench propagated south–southeast, the North Banda basin opened between 12.5 and 7.1 Myr ago[2], followed by opening of the South Banda basin between 6.5 and 3.5 Myr ago[1]. At 3.5 Myr ago, when most of the embayment was consumed north of Timor, the trench and volcanic arc collided with the southern embayment margin in the northern Timor region[3,4]. Finally, since 2 Myr ago, the Weber Deep was created marking the complete consumption of the embayment by rollback. During the entire evolution the Java trench part of the subduction zone remained relatively stationary in the absolute motion frame (see Fig. 3) whereas the Banda trench moved east–southeast into the northward-moving Australian plate (see Supplementary Movie S3).

The deep flat-lying portion of the Banda slab records the early stages of embayment subduction (see Fig. 3d). The flat slab supports our rollback model and demonstrates that south- to south–southeast-directed rollback occurred at a higher speed than the northward motion of Australia after the slab reached the base of the upper mantle at 660 km (see Fig. 3c,d). In the absolute motion frame, the slab below Timor is relatively stationary in the mantle but now probably steepening as a result of continuing northward motion of Australia and the southern Banda arc as evidenced by global positioning system observations (see Supplementary Information S1). The slab is possibly at the stage of being

overridden, providing an explanation for slab rupture seismic activity[27] before total detachment. A similar process occurred earlier (~23 Myr ago) directly north of the Sula spur.

One important factor determining the curvature and spoon shape of the present-day slab is the shape of the former continental margin to which the subduction trench rolled back. Another important factor is deformation of the Banda slab resulting from its interaction with the upper mantle. Under Buru, the slab is disconnected from the surface (see Fig. 2) and intermediate depth seismicity is absent (see Supplementary Movies S1 and S2). In our evolutionary model this part of the subducted slab incorporates the delaminated continental lithosphere of the western Sula spur. It arrived in its present position as a result of mantle resistance to northward slab transport leading first to tearing, and then to rotation of the slab to bring it to its present position, effectively completing the spoon shape across the entire upper mantle (see Fig. 3).

The shape of the slab cannot be explained only by rollback. We propose that beneath the northeast Banda arc (Seram–Aru) the slab is still continuous and experiences mantle resistance to northward transport. Consequently, a slowing down in northward motion of the north promontory of the Australian continent (Seram–Bird's Head) has occurred whereas the Australian plate, south and directly east of the Weber Deep (Aru–Timor), is still moving north at ~7 cm yr^{-1} (see Supplementary Information S1). This induced progressive folding of the Banda slab, which increased slab curvature, allowed further sinking of the slab and explains the spoon shape. It also caused further subsidence of the extending upper plate. This may explain the strong curvature in intermediate depth seismicity[7] (see Supplementary Movies S1 and S2), the spectacular ~7 km Weber Deep[4], unusual focal mechanisms[7], the anticlockwise rotation of the entire northern promontory and north–south contraction across the entire region from the Wetar thrust in south Banda to the Seram–Bird's Head region (see Supplementary Information S1). In this scenario, there is no requirement for southwest-directed 'Pacific' plate subduction[13] below Seram to explain the observed contraction. Mantle resistance would have become increasingly effective in the later stages of subduction as the spoon shape matured, consistent with evidence for formation of the Seram trough since ~4 Myr ago[28]. We suggest that the observed westward component of crustal flow north and northeast of Seram is related to the coupling between the Australian and Pacific plates and the strong reduction of Australian northward motion resulting from mantle resistance to slab transport. Although there are many factors that determine focal mechanisms locally (for example, slab–mantle coupling, slab rupture), slab folding explains the unusually large numbers of focal mechanisms with horizontal P axes[6,7,27] in the slab.

Last, the external trough system enclosing the entire island arc (see Fig. 1) shows little evidence of significant contraction in the past 4 Myr, except north of Seram[28]. The character of the trough changes around the arc. In the Aru region there are abundant extensional features close to the shallow subduction hinge consistent with the last rollback phase. South of Timor it is a foredeep produced by loading following arrival of the arc at the hinge and perhaps to steepening of the slab. The Seram trough is also partly a foredeep because of thrust loading in Seram. In our model the trough is interpreted as the topographic expression of a down-flexed and thrust-loaded Australian margin, at the final stage of subduction, rather than a subduction trench. However, we propose that the trough is also the hinge zone marking the limit of delamination of the crustal part of the continental margin that permitted continued subduction of the deeper lithosphere without a subduction fault reaching the surface. This process continues today and explains much of the uplift and upper crustal deformation around the Banda arc. Our delamination hypothesis also offers an explanation for the unusual Seram–Ambon volcanic rocks[8,11], as injection of hot mantle is likely to contribute to melting of overlying continental crust and induce mantle melting.

We argue that it is not the relative motion between Australia and Southeast Asia (or between the Pacific and Seram–Bird's Head block), but primarily the strong negative buoyancy of the Jurassic Banda embayment, that drove subduction and determined direction and speed of slab rollback into the embayment. Absolute plate motions and interaction between slabs and mantle are keys to understanding deformation of the Australian plate and the Banda region, the extreme curvature of the arc and the spectacular shape of subducted lithosphere, and help explain the complex tectonic evolution.

Methods

The reconstructions were made with the ATLAS computer program and plate motion model for the main plates in the Indo-Atlantic hotspot frame[26] using methods previously described[8]. The complete Southeast Asia model has been updated and extends back to 160 Myr ago with an interpreted spreading history of the now-subducted Tethys and Indian oceans, based on the timing of rifting of blocks from western Australia identified in Southeast Asia, and geological evidence concerning timing of magmatism and collision[25]. The anomalies shown in the Indian Ocean and Banda embayment and the reconstructed Sula spur are based on this reconstruction. On the reconstruction maps (see Fig. 3 and Supplementary Movie S3) present-day coastlines are shown for reference. Areas filled in green are mainly arc, ophiolitic and accreted material formed at plate margins. Areas filled in cyan are submarine arc regions, hotspot volcanic products and oceanic plateaux. Eurasian crust is coloured in shades of yellow. Areas that were part of Gondwana in the Jurassic are coloured in shades of red. To the west of Australia and New Guinea oceanic crust older than 120 Myr is shaded blue–green. Magnetic anomalies are shown as light white lines. Active spreading centres are heavy red lines. Subduction zones and transform faults are heavy white lines.

The tomographic images presented here (see Fig. 2 and Supplementary Movies S1 and S2) are taken from the global tomography model BS2000 (ref. 29) of P-wave speed anomalies computed from ~8 million P-wave travel times and based on a data-density-dependent cell parameterization. The model stems from a step-wise linearization approach involving three-dimensional seismic ray tracing to attain consistency between data, ray geometry and the tomographic model. The tomographic approach incorporates the estimation of station averages and of earthquake mislocation effects on the data. All images are shown as percentage deviations from the background radial P-wave speed model ak135 (ref. 30).

Supplementary Movie S1 shows imaged structures in the geographic map view with increasing depth. Supplementary Movie S2 shows a sequence of north–south-oriented vertical sections along the Sunda–Banda arc starting in the west and ending in the eastern Banda region. The azimuth of each section is N 15° E. The caption of Fig. 2 gives information about the colour contouring and layout of these sections. The white dots in Supplementary Movies S1 and S2 are hypocentres from the earthquake data set used in tomography[29]. In Supplementary Movie S1 the hypocentres within 7.5 km of the indicated depth are plotted. In Supplementary Movie S2 hypocentres are plotted within 12 km of the section plane. Model resolution tests with a variety of synthetic anomaly models[29] show that the tomography model is spatially sufficiently well resolved in the Banda region to warrant our interpretations. First-order features interpreted here as the spoon shape of the slab, the flat-lying part of the slab or the slab detachment under Buru are spatially well resolved. The Supplementary Information S2 has examples of resolution tests.

We note that the tectonic reconstruction model and the tomography model used here are completely independent developments concerning methods, data and interpretation.

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Author contributions

R.H. was responsible for tectonic reconstructions. W.S. was responsible for tomography and global positioning system analysis. Both authors contributed equally to development of ideas, interpretation and production of figures and manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to W.S. or R.H.