Banda Arc Experiment—Transitions in the Banda Arc-Australian Continental Collision

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ABSTRACT

Eastern Indonesia is one of the least well-understood geological domains on Earth, yet the region is one of the few places which is currently undergoing arc-continent collision. The Banda arc seismic experiment was designed to unravel some of the complex dynamics of convergent tectonics. This passive source experiment is composed of 30 broadband instruments that extend across the Nusa Tenggara Timur region of Indonesia and across Timor-Leste. This along-strike deployment allows for seismic imaging and assessment of the spatiotemporal evolution of the collision of oceanic to continental lithosphere of the Indo-Australian plate with the active volcanic arc. The experiment has been continuously recording broadband seismic data since early 2014 and will continue through the end of 2016, and the data will be archived at the Incorporated Research Institutions for Seismology Data Management Center under network code YS and will be available at the end of 2018.

INTRODUCTION

In eastern Indonesia, the northern edge of the Australian continent is colliding with the active volcanic arc at ~7.5 cm/yr (Bock et al., 2003), effectively capturing the initiation and continuation of convergent orogenesis. To the west of the Banda arc seismic array, the oceanic lithosphere of the Indo-Australian plate is subducting beneath the Eurasian plate, creating a long volcanic arc that extends from Sumatra to Flores Island (Fig. 1a). There, the Indo-Australian plate composition changes to oceanic plateau (Scott plateau) and then to continental lithosphere of Australia as it collides with the Banda arc, creating an uplifted forearc, and potentially, subducting continental lithosphere (Hamilton, 1979; McCaffrey et al., 1991; Audley-Charles, 2004; Harris, 2011). The amount and extent of continental subduction as well as the timing and rate of the continental collision are variable along the arc. The along-strike variation in the structure and composition of lithosphere allows for assessing the spatiotemporal evolution of

the subduction-related collision based upon seismic images created by our broadband experiment. This highly seismogenic subduction zone setting and continental collision has produced a very complex geologic history but is an ideal locale to study the transition from subduction to arc-continent collision.

One observation of the transition from oceanic subduction to continental collision is through lithospheric deformation, as reflected in seismicity (Fig. 1a). Wadati–Benioff zones can be traced down to below 600 km beneath much of the arc (Cardwell and Isacks, 1978; Das, 2004), but there are interesting spatial gaps in shallow and intermediate depth seismicity such as beneath the island of Wetar between ~70 and 350 km and beneath the island of Timor (Fig. 1b). This lack of seismicity beneath the island of Wetar correlates with the extinct volcanic section of the arc and was termed the Wetar seismic gap (WSG; Sandiford, 2008; Ely and Sandiford, 2010). Up-dip from the WSG, there are few shallow earthquakes beneath Timor in comparison with the rest of the region. These patterns have been interpreted as being related to the collision and subsequent changes in lithospheric structure (Sandiford, 2008), and specifically to tearing of the oceanic slab away from continental lithosphere. Further evidence for such tearing comes from the distribution of moment release within the slab (McCaffrey, 1988; Das, 2004; Sandiford, 2008; Ely and Sandiford, 2010), which indicates that the slab is deforming heterogeneously.

Seismic tomography has been used extensively as a tool to investigate the dynamics of the study area (Widiyantoro and van der Hilst, 1997; Fichtner et al., 2010; Spakman and Hall, 2010; Widiyantoro et al., 2011), but due to the limited station coverage in the past, the resolution of the mantle and lithosphere is variable and in some places quite poor, especially at the transition between oceanic and continental subduction in the uppermost mantle and lithosphere, which is fundamental to our understanding of the collisional processes. Nonetheless, a few of the prior published models suggest that slab
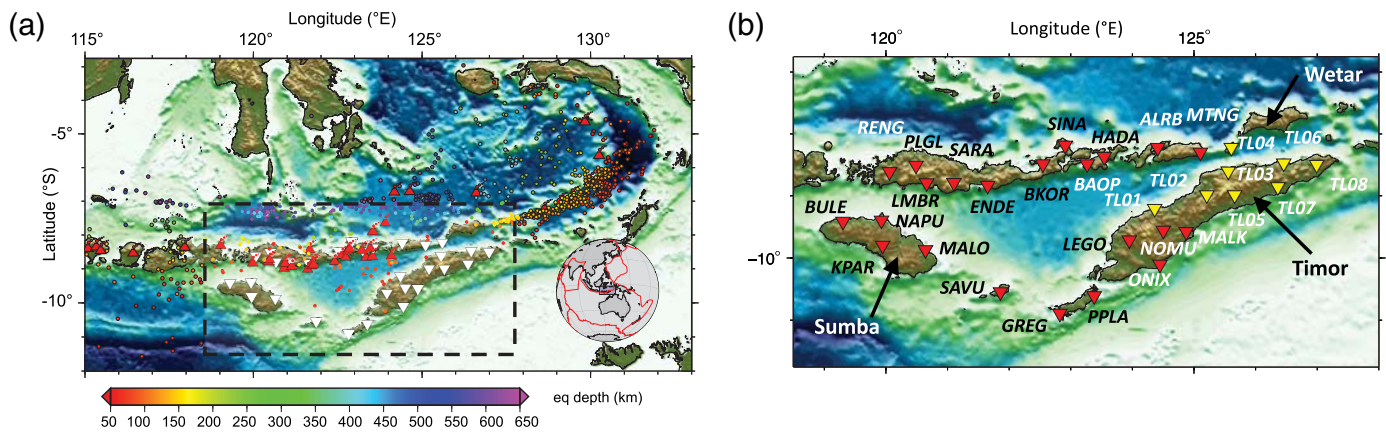
▲ **Figure 1.** (a) Generalized tectonic setting of the Banda arc with active volcanoes plotted in red in the online version, seismicity (Das, 2004), and the Banda arc (YS) network shown by inverted white triangles. The dotted line box shows the location of the seismic array map in (b) and the inset shows the location of the map on Earth. (b) Map of the YS network of broadband seismometers (2014–2016). Light colored (yellow in online version) inverted triangles are instruments deployed in Timor-Leste and dark colored (red in online version) inverted triangles are instruments deployed in Nusa Tenggara Timur region of Indonesia. The stations labeled with black font indicate stations with STS-2/Q330 instrumentation and those with white font indicate stations with Trillium 120PA/Taurus instrumentation. The color version of this figure is available only in the electronic edition.

tearing may occur (Widiyantoro and van der Hilst, 1997) and that there may be a significant amount of continental subduction beneath the active arc (Fichtner *et al.*, 2010).

Even with these prior studies, many questions remain unanswered about the transition from subduction to arc-continental collision, and our broadband passive source experiment thus offers a rare glimpse into a fundamental process that has shaped Earth's evolution over geologic time. This deployment will provide new data to compare with the existing constraints on the degree of continental subduction (e.g., location and chemistry of active and recent volcanism, mapped thrust sheets, dating of uplifted coral terraces, Global Positioning System, and seismicity) and will make it possible to produce new high-resolution images

of the lithospheric structure and subducted slab morphology based on broadband seismic data recorded at this array.

INSTRUMENT DEPLOYMENT AND DETAILS

We completed a temporary installation of 30 broadband seismometers during 2014, as part of the National Science Foundation (NSF) funded Banda arc project; these instruments will remain in place until the end of 2016 (Fig. 1b). The first eight instruments were deployed in March 2014 and have been continuously recording ground motion, spanning the geographic range of Timor-Leste. The logistics and fieldwork was completed in collaboration with scientists at the Instituto Petróleo e Geologia of Timor-Leste. These eight instruments owned by the

▲ **Figure 2.** Photographs of example field sites and instrumentation. (a) Nanometrics instrumentation at TL05 in the village of Same, Timor-Leste. (b) STS-2/Q330 instrumentation at station LEGO in Lelogama, West Timor, Indonesia. The color version of this figure is available only in the electronic edition.
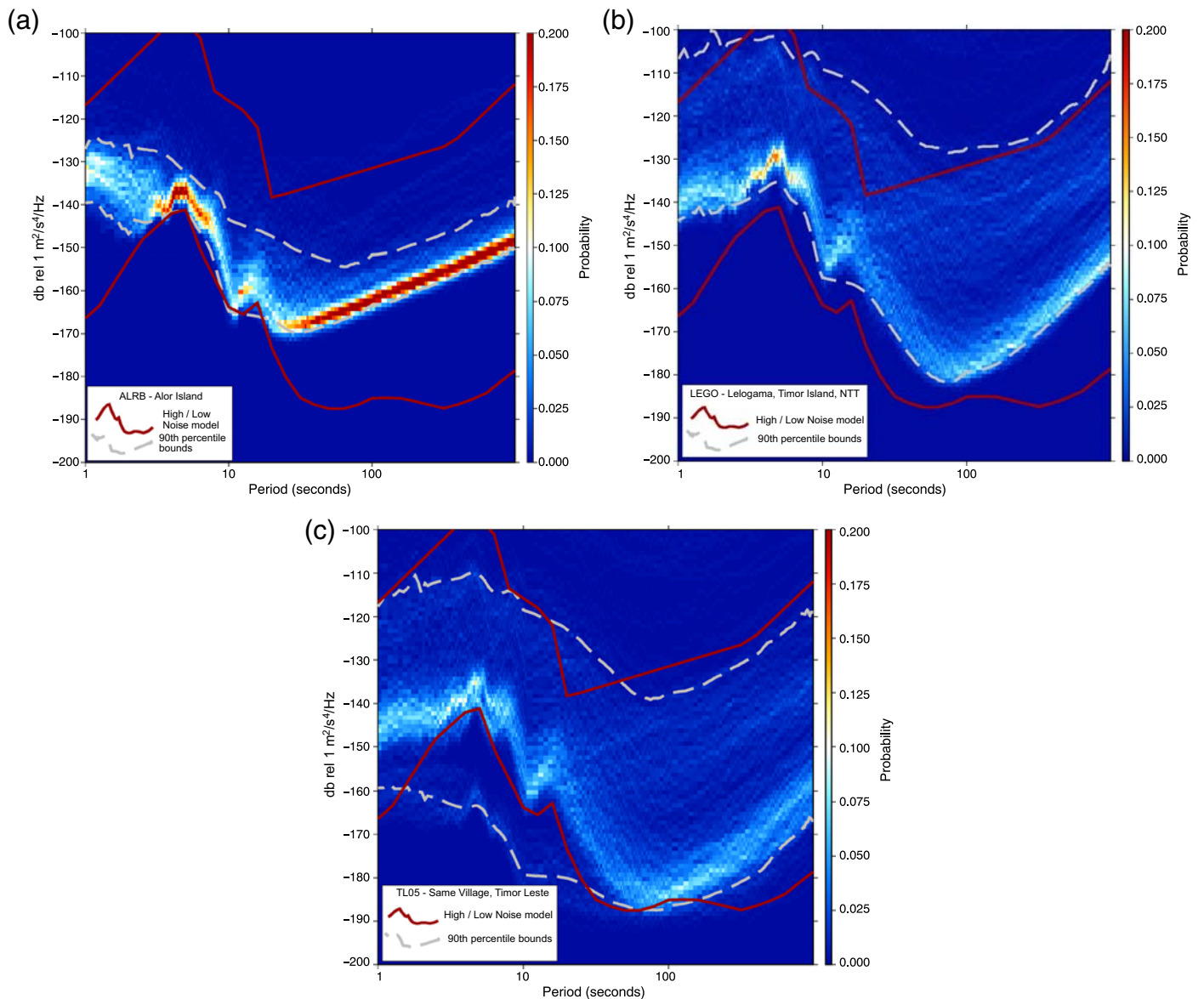
▲ **Figure 3.** Probability density function (PDF) of power spectral densities (PSDs) for stations (a) ALRB, (b) LEGO, and (c) TL05. LEGO is equipped with a STS-2 sensor, and ALRB and TL05 are equipped with Trillium 120PA sensors. High- and low-noise models are those of Peterson (1993). The color version of this figure is available only in the electronic edition.

University of Southern California (USC) are Nanometrics Trillium 120PA with Taurus digitizers. The additional 22 broadband seismometers in the Nusa Tenggara Timur region of Indonesia were deployed in September–November 2014 in collaboration with colleagues at the Institut Teknologi Bandung and Badan Meteorologi, Klimatologi, dan Geofisika (Fig. 1b). These 22 instruments are composed of 7 additional Trillium 120PAs with Taurus digitizers (owned by USC) and an additional 15 Program for Array Seismic Studies of the Continental Lithosphere (PASS-CAL) instruments that consist of Streckeisen STS-2 sensors and Kinemetrics Q330 dataloggers. All the stations are recording continuous time series data for three components at 50 samples/s.

The station design was based upon prior experience by the team and consists of a buried sensor vault made out of large plastic drums with a water-tight ring that purchased in the United States and shipped with instruments (Fig. 2). This style of vault also has a separate water-tight action packer or transport case that stores the electronics (data acquisition systems [DASs]) and battery that remains on the surface. The seismic stations are powered by lead-acid car batteries purchased in country and are charged with two 36 W solar panels for the Nanometrics stations (Fig. 2a) and a 65 W solar panel for the STS-2 stations (Fig. 2b). Because of the low-latitude location of the experiment, the 65 W panels were installed such that they also provided shade for the DAS box.

The stations were sited and installed with the help from our local collaborators and were often placed near municipal buildings or buildings owned by friends and family of our local col-
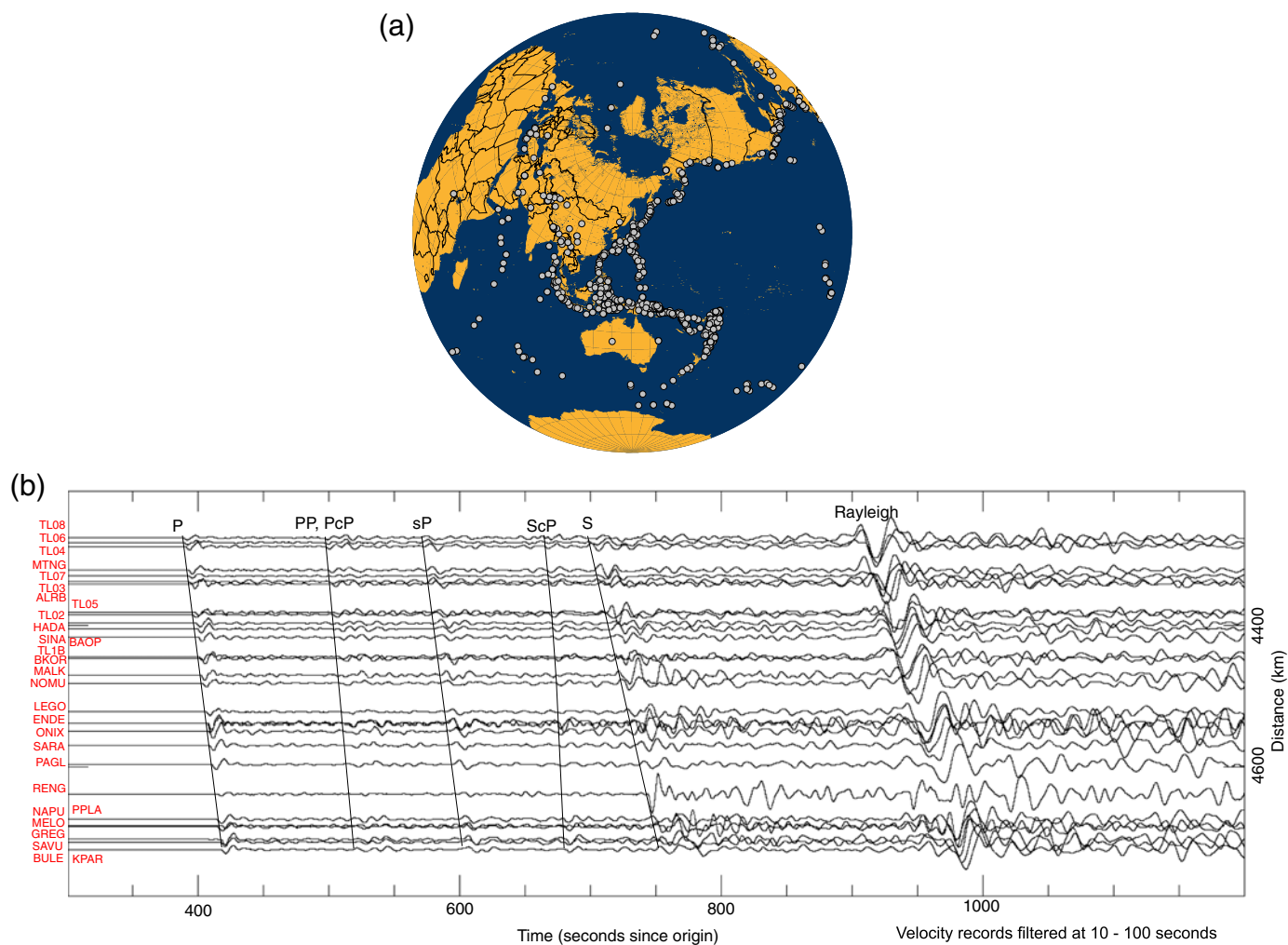
▲ **Figure 4.** (a) Plot of M_w 5.5 and greater earthquakes recorded by the Banda arc array through 15 June 2016. (b) Record section of band-pass-filtered (10–100 s) waveforms for the 30 May 2015 M_w 7.8 Chichi-Jima ∼664-km-deep earthquake recorded on the Banda arc network. Figure (B) made with SAC. The color version of this figure is available only in the electronic edition.

laborators to more effectively protect the instruments from theft or damage (Fig. 2). Because of these limitations in site locations, the time series are often noisy, as discussed in the next section, but security has not been an issue during this experiment.

OVERALL DATA QUALITY AND AVAILABILITY

The stations are serviced approximately every six months at the end (March) and beginning (September) of the wet season. Because of the remote locations and poor road conditions, many of the stations would not be accessible at other times of the year.

Examples of the background noise signal from three different stations are shown in Figure 3: station ALRB on the relatively small island of Alor; and two stations on the island of Timor, LEGO and TL05. These plots show probability density functions (PDFs) of power spectral densities (PSDs) of the stations from installation until 17 June 2016. The computations are slightly modified from Peterson (1993) and McNamara and Buland (2004) and Incorporated Research Institutions

for Seismology (IRIS) MUSTANG tool. The PSDs are computed from 17 Hanning tapered windows of the medium sample rate vertical channel (BHZ) per day, each with 50% overlap with the neighboring windows, and then averaged via Welch's method. The PSDs are interpolated via a $\log_{10}$ interpolation algorithm and then stacked into probability space for the PDFs. Station ALRB shows a relatively compact PDF, with signal just above the low-noise model at the primary and secondary microseismic peaks (∼8 and 16 s), but a long-period signal well above the low-noise model at greater than ∼25 s period. Stations LEGO and TL05 on the island of Timor show less compact PDFs with the 90th percentile values spanning a large range. However, the largest probability peaks are near the low-noise model at the microseismic peaks and at longer periods, suggesting relatively quiet long-period recording, which is rare for island stations. Signals below the low-noise model are unlikely real, but may be due to recording errors, and signals above the high-noise model may either be recording errors or large signals from teleseismic earthquakes. Although some of

the stations are noisy, the stations were all deployed in secure locations allowing for overall high return on the data and clear teleseismic and local earthquake signals. However, one of the first Timor-Leste stations installed (TL01) in Oecussi was discovered to be particularly noisy after the first service run in October 2015. The station was moved to another nearby location TL1B in March 2015 a few kilometers away, which reduced the amount of cultural noise.

A few issues affected data availability for three stations during the deployment. One of the Trillium 120PA sensors in Timor-Leste (station TL07) was found to have an audible 2–3 Hz pinging sound during recentering as well as observing an inability of the sensor to stabilize (i.e., to stay centered) during the first service run in September 2014. It was shipped back to be repaired by Nanometrics and was then reinstalled in the same location in March 2015, which resulted in a ∼7-month data gap. A wildfire occurred on the island of Sumba on 3 October 2015 that burned down the site of one of the PASSCAL instruments installed in Tambolaka, Sumba Barat Daya (station BULE). Only the STS-2 sensor survived the fire. The last data from this station was collected on 6 September 2015, which provided about a year worth of data in total. One of the STS-2 sensors, at station LMBR, had continuous issues with all channels beginning mid-April 2015 just after the first service run. Problems incurred include monsoonal flooding and accidental severing of cables after this service. After determining that the masses in the sensor were not responding to any tests and replacing the cables during the next service run in September 2015, the sensor was replaced with the STS-2 from BULE in March 2016, but was still unable to center and is still only recording digital noise.

INITIAL OBSERVATIONS

The deployment (as of June 2016) has already recorded over 600 local earthquakes with magnitude greater than M_w 4.5 in the Banda arc region and has also recorded ∼1000 teleseismic earthquakes greater than 5.5 in the ∼2 years the experiment has been active (Fig. 4a). An example record section of one of these teleseisms, the 30 May 2015 M_w 7.8 Chichi-Jima, ∼664-km-deep earthquake, is shown in Figure 4b. The large number of local events will provide us with a wealth of data to be used for many types of analyses such as waveform analysis (Miller et al., 2016), local shear-wave splitting (Harris et al., 2015), and importantly a new, regional earthquake catalog. The teleseismic data will be used for many types of structural seismology analyses that will provide new high-resolution images and inference into structure and evolution of the crust and mantle. The archived data will become openly available in 2 years (late 2018) via the IRIS Data Management Center (DMC) after the deployment has finished recording data as outlined by NSF–Earth Sciences Division guidelines.

INITIAL RESULTS

As of this article, three publications are being prepared or are in press with the data collected so far. Ambient seismic noise tomog-

raphy has been utilized to prepare a shear-velocity model for the upper 50 km (Porritt et al., 2016). From this model, we report low shear-velocity anomalies associated with sedimentary units from the incoming Australian plate vertically offset by the high shear-velocity backstop of the Banda terrane (Fig. 5). We also observe that high shear velocities of Sumba Island are contiguous through the Savu Sea, but are underlain by a low velocity associated with the top of the subducting Scott plateau. Finally, we suggest that velocity offsets in the active inner arc are associated with the lateral offset of oceanic subduction and continental collision.
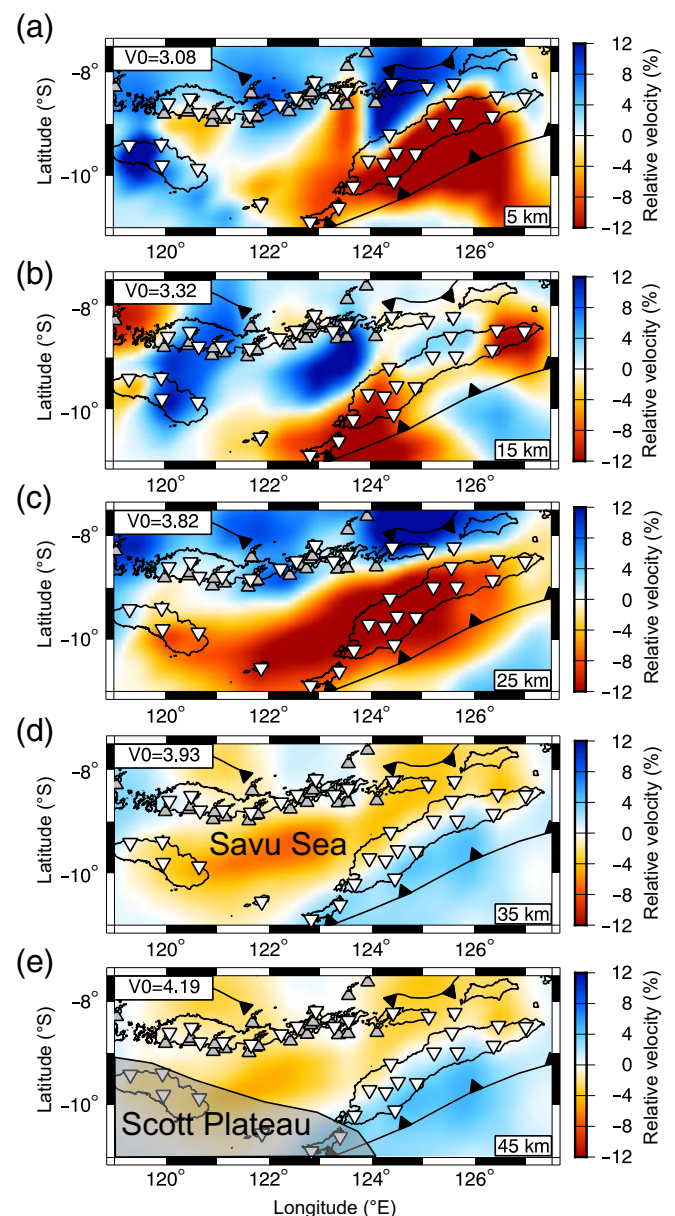
▲ **Figure 5.** Maps of relative shear velocity (reference velocity labeled in upper left) at depth (labeled in lower right corner) from an inversion of ambient noise-derived phase velocity maps (reproduced from Porritt et al., 2016). Identification of the Scott plateau is inferred from bathymetry and seismic velocity at depth. The color version of this figure is available only in the electronic edition.
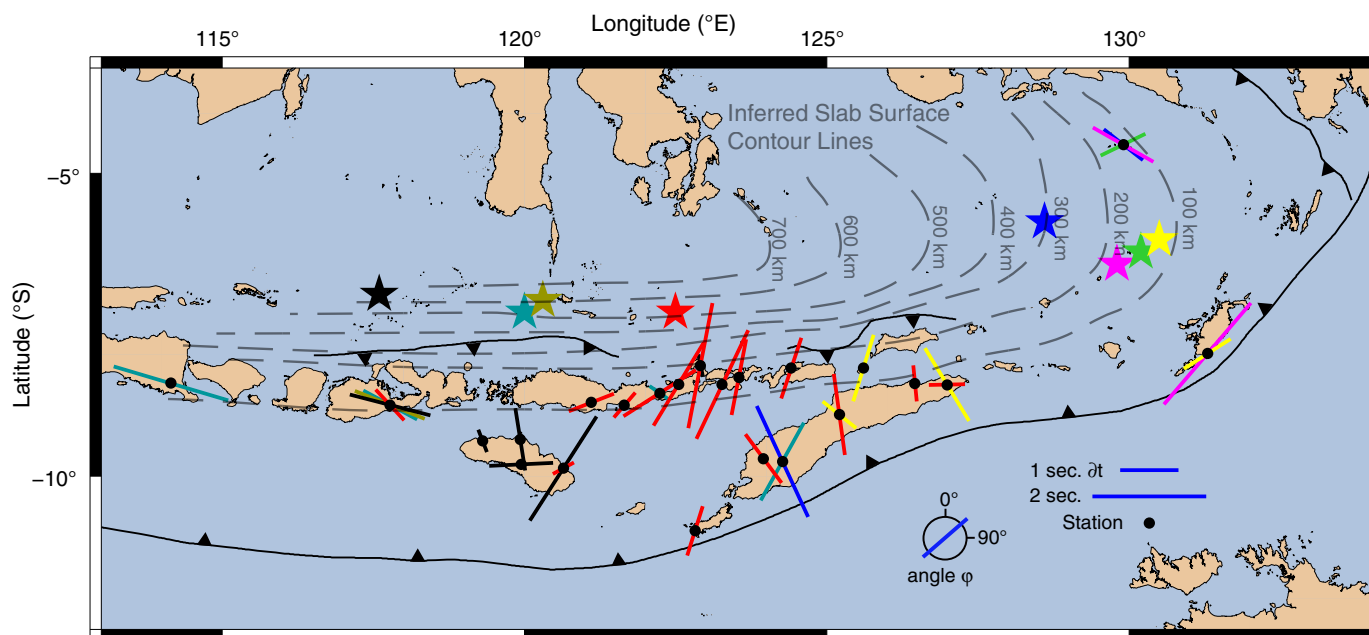
▲ **Figure 6.** Splitting measurements for local earthquakes that occurred during the first half of the deployment (2014–2015) plotted as bars at the station locations. Splitting time delay (δt) scales to bar length and bar orientation is equal to the inferred fast axis (φ). Stars represent earthquake epicenters and are color-coded to match relevant splitting measured. The inferred slab surface contour lines are based upon seismicity (Das, 2004). The color version of this figure is available only in the electronic edition.

Although dispersion curves from ambient noise tomography have been shown to stabilize with 1–2 years worth of data (Bensen *et al.*, 2007; Porritt *et al.*, 2011), studies requiring a distribution of local or teleseismic earthquakes benefit from having more data collection time. Therefore, the studies mentioned in the Initial Observations section above are not complete; however, preliminary results analyzing the high-frequency character of local deep focus direct *P* waves (Miller *et al.*, 2016) and seismic anisotropy (Harris *et al.*, 2015) are summarized here. Through waveform analysis of the many deep earthquakes occurring in the region, initial results indicate that the energy associated with the *P*-wave first arrival indicates a large amount of variation between waveforms at different stations along the arc, both in terms of frequency content and maximum amplitudes. These results do not appear to be a result of site/local geology effects, but suggest that we may be able to image a change in subducted lithospheric structure or composition along strike.

Additional preliminary results on local and teleseismic shear-wave splitting have been presented at the American Geophysical Union Fall 2015 meeting (Harris *et al.*, 2015). These very initial observations from just a few shear-wave splitting analyses of teleseismic core (*SK*(*K*)*S*) phases reveal an approximately trench-parallel fast axis along strike, which is consistent with other subduction settings and can be interpreted as mantle flow being deflected around a descending slab (e.g., Long and Becker, 2010). Conversely, our splitting analysis of local (*S*) phases illustrates a more complicated distribution of fast axes that varies significantly along strike (Fig. 6). To first order, these measurements appear to vary more along the strike of the arc than the core phase splits. This could be related to heterogeneous

structure of the downgoing plate, corner flow patterns imparted by the collision, or a slab tear as suggested by previous studies (Ely and Sandiford, 2010). However, preliminary results indicate a general trend of arc-normal fast directions that are observed near the middle of the array, and where the collision is most advanced, near Timor, we observe a discontinuous prevalence of roughly trench-perpendicular fast axes. This suggests that complex local splitting measurements and discrepancies between local and teleseismic phases could be related to the ongoing collision of the Australian continental lithosphere with the Banda arc.

SUMMARY

Challenging logistics have been an obstacle for this experiment in Nusa Tenggara Timur Indonesia and Timor-Leste, but initial observations and results indicate that the broadband data collected will allow for addressing fundamental science questions about arc–continent collision. In addition, many other related and unrelated questions about deep Earth structure, seismic hazard, and tectonics will be addressed with these data.

DATA AND RESOURCES

The seismograms and preliminary results shown here were collected as part of the National Science Foundation (NSF) funded Banda arc experiment using 15 Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) broadband instruments and 15 broadband instruments owned by University of Southern California (USC). Data will be available from the Incorporated Research Institutions for Seismology Data Management

Center (IRIS-DMC) for network YS at the end of 2018 (http://ds.iris.edu/gmap/YS?timewindow=2014-2016, last accessed June 2016). Data on active volcanoes are obtained from the Smithsonian Volcano Database (Global Volcanism Program, 2013). ⊜

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