GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48246.1

Manuscript received 7 August 2020
Revised manuscript received 19 October 2020
Manuscript accepted 2 December 2020

Inherited lithospheric structures control arc-continent collisional heterogeneity

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ABSTRACT

From west to east along the Sunda-Banda arc, convergence of the Indo-Australian plate transitions from subduction of oceanic lithosphere to arc-continent collision. This region of eastern Indonesia and Timor-Leste provides an opportunity for unraveling the processes that occur during collision between a continent and a volcanic arc, and it can be viewed as the temporal transition of this process along strike. We collected a range of complementary geological and geophysical data to place constraints on the geometry and history of arc-continent collision. Utilizing ~4 yr of new broadband seismic data, we imaged the structure of the crust through the uppermost mantle. Ambient noise tomography shows velocity anomalies along strike and across the arc that are attributed to the inherited structure of the incoming and colliding Australian plate. The pattern of anomalies at depth resembles the system of salients and embayments that is present offshore western Australia, which formed during rifting of east Gondwana. Previously identified changes in geochemistry of volcanics from Pb isotope anomalies from the inner arc islands correlate with newly identified velocity structures representing the underthrusted and subducted Indo-Australian plate. Reconstruction of uplift from river profiles from the outer arc islands suggests rapid uplift at the ends of the islands of Timor and western Sumba, which coincide with the edges of the volcanic-margin protrusions as inferred from the tomography. These findings suggest that the tectonic evolution of this region is defined by inherited structure of the Gondwana rifted continental margin of the incoming plate. Therefore, the initial template of plate structure controls orogenesis.

INTRODUCTION

The Indo-Australian plate is subducting beneath Eurasia in Indonesia, producing the ~5200-km-long archipelago with hundreds of active volcanoes and a well-defined Wadati-Benioff zone (Fig. 1A). The northeastward motion of Australia with respect to Eurasia is ~7 cm/yr, but convergence is locally partitioned due to variable plate-boundary geometry and different types of convergent margins (e.g., Koulali et al., 2016). In eastern Indonesia, the incoming plate structure transitions from oceanic lithosphere to Australian continental lithosphere at the junction of the Sunda-Banda arc, resulting in arc-continent collision. This results in two chains of islands, the inner volcanic arc to the north, and the nonvolcanic islands (Timor, Sumba, Rote, and Savu) to the south. A section of the inner arc volcanoes is inactive from Alor to Romang north of eastern Timor (Fig. 1), which has been inferred to be due to the collision of the Australian continent (Harris, 2011; Hall, 2012). Despite these first-order controls on the collision, there is no clean jump between the oceanic and continental lithosphere within the Indo-Australian plate; instead, there is a complex transition due to the inherited structure of the precollisional Australian margin. During the breakup of east Gondwana in the Late Jurassic (Heine and Müller, 2005), a broad, long (several thousand kilometers) system of salients and embayments formed at the edge of the Indo-Australian plate (e.g., Charlton, 2000; Keep and Haig, 2010). These structures correspond to the rifted upper- and lower-plate margins (e.g., Charlton, 2004), which are depicted in the "jagged-edge" geometry seen in the present-day bathymetry of the Wallaby, Exmouth, and Scott Plateaux offshore northwestern Australia (Fig. 1A).

To study the spatiotemporal evolution of the transition from oceanic subduction to arc-continent collision along the western Banda arc, diverse geological, geodetic, seismic, and geomorphic data have been collected. This experiment included a deployment of 30 broadband seismometers (Miller et al., 2016), with the primary aim to image the structure of the crust and mantle beneath the region (Fig. 1B). At mantle depths, the tomographic images from these new data (Harris et al., 2020; Supendi et al., 2020) and from previous studies (e.g., Widiyantoro and van der Hilst, 1996; Spakman and Hall, 2010) show a steeply dipping, fast-velocity slab with some structural variations at depths >200 km. These morphological changes at depth are inferred to result from the transition from oceanic subduction to continental subduction and collision, imparting surface expression in terms of variations in volcanic activity and magmatic arc chemistry (e.g., Hilton et al., 1992; Elburg et al., 2004, 2005).

While this first-order transition has dominated prior interpretation of structure in this region, our new crustal and uppermost mantle (<100 km) velocity models indicate a more subtle confluence of lithospheric structure and morphological inheritance as tectonic drivers. We argue that complexities found in the new tomographic images can be understood by linking the velocity anomalies to the incoming plate structures. The subaerial topography of the Banda arc appears to have evolved in response to these structural complexities in the downgoing slab, as previously identified on Sumba (e.g., Harris, 1991; Fleury et al., 2009) and on Savu and Rote (e.g., Roosmawati and Harris, 2009),

CITATION: Miller, M.S., et al., 2021, Inherited lithospheric structures control arc-continent collisional heterogeneity: Geology, v. 49, p. , https://doi.org/10.1130/G48246.1

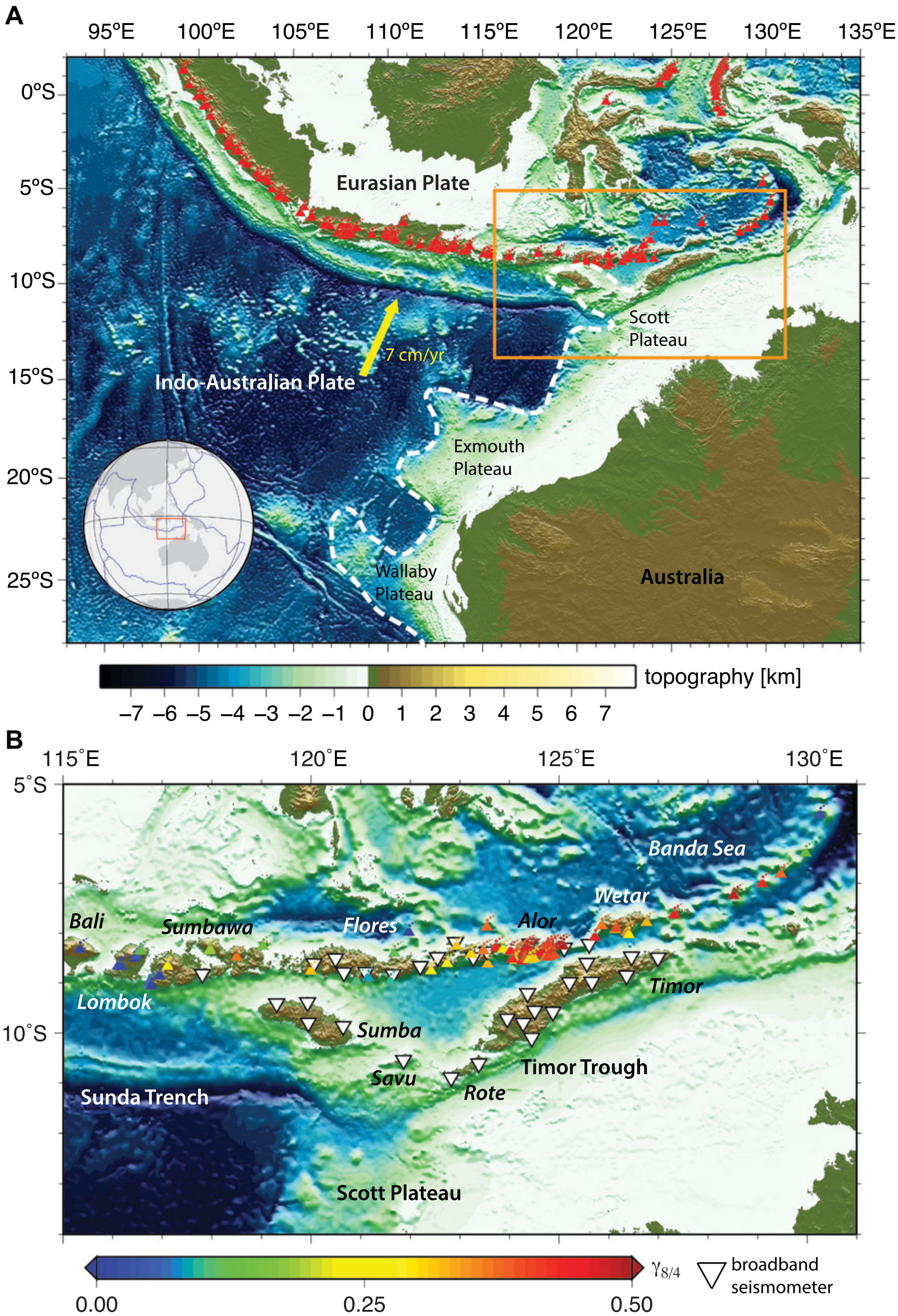

Figure 1. (A) Generalized tectonic setting of the Sunda-Banda arc, with active volcanoes plotted in red (Siebert and Simkin, 2002). Yellow vector represents relative plate motion from model NUVEL-1A (DeMets et al., 1994); white dashed line marks approximate ocean-continent boundary from the paleo–spreading ridge of the East Gondwana Rift; and inset shows global map location. Orange rectangle indicates location of map in B. (B) Network of broadband seismometers shown with inverted white triangles and volcano symbols colored by Pb isotope anomalies ($\gamma_{8/4}$) from Elburg et al. (2004) and M.A. Elburg (2011, personal commun.). Major islands are labeled with italic font.

and as suggested here also for the highest elevations on Timor. These relationships indicate that heterogeneities in the subducting plate structure may control where and when exhumation and erosion of the accretionary wedge take place during initial phases of arc-continent collision. This highlights new avenues for understanding collisional processes in the context of long-term continental dynamics from a combination of geological and geophysical approaches, with implications for transport of continental material throughout the Wilson cycle.

DATA AND METHODS

Ambient Noise Tomography

We used broadband seismic data (Miller et al., 2016) to produce ambient noise tomographic images of the crust and uppermost mantle. These were constructed by measuring short-period (6–37 s) Rayleigh wave dispersion from ~4 yr of continuous records from 33 broadband stations (Fig. 1). First, we measured Rayleigh wave phase velocity dispersions at periods of 6 s to 37 s from the stacked cross-correlations of ~4 yr of continuous vertical-component seismograms (March 2014–December 2018), following the procedures described by Bensen et al. (2007). Next, we performed a three-dimensional (3-D) surface wave inversion developed by Fang et al. (2015) to resolve the shear-wave velocity in the uppermost 70 km (Fig. S1 in the Supplemental Material[1]). The algorithm utilizes the fast-marching ray-tracing method to calculate synthetic traveltimes and ray paths and then directly inverts all data to a 3-D shear-wave velocity model by a linearized iteration (Zhang and Miller, 2021). Detailed processing and inversion parameters are described in the Supplemental Material.

Uplift Modeling

To explore the surface expression of deformation and its evolution in space and time, we analyzed the subaerial topography. We reconstructed uplift histories using the morphology of river profiles, which encode the history of rock uplift experienced by a drainage basin (e.g., Kirby and Whipple, 2001; Pritchard et al., 2009; Roberts et al., 2013). Given equal discharge and bedrock erodibility, a fluvial knick zone generated by uplift will erode more rapidly than neighboring reaches, and steepened reaches will propagate upstream. By parameterizing these erosional processes, observed river profiles can be inverted in a space-for-time substitution to estimate an uplift history (Kirby and Whipple, 2001). We applied a 1-D inversion (Pritchard et al., 2009) to the islands of the Banda arc (see the Supplemental Material). Data from uplifted marine terraces and synorogenic basins (Hantoro et al., 1994; Merritts et al., 1999; Muraoka et al., 2002; Nexer et al., 2015) provided independent constraints on the river profile inversions, making this region especially suited to this approach by allowing accurate parameterization of the uplift model.

RESULTS AND DISCUSSION

The ambient noise tomography shows a strong high-to-low velocity contrast that strikes in a southwest-to-northeast direction, roughly parallel to the Timor Trough from shallow crustal depths through to the mantle lithosphere (Fig. 2A; Fig. S1). However, there are significant, smaller-scale velocity patterns, such as the higher velocities in central Timor that are present at ~30–60 km depth. These higher velocities are bounded by more moderate-shear-velocity

[1]Supplemental Material. Description of the methodology. Please visit https://doi.org/10.1130/GEOL.S.13584929 to access the supplemental material, and contact editing@geosociety.org with any questions.

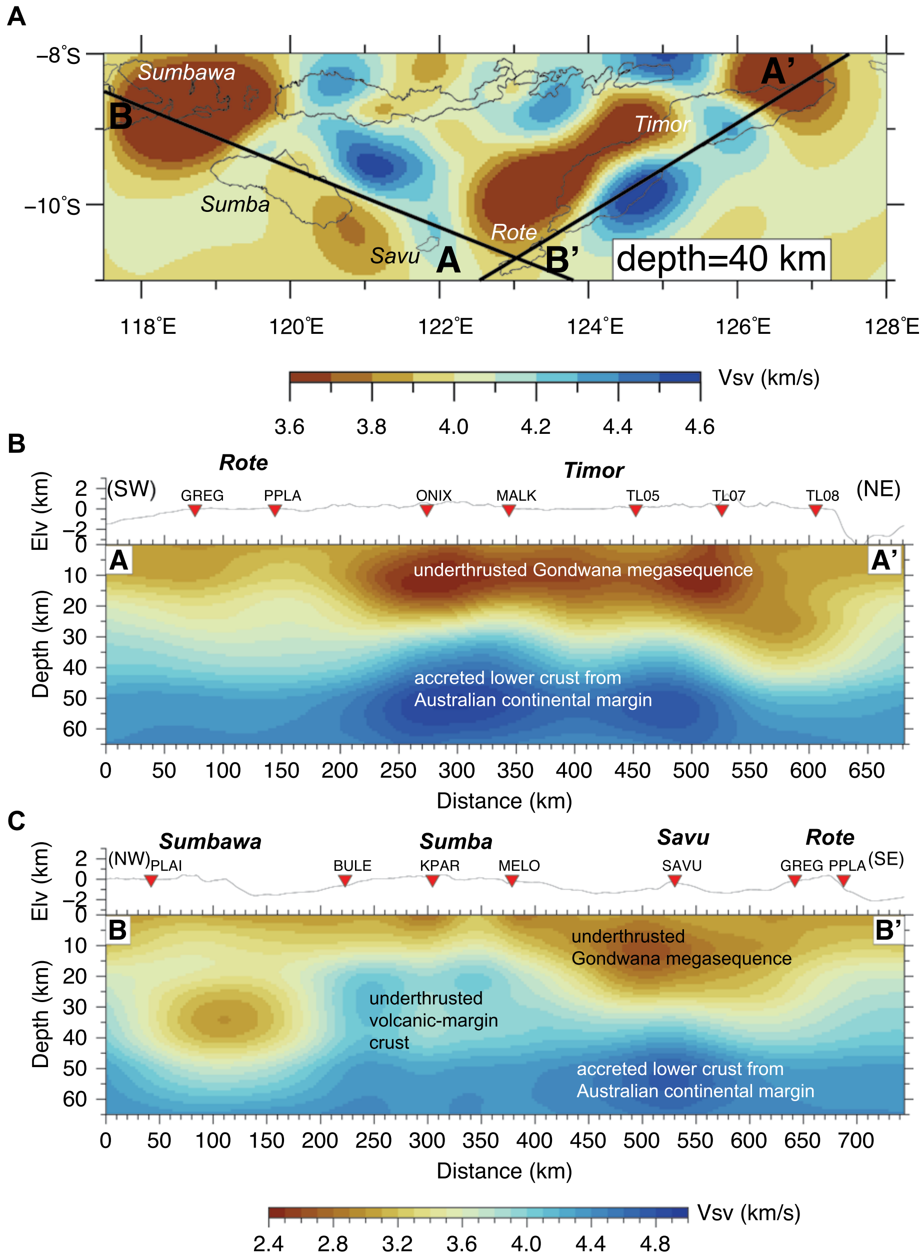

Figure 2. (A) Horizontal slice through ambient noise–based shear-wave-velocity tomography model at 35 km depth. Black lines indicate position of two profiles shown in B and C. (B) Vertical cross section through the islands of Timor and Rote, parallel to strike of the island and Timor Trough (Elv—elevation). This profile is effectively parallel to the paleo–spreading ridge during breakup of Gondwana, which shaped the northwestern margin of Australia. Top panel indicates topography and bathymetry, with red inverted triangles indicating positions of seismometers along the imaging profile. (C) Vertical cross section from Sumbawa across Sumba southeast to Savu and then Rote. This profile is effectively perpendicular to the paleo–spreading ridge. Top panel indicates topography and bathymetry, with red inverted triangles indicating positions of seismometers along the imaging profile.

material to the southwest and northeast beneath Timor. These observations are even more apparent in the cross section (Fig. 2B). The profile that runs along strike through Sumba (Fig. 2C) shows a moderately fast velocity region between ~20 and 40 km depths, which is bounded by slower velocities to the northwest, beneath Sumbawa, and to the southeast beneath Rote.

We interpret these velocity anomalies to be subducted structures inherited from the incoming and downgoing Indo-Australian lithosphere. The Australian passive margin is actively colliding at the Timor Trough (Fig. 1A), and its southwestern extent consists of relict salients and embayments that were formed during the breakup of Gondwana in the Jurassic (Heine and Müller, 2005). The relict structures are clearly depicted in the bathymetry (Fig. 1A). The embayments are primarily composed of typical oceanic lithosphere, but the salients, such as the Scott and Exmouth submarine plateaus, are underlain by continental crust with the oceanic side consisting of volcanic-margin crust (e.g., Charlton, 2004; Heap and Harris, 2008). Haig and McCartain (2007) and Charlton (2000) suggested that the Timor region was originally a plateau with similar structure to those presently offshore northwest Australia. Our seismic images reveal that this structure exists at depth beneath the convergent margin. Profile B-B′ from Sumbawa through Sumba to Rote (Fig. 2C) effectively captures the structure of the subducted salient (identified with the higher velocities) that is parallel to the paleo–spreading direction from the breakup of Gondwana (Rigg and Hall, 2012). Profile A-A′ through Timor (Fig. 2B) shows the structure of the subducted salient that is perpendicular to the paleo–spreading direction from the breakup of Gondwana.

The role of Scott Plateau subduction in driving the uplift and tilting of Sumba has been discussed (e.g., Harris, 1991; Fleury et al., 2009; Rigg and Hall, 2012), and we found this likely reflected in the high-shear-wave-velocity zone beneath Sumba (Fig. 2C). Intriguingly, we also found the subducting volcanic-margin protrusion imaged at depth beneath Timor as faster velocities, coinciding with the two regions of highest topography on this island (Figs. 2B, 3A, and 3C). Thus, the structure of the incoming plate may exert a strong control on surface deformation, not only in the somewhat unusual case of Sumba, but also associated with the fold-and-thrust tectonics of Timor. These observations suggest that heterogeneous slab structures can play important roles in determining the rocks that are uplifted and exhumed during early stages of continental collision. We propose that this first-order structure sets the template on which crustal tectonics superimpose small-scale variations in uplift and exhumation, as seen on Timor (e.g., Tate et al., 2014). Recognizing the complexity of deep structure, as reflected in the inferred velocity, strength, and lateral extent of these structures, may therefore be critical to interpreting the geological and sedimentary record of continental collision, and the ways in which the initial template controls eventual orogenic structure deserve further attention in efforts to understand collisional tectonics.

Curiously, the most rapid uplift on Timor seems to have shifted from the center of the island, where topography is highest and uplift was presumably sustained for the longest period of time, to the east and west ends, where rates have been fastest over the past several 100 k.y. based on the uplift inversion (Fig. 3B; Fig. S3). The regions of rapid recent uplift coincide with the edges of the volcanic-margin protrusion (faster velocities in blue in the tomography), where we see a transition to slower shear-wave velocities (indicated by brown colors), inferred to be the Gondwanan margin megasequence extending

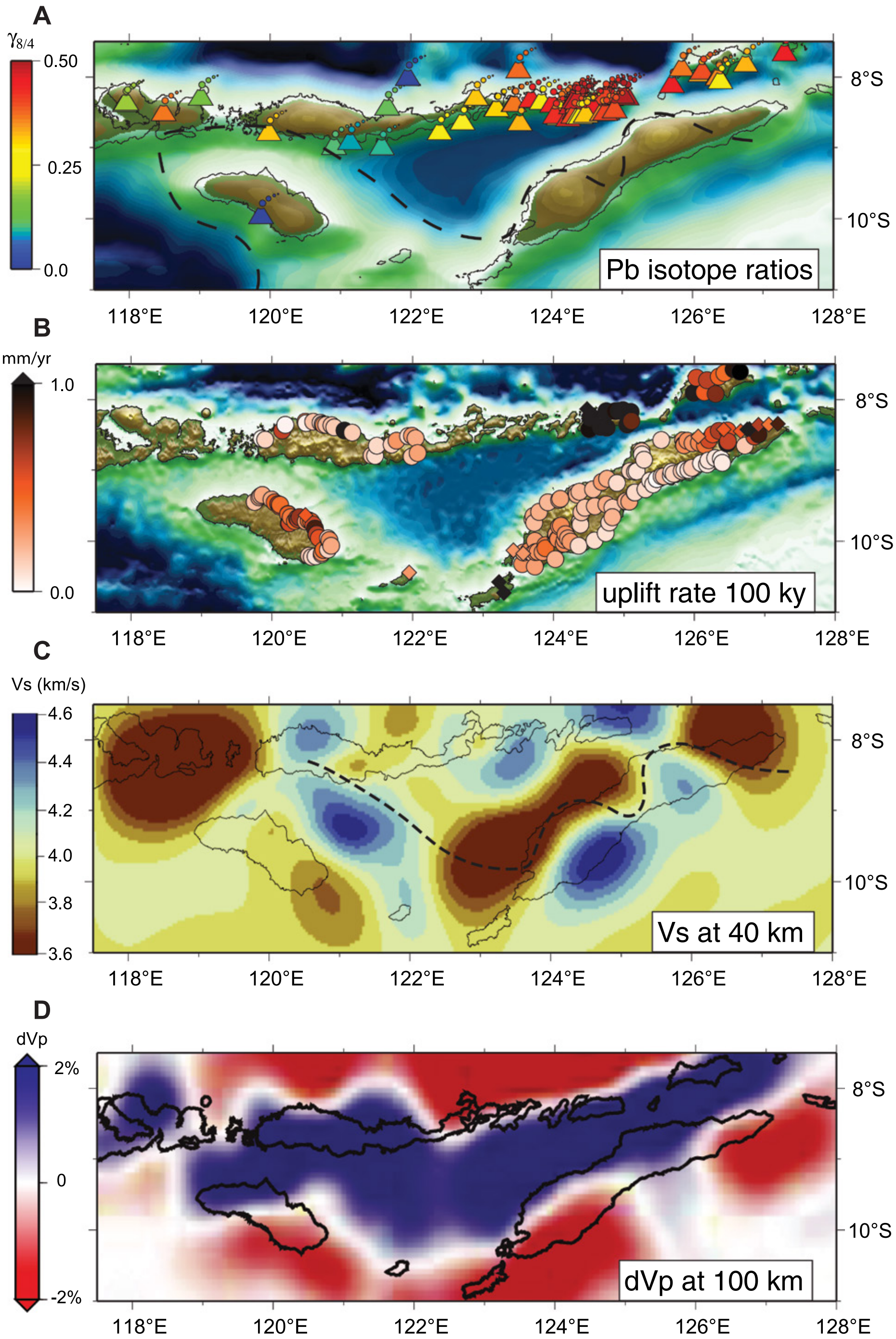

Figure 3. (A) Smoothed ETOPO1 (1 arc-minute global relief model; https://www.ngdc.noaa.gov/mgg/global/) topography (Amante and Eakins, 2009; color scale as in Figure 1) with volcano symbols colored by lead (Pb) isotope anomalies ($\gamma_{8/4}$) from Elburg et al. (2005) and M.A. Elburg (2011, personal commun.). Black thick dashed line represents inferred locations of the Scott Plateau and Timor plateau, which also correlate spatially to two locations of highest topography on Timor. (B) Reconstructed uplift rates for past 100 k.y., where circles are rates inferred for each river profile. (C) Ambient noise tomography at 40 km depth. Black thin dotted line represents inferred shape of underthrusted ocean-continent boundary structure of incoming/downgoing Australian plate, including the Scott Plateau and inferred Timor plateau at 40 km depth. Note that the shapes of structures are reminiscent of existing salients and embayment bathymetry offshore western Australia (Fig. 1A). (D) P-wave tomography (Harris et al., 2020) at 100 km depth illustrating slab structure (blue) inferred from fast velocity anomalies.

to greater depth. Such an along-strike pattern is also found in the effective elastic thickness (EET) estimates of Tandon et al. (2000), who inferred a swath of relatively large EET ("strong" lithosphere) values in central Timor, and lower EET values at both ends of the island where uplift is most rapid, possibly assisted by relatively weaker lithosphere.

North of the forearc islands, the pattern of Pb isotope variations ($\gamma_{8/4}$, as defined by Elburg et al. [2004]; i.e., the measured $^{208}Pb/^{204}Pb$ ratio relative to a linear reference based on $^{207}Pb/^{204}Pb$) in igneous rocks from the active and inactive volcanoes of the Sunda-Banda arc, shown in Figures 1B and 3A, corresponds to major lithologic changes in crustal components entering the subduction system. The distinct change in Pb isotope ratios across ~122°E and the similarly anomalous along-arc variations in radiogenic $^{3}He/^{4}He$ ratios (cf. Hilton et al., 1992) are inferred to represent the continent-ocean boundary in the subducted plate. A corresponding, broad transition is also observed in teleseismic body wave tomography (Zenonos et al., 2019; Harris et al., 2020; as in Fig. 3D) and surface wave models (Fichtner et al., 2010). However, these previous imaging studies were not able to resolve the smaller-scale variations that are seen in the ambient noise tomography–based images (Fig. 2).

There are also smaller-scale variations in the isotope ratios. The maximum $\gamma_{8/4}$ values (Figs. 1A and 3A) on Alor near 124°E–125°E also coincide with anomalous $^{3}He/^{4}He$ values (Hilton et al., 1992), which are inferred to be located in the central section of the active collisional zone. However, west of 122°E, between western Flores and the island of Sumbawa, $\gamma_{8/4}$ decreases and then becomes more variable along strike before decreasing significantly to minimum values on Bali and Lombok. This second-order pattern likely reflects the introduction of a different, presumably continental, subducted component into the subarc environment (Elburg et al., 2004). We suggest that the seismic images beneath the arc-continent collisional region together with the anomalous $\gamma_{8/4}$ values on the island of Sumbawa and the change from the unidirectional trend seen along the arc are indicative of the subduction of the inherited structures on the incoming Indo-Australian plate.

CONCLUSIONS

Independent observations from our new ambient noise tomography–based images, river profile uplift inversions, topographic analyses, and existing isotope signatures of the volcanic rocks along the Sunda-Banda arc together illustrate the importance of inherited complex structural variations along a collisional plate boundary. Recognizing the complexity of incoming (and downgoing) plate structure may therefore be critical to interpreting the geological and sedimentary record of continental collision. The ways in which the initial template controls eventual orogenic structure deserve further attention in efforts to understand collisional tectonics.

ACKNOWLEDGMENTS

This work was supported by U.S. National Science Foundation Tectonics/Geophysics/Global Venture Fund grants EAR-1250214 and EAR-1853856. Many thanks go to our colleagues at the Institute of Petroleum and Geology (IPG, Timor-Leste), the Indonesian Institute of Meteorology and Geophysics (BMKG), and Institut Teknologi Bandung (ITB, Indonesia) as well as the U.S. Embassy in Jakarta and The Incorporated Research Institutions for Seismology (IRIS) Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL), who made the work possible. Special thanks to B. Duffy, R. Harris, and an anonymous reviewer for their comments on the manuscript.

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Printed in USA