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Continent–arc collision in the Banda Arc imaged by ambient noise tomography

Robert W. Porritt [a,*], Meghan S. Miller [a], Leland J. O'Driscoll [a], Cooper W. Harris [a], Nova Roosmawati [a], Luis Teofilo da Costa [b]

[a] *Department of Earth Science, University of Southern California, United States*
[b] *Institute of Petroleum and Geology, IPG, Timor-Leste*

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A B S T R A C T

The tectonic configuration of the Banda region in southeast Asia captures the spatial transition from subduction of Indian Ocean lithosphere to subduction and collision of the Australian continental lithosphere beneath the Banda Arc. An ongoing broadband seismic deployment funded by NSF is aimed at better understanding the mantle and lithospheric structure in the region and the relationship of the arc–continent collision to orogenesis. Here, we present results from ambient noise tomography in the region utilizing this temporary deployment of 30 broadband instruments and 39 permanent stations in Indonesia, Timor Leste, and Australia. We measure dispersion curves for over 21,000 inter-station paths resulting in good recovery of the velocity structure of the crust and upper mantle beneath the Savu Sea, Timor Leste, and the Nusa Tenggara Timur (NTT) region of Indonesia. The resulting three dimensional model indicates up to ∼25% variation in shear velocity throughout the plate boundary region; first-order velocity anomalies are associated with the subducting oceanic lithosphere, subducted Australian continental lithosphere, obducted oceanic sediments forming the core of the island of Timor, and high velocity anomalies in the Savu Sea and Sumba. The structure in Sumba and the Savu Sea is consistent with an uplifting forearc sliver. Beneath the island of Timor, we confirm earlier inferences of pervasive crustal duplexing from surface mapping, and establish a link to underlying structural features in the lowermost crust and uppermost mantle that drive upper crustal shortening. Finally, our images of the volcanic arc under Flores, Wetar, and Alor show high velocity structures of the Banda Terrane, but also a clear low velocity anomaly at the transition between subduction of oceanic and continental lithosphere. Given that the footprint of the Banda Terrane has previously been poorly defined, this model provides important constraints on tectonic reconstructions that formerly have lacked information on the lower crust and uppermost mantle.

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1. Introduction

Coupling across convergent boundaries is fundamental to many plate boundary and plate tectonic processes. Most commonly, convergent boundaries take the form of subduction of oceanic plates where negatively buoyant oceanic lithosphere pulls the downgoing plate into the lower mantle. This style of convergence often results in a relatively narrow zone of deformation focused along the plate interface. However, when anomalously buoyant subducting lithosphere (e.g. continental or volcanic arc) encounters a convergent boundary, the downgoing plate resists subduction leading to a complex deformational environment. While the understanding of the process of oceanic subduction has advanced to reveal subtleties in the variations of subduction parameters, the process of continent–arc collision is not well-represented on the modern Earth (e.g Moresi et al., 2014 and references therein). The southeast Asian archipelago is one such region of continent–arc collision and therefore provides a unique opportunity to investigate these processes (e.g. Audley-Charles, 1968; Harris, 2011; Hall and Spakman, 2015).

The Banda Arc is a collisional environment where various plate fragments in southeast Asia interact with the northwestern Australian plate (i.e. Hamilton, 1979). This collision is occurring at the eastern termination of the Java Trench where the Indian Ocean plate subducts under Eurasia forming the Indonesian Arc. The seafloor ages here increase to the east along the arc reaching Jurassic ages south of the Island of Sumba (Müller et al., 2008) where the lithosphere transitions from oceanic to the Australian

* Corresponding author. Tel.: +1 906 281 3675.
E-mail address: rporritt@usc.edu (R.W. Porritt).

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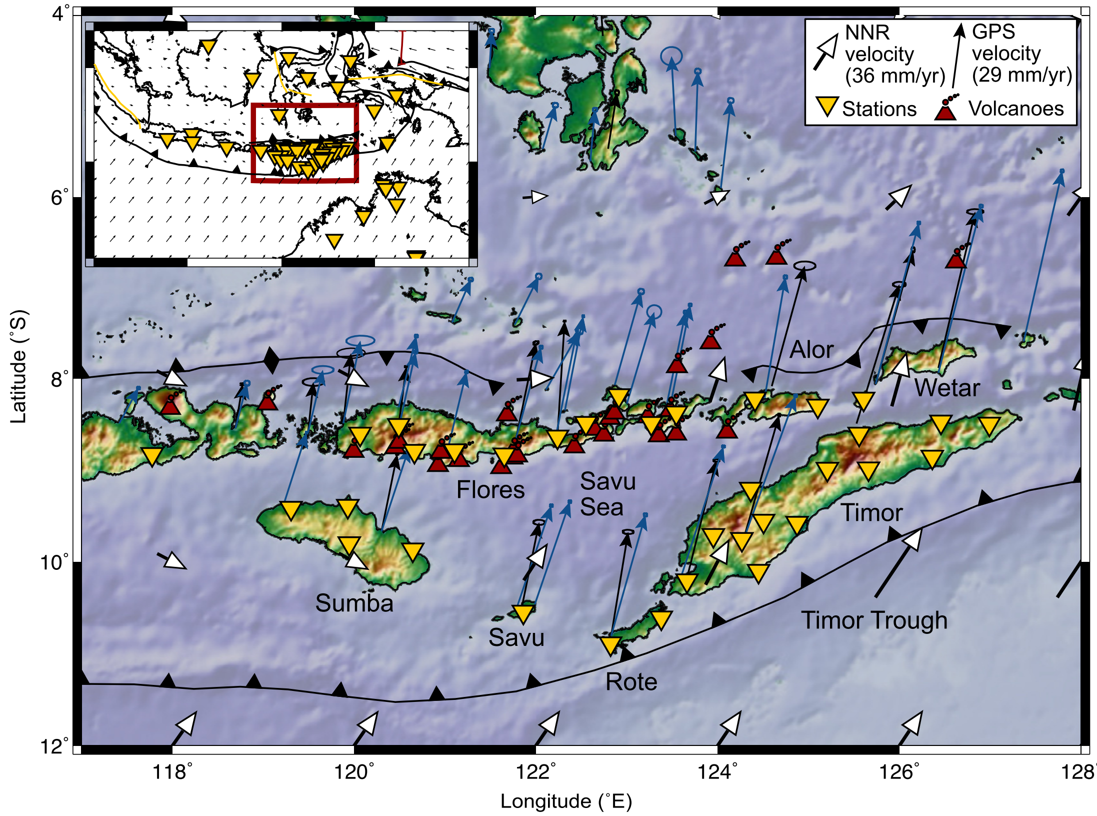

Fig. 1. Location map depicting seismic recording stations in the Banda Arc. Yellow inverted triangles indicate stations, red triangles with bubbles indicate quaternary active volcanoes of the Banda Arc. Solid lines indicate plate boundaries from the USGS; teeth indicate the overriding plate. GPS velocity vectors referenced to a stable Sunda block and their uncertainties are shown in black arrows (Bock et al., 2003; Calais et al., 2006; Simons et al., 2007; Nugroho et al., 2009) and blue arrows (Koulali et al., 2016) and the no net rotation plate motion is shown with white arrowheads (DeMets et al., 2010). Inset map indicates all stations used in the study and a larger scale view of the plate motion velocity vectors. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

continental margin. At this transition, there is a significant bifurcation of the arc, as the volcanic arc goes from a single linear chain to a set of inner and outer arc islands, with the inner arc being volcanically active and the outer arc representing the collisional front. It is this inner and outer arc system that is collectively referred to as the Banda Arc. The collisional orogen is relatively young based on plate reconstructions (e.g. Harris, 1991; Hall, 2002). However, other data from onshore geological investigations offer a range of ages of initiation of the collision from ∼16 Ma to ∼1 Ma (Audley-Charles, 1968; Rutherford et al., 2001; Keep and Haig, 2010; Spakman and Hall, 2010; Harris, 2011; Hall and Spakman, 2015).

Oblique convergence along the plate boundary is evident up the orientation of the Timor Trough, plate motions in a no-net rotation frame (DeMets et al., 2010), and GPS velocity vectors (Bock et al., 2003; Calais et al., 2006; Simons et al., 2007; Nugroho et al., 2009; Koulali et al., 2016) (see Fig. 1). In the no-net rotation frame, the Australian plate is moving to the northeast as the islands of Flores and Sumba move towards the east, but the GPS vectors relative to the Sunda block show north-northeast displacements. This suggests the collision progressed with initial collision along a promontory of the Australian plate and then continued southwestward along the Timor Trough. This effective time-space trade-off allows investigation into the temporal evolution of arc–continent collision by comparing different sections of the orogen (e.g. Harris, 2011). Past studies have either taken a large-scale view from teleseismic imaging (e.g. Widiyantoro et al., 2011; Hall and Spakman, 2015) or very small scale views from mapping outcrops (e.g. Audley-Charles, 1968; Rosidi et al., 1979; Harris et al., 1998, 2009; Roosmawati and Harris, 2009; Harris, 2011; Tate et al., 2015) and active source seismic images (e.g. Lüschen et al., 2010; Rigg and Hall, 2012).

The region is among the most seismically active globally and has a clearly defined Wadati–Benioff zone tracing out a northward dipping slab to ∼600 km depth (Das, 2004). This structure is confirmed by global P wave tomography (e.g. Widiyantoro et al., 2011) which indicates a high velocity body coincident with the seismicity (e.g. Das, 2004; Ely and Sandiford, 2010) and follows the trench continually from the Java Trench around the Timor Trough to southward dipping subduction at the northeastern end of the Banda Sea. However, it is argued whether there is a single slab or two slabs around this juncture at the eastern end of the Banda Sea (e.g. Milsom, 2001; Das, 2004; Widiyantoro et al., 2011).

Recent imaging by Fichtner et al. (2010) using full waveform tomography indicates the presence of high velocity material at 200 km depth under Timor and eastward, but not under the western part of the Banda Arc. They infer that this high velocity anomaly is subducting Australian continental lithosphere due to the correspondence with He^3/He^4 ratios of ∼1 (Hilton et al., 1992), which indicates continental material in the source of arc magmas. Furthermore, the imaged high velocity body is continuous with the Australian cratonic lithosphere, suggesting a connected plate. This suggests that the Australian lithosphere is subducting, but their model lacks the necessary resolution to determine what happened to the lower density continental crust. Therefore, higher resolution images of the system are needed, such as those that are achievable through the newly developed method of ambient noise tomography.

Crustal duplexing during the collision has largely been determined through structural mapping of the islands (e.g. Audley-Charles, 1968; Rosidi et al., 1979; Harris et al., 1998, 2009;

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