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Key Points:

- Remotely triggered tremor on Sumbawa, Indonesia
- Determination of triggering threshold and key triggering factors
- Fluid-driven tremor generation possibly connected to episodic tremor and slip

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Remotely triggered nonvolcanic tremor in Sumbawa, Indonesia

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Abstract We present, for the first time, evidence for triggered tremor beneath the island of Sumbawa, Indonesia. We show triggered tremor in response to three teleseismic earthquakes: the M_w 9.0 2011 Tohoku earthquake and two oceanic strike-slip earthquakes (M_w 8.6 and M_w 8.2) offshore of Sumatra in 2012. We constrain an apparent triggering threshold of 1 mm/s ground velocity that corresponds to about 8 kPa dynamic stress. Peak tremor amplitudes of about 180 nm/s are observed, and scale with the ground velocity induced by the remote earthquakes. Triggered tremor responds to 45–65 s period surface waves and predominantly correlates with Rayleigh waves, even though the 2012 oceanic events have stronger Love wave amplitudes. We could not locate the tremor because of minimal station coverage, but data indicate several potential source volumes including the Flores Thrust, the Java subduction zone, or Tambora volcano.

1. Introduction

Nonvolcanic tremor (NVT) provides important information about dynamics of plate boundaries, but the underlying mechanisms driving NVT are not understood. NVT is ubiquitous and observed worldwide, and to date this includes Alaska and Aleutians [*Gomberg and Prejean*, 2013], California [*Gomberg et al.*, 2008; *Chao et al.*, 2012b], Cascadia [*Aiken et al.*, 2013], Chile [*Gallego et al.*, 2013], Costa Rica [*Walter et al.*, 2011], Cuba [*Peng et al.*, 2013], Japan [*Miyazawa and Brodsky*, 2008; *Obara*, 2012], Mexico [*Zigone et al.*, 2012], New Zealand [*Fry et al.*, 2011], and Taiwan [*Chao et al.*, 2012a]. In this paper, we expand this list to now include Sumbawa, Indonesia.

The characteristic seismic signature of tremor is emergent and irregular bursts of seismic energy depleted in high frequencies, and lasting from seconds to days. Naturally occurring tremor, termed ambient or background tremor, is distinguished from triggered tremor that is usually in phase with peak Love wave or Rayleigh wave amplitudes [*Guilhem et al.*, 2010; *Chao et al.*, 2012a, 2012b] of remote or regional earthquakes. Body wave triggering of tremor is rare but has been observed for both *P* and *S* waves [*Ghosh et al.*, 2009; *Shelly et al.*, 2011; *Hill et al.*, 2013]. The threshold for tremor triggering is remarkably low, responding to transient stresses as low as 1 kPa [*Guilhem et al.*, 2010], and some correlations are observed with tidal stressing [*Rubinstein et al.*, 2008; *Gallego et al.*, 2013; *Thomas et al.*, 2013]. This has lead to a general acceptance that high-pressure fluids are likely involved in their genesis [*Beroza and Ide*, 2011].

Among others, *Shelly et al.* [2007] suggest that tremor may result from a consecutive occurrence of small low-frequency earthquakes. Tremor typically originates from within the transition zone between locked and freely slipping parts of plate-boundary faults, at depth of 15–40 km downdip [*Rogers and Dragert*, 2003; *Shelly et al.*, 2006], and tremor is often associated with slow-slip earthquake (termed episodic tremor and slip, ETS) [*Bartlow et al.*, 2011; *Beroza and Ide*, 2011; *Miller*, 2013]. Understanding the mechanisms driving ETS presents an important challenge because it is likely a dominant aspect of the evolutionary processes leading to tsunamigenic, megathrust subduction zone earthquakes.

This study reports and analyzes, for the first time, the occurrence of triggered tremor beneath Sumbawa, Indonesia, following three teleseismic earthquakes since 2011.

2. Study Area and Data Availability

The island of Sumbawa, Indonesia, is part of the Lesser Sunda Group about 250 km north of the Australian/Eurasian plate collision at the Java Trench with a convergence rate of approximately 70 mm/yr

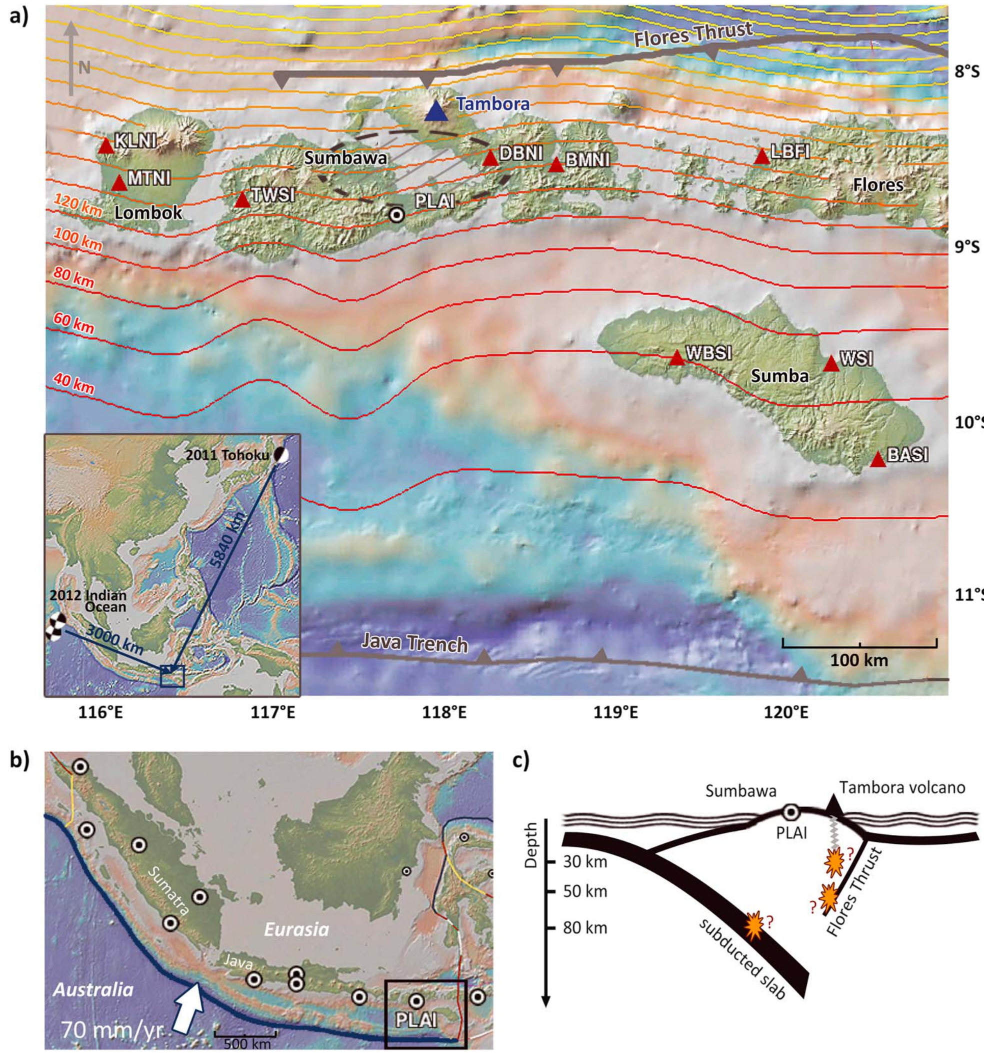

Figure 1. (a) Map of Sumbawa, Indonesia. The mapped area and the distances to the triggering earthquakes are marked in the inset. Thin solid lines mark the extension of the subducted slab with depth which is indicated on the left [*Hayes et al.*, 2012]. The circle denotes the location of the GEOFON station PLAI, triangles (except for Tambora volcano) mark seismic stations of the Indonesian BMG-Net. The encircled area in the middle represents a potential source area for triggered tremor on the Flores Thrust. (b) Tectonic setting of Indonesia. The thick blue line marks the elongation of the Java Trench subduction zone. Thin lines represent continental margins. Circles denote the locations of seismic stations of the GEOFON network. The rectangle indicates the area mapped above. (c) Sketch illustrating the three potential source regions for the triggered tectonic tremor. Tremor could be located at depth within the Tambora volcanic complex, below the locked zone of the Flores Thrust or on a deep section of the subducted slab. The sketch is not drawn to scale.

[*Tregoning et al.*, 1994]. The tectonic setting of Indonesia is shown in Figure 1b. *Silver et al.* [1983] and *McCaffrey and Nabelek* [1984] documented back-arc thrusting on the eastern Sunda Arc which is mapped as the Flores Thrust in Figure 1a that dips toward the south beneath Sumbawa.

Seismic stations around Sumbawa (see Figure 1a) include PLAI, which is part of the GEOFON global broadband seismic network [*Hanka et al.*, 2010]. The other stations belong to the broadband BMG-Net operated by the Indonesian Agency for Meteorology, Climatology, and Geophysics. The sampling rate for PLAI is 50 Hz or 100 Hz, and data can thus be used in this study. Unfortunately, the BMG-Net data insufficiently sample at 20–25 Hz and could not be used because of filtering limitations. Data were accessed via the European Integrated Data Archive and processed with ObsPy [*Beyreuther et al.*, 2010]. Initially searching for remotely triggered tremor by the M_w 9.0 2011 Tohoku earthquake, we checked all Indonesian GEOFON stations

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Table 1. List of Teleseismic Earthquakes Used in This Study[a]

Region	M_w	Date	Distance (km)	Angle (deg)	PGV (mm/s)	Stress (kPa)
Indian Ocean	8.6	11.04.2012	3000	23	3.20	27.0
Tohoku	9.0	11.03.2011	5840	−65	1.01	8.43
Indian Ocean	8.2	11.04.2012	3000	20	0.96	7.99
Philippines	7.6	31.08.2012	2380	−65	0.56	4.69
Pakistan	7.7	24.09.2013	6890	37	0.14	1.16
Kermadec	7.6	06.07.2011	7200	28	0.10	0.83
Solomon	8.0	06.02.2013	5200	6	0.08	0.68
Iran	7.7	16.04.2013	7250	37	0.06	0.49
New Guinea	7.1	14.12.2011	3200	0	0.05	0.39
Fiji	7.3	15.09.2011	6860	20	0.03	0.27
Kermadec	7.4	21.10.2011	7200	28	0.03	0.23
Tohoku	7.3	09.03.2011	5850	−65	0.02	0.20
Kamchatka	7.7	14.08.2012	7020	−71	0.02	0.18
Costa Rica	7.6	05.09.2012	17500	−5	0.02	0.17
Tonga	7.4	23.05.2013	7090	21	0.02	0.17
Vanuatu	7.1	02.02.2012	5530	16	0.02	0.16
Chile	7.1	25.03.2012	15000	79	0.01	0.03

[a]Only the upper three triggered tremor beneath Sumbawa. The distance is given from the epicenter to PLAI station. The angle denotes the angle of the incident seismic waves with respect to the Flores Thrust or the Java Trench (with reversed sign). Peak ground velocity (PGV) was measured for the Rayleigh waves. Stress denotes the estimated peak dynamic stress on the surface imposed by the seismic waves, using the given PGV, *S* wave velocity $v_s = 3.6$ km/s [*McCaffrey et al.*, 1985] and a shear modulus of 30 GPa.

(see Figure 1b) and ultimately found tremor only on PLAI. We thus searched station PLAI (installed in March 2011) for triggered tremor in response to teleseismic surface waves from several earthquakes larger than M_w 7 (see Table 1).

3. Triggered Tremor

We identify triggered tremor as an emergent seismic signal depleted of high frequencies that is modulated in amplitude by surface waves of teleseismic earthquakes. Of the 17 teleseismic events studied, three earthquakes triggered tremor beneath Sumbawa: the M_w 9.0 2011 Tohoku earthquake and the two M_w 8.6 and M_w 8.2 2012 strike-slip earthquakes in the Indian Ocean offshore Sumatra. Measured on PLAI, Rayleigh waves of these events induced a peak ground velocity (PGV) of 1–3 mm/s and dynamic stresses between 8 kPa and 27 kPa. Love waves induced even larger PGVs of 2–7 mm/s and dynamic stresses between 17 kPa and 58 kPa. The M_w 7.6 2012 Philippines event induced ground motions just slightly weaker (PGV 0.6 mm/s and 5 kPa) without triggering any tremor. For the triggering earthquakes, Rayleigh wave periods are in the 45–65 s range and Love wave periods range from 65 s (M_w 8.6 and M_w 8.2 Indian Ocean) to 110 s (M_w 9.0 Tohoku). Both Love and Rayleigh wave periods are approximately 40 s for the nontriggering Philippines event.

Figure 2 shows triggered tremor signals recorded on the PLAI station. For the Tohoku event, tremor is triggered by Rayleigh waves, whereas for the two strike-slip events triggered tremor appears to be initiated during the Love wave train but reaches maximum amplitudes within the Rayleigh waves. Note that triggering is mainly due to the Rayleigh waves although Love wave amplitudes are up to twice as large, especially for the M_w 8.2 Indian Ocean event. Generally, the tremor signal is stronger on the horizontal components than on the vertical. On the horizontal components peak tremor amplitudes range from approximately 60 nm/s (M_w 8.2 Indian Ocean) to about 190 nm/s (M_w 8.6 Indian Ocean) and seem to correlate with the surface wave induced PGV—the larger the surface wave PGV, the larger the tremor peak amplitude.

For Figure 2 frequency filters were applied to show tremor signals that are not obscured by noise or body wave coda. However, the spectrum of the tremor shows slightly lower frequencies, ranging from 3 to 12 Hz while being strongest around 5 to 7 Hz as shown for the M_w 8.6 Indian Ocean event in Figure 3.

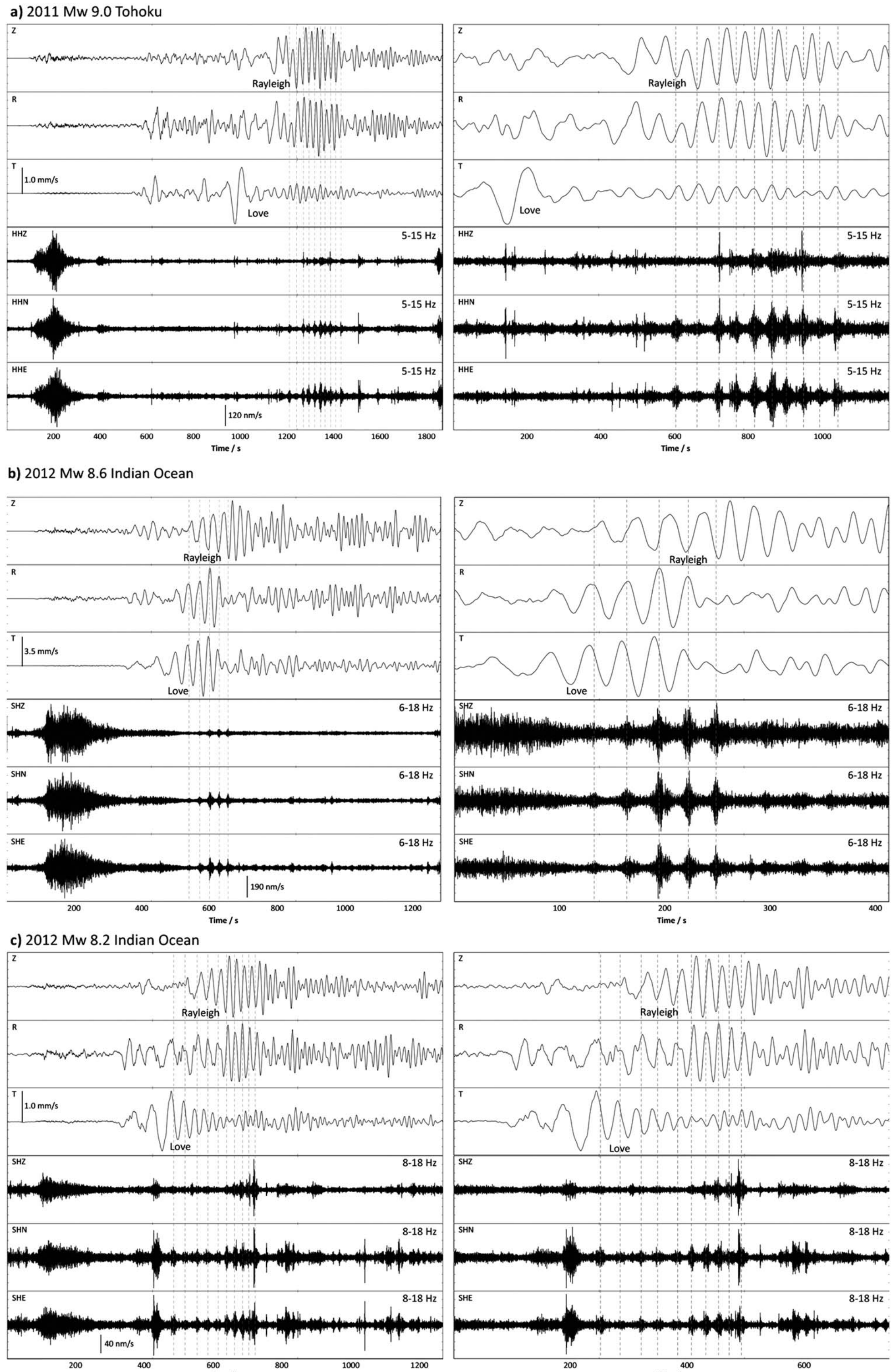

Figure 2. PLAI recordings of tremor triggered by (a) the M_W 9.0 2011 Tohoku earthquake, (b) the M_W 8.6 2012 Indian Ocean strike-slip earthquake, and (c) the M_W 8.2 2012 Indian Ocean event. All waveforms show ground velocity, and no time shifting was applied. The upper three traces show the unfiltered and rotated waveforms of the teleseismic event, respectively. The lower three traces display filtered and unrotated waveforms and show the triggered tremor signal along with body wave arrivals and codas. Love and Rayleigh wave trains are labeled, and the dashed lines denote the center of clearly visible tremor spikes. The frequency filters have been chosen such that they yield a good signal-to-noise ratio for plotting purposes. See Figure 3 for the complete frequency content of the tremor signal. The left column shows the entire teleseismic signal while the right part is a zoom in on the surface waves only.

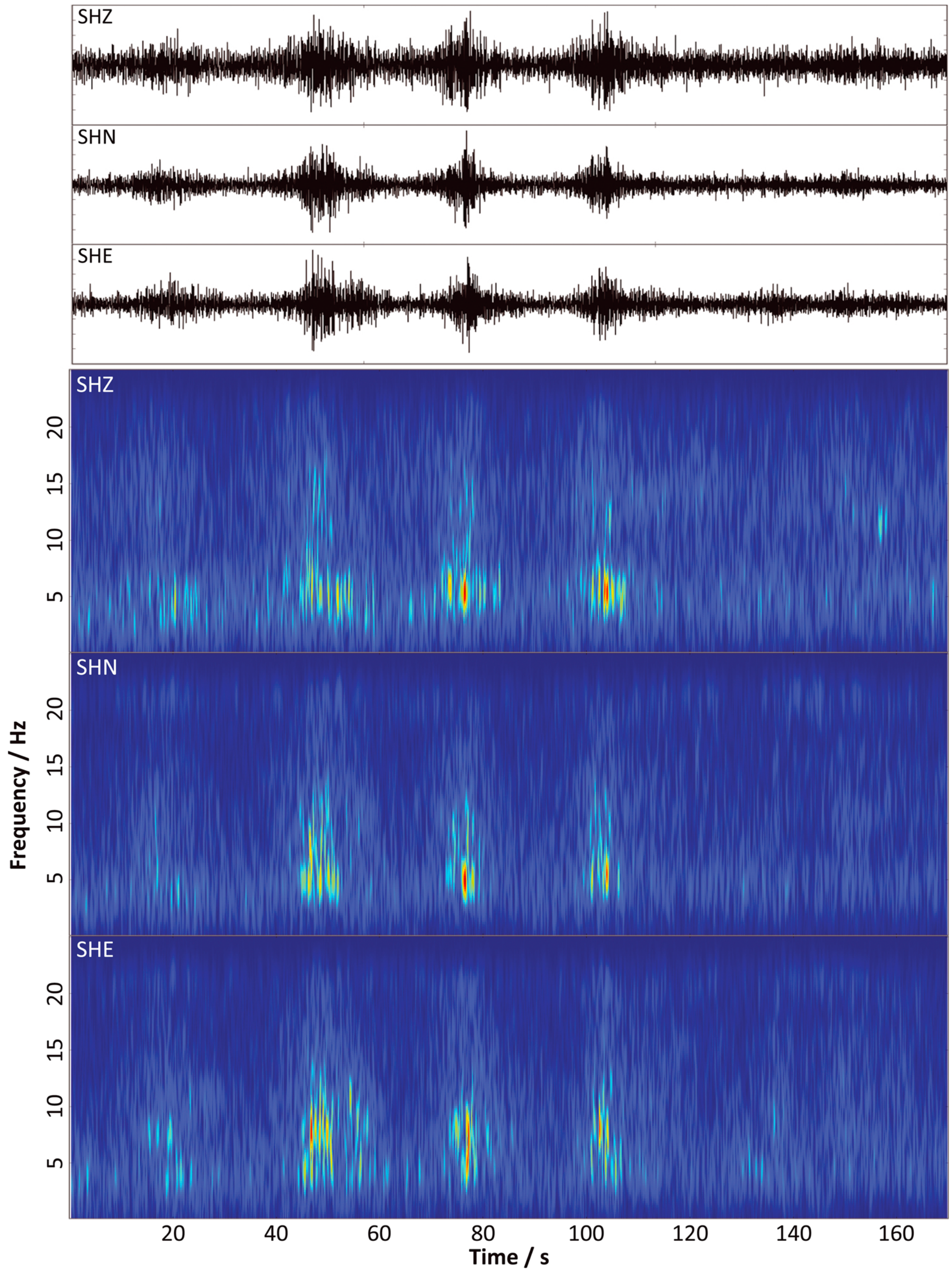

Figure 3. Spectrum of tremor spikes induced by the M_w 8.6 2012 Indian Ocean event. Data were high-pass filtered for frequencies > 4 Hz such that the spectrum is not dominated by body wave codas. Frequencies of the tremor range up to 15 Hz while the signal is strongest in the 5–10 Hz region. Note that the signal might be composed of lower frequencies as well, which are lost due to the prefiltering. The spectral content of tremor triggered by the 8.2 Indian Ocean and 9.0 Tohoku earthquakes is similar.

This evidence for tremor triggered by three different earthquakes is only observed on the PLAI station, and thus, the tremor cannot be located. Although several BMG-Net stations are near PLAI (the closest being 70 km from PLAI) the low sampling rate of 20–25 Hz (thus allowing filters lower than 10 Hz only) prevents application of a reliable filtering scheme in the frequency range (5–15 Hz) required to reveal the weak triggered tremor within the noise and teleseismic signals. Thus, no clear signal of triggered tremor could be found in the data of the close TWSI, DBNI, or any BMG-Net stations. The closest neighboring GEOFON stations are 400–500 km distant and do not record signals similar to what is seen on PLAI.

4. Discussion

We find a strong correlation between teleseismic surface waves and the onset of emerging characteristics of the frequency content, indicative of triggered tremor. Tremors in Figure 2 are not perfectly in phase with the respective surface waves because the signal was not time shifted to resemble the correlation at the source volume. Still, periodicity and amplitude of the triggered tremor correlate very closely with those of the surface waves. The observed tremor is the first evidence for triggered tremor along the Sunda Arc, Indonesia.

Only one station (PLAI) provided suitable data to reliably pick up the tremor, so the source of the tremor cannot be located. However, trying to match tremor bursts with cycles of surface wave ground motion, we find that peak tremor amplitudes (on horizontal components) are delayed by approximately 10 s compared to peak Rayleigh wave ground motion, thus placing the tremor about 30–50 km from PLAI (assuming a shear wave velocity of 3–5 km/s). This result is not well constrained, and there could be substantial variation for the two Indian Ocean events. But since the 10 s delay between surface wave arrivals at PLAI and the onset of tremor applies to both the 9.0 Tohoku and the 8.2 Indian Ocean events (with different incidence angles), this suggests that the tremor source generally resides beneath PLAI.

A depth of 30–50 km suggests an origin associated with the Flores Thrust rather than the Java subduction zone interface. Nonvolcanic tremor typically occurs downdip at about 15–40 km depth [*Rogers and Dragert*, 2003; *Shelly et al.*, 2006] on plate-boundary faults, but the PLAI station would be more than 120 km distant from the subduction interface, likely yielding less distinctive tremor signals and weaker correlation in time than observed. Additionally, the Java subduction zone is older (150 Ma [*Widiyantoro and van der Hilst*, 1996]), and thus colder, than typical tremor generating subduction zones. The Sumbawa section of the Flores Thrust is seismically active, and local earthquakes that fall near the marked area in Figure 1 (U.S. Geological Survey Advanced National Seismic System Comprehensive Catalog) show thrust mechanisms and extend down to about 26 km, possibly indicating the depth of the locked zone. Hence, nearby earthquakes reveal that this southward dipping structure is in the typically tremor generating depth range of 15–40 km beneath PLAI. This would be the first observation of tectonic tremor on a nonsubduction zone thrust fault.

However, *Fry et al.* [2011] report triggered tremor from depth of 50–60 km at New Zealand, where the age of the subducted slab is 120 Ma [*Ide*, 2012]. Similarly, given the age of the subducted slab near Sumbawa, tremor might also be generated at a very deep section of the Java subduction zone. This section would be close enough to PLAI (see Figure 1) to allow for the observed signal strength and correlations.

Another possibility for the tremor source is the Tambora volcano. We rule out that the observed signals show volcanic tremor since Tambora volcano was not in an erupting state or state of unrest at the time. However, it is possible that the tremor reflects triggering of volcanic-related low-frequency earthquakes from within the Tambora complex, as *Obara* [2012] suggests for tremor on Hokkaido, Japan. Yet no information is available about the occurrence of low-frequency earthquakes at Tambora volcano, and the interplay of tectonic and volcanic tremor at volcanic centers is unknown. Since we cannot rule out any of the aforementioned scenarios, future targeted studies to refine the tremor source should be conducted. The three suggested scenarios for the origin of the tremor are illustrated in Figure 1c. Please note that the sketch is not drawn to scale.

For all earthquakes studied (see Table 1), Figure 4 shows induced dynamic stress and the incidence angle of the seismic waves with respect to (Figure 4b) the Flores Thrust or (Figure 4d) the Java Trench (assuming both strike approximately E-W). The three triggering earthquakes induced recognizably greater peak ground velocity (PGV) and dynamic stresses on Sumbawa than all of the other earthquakes, the exception being the M_w 7.6 2012 Philippines event. Although the Philippines event did not trigger any tremor, it is interesting because the incidence angle is almost identical to the M_w 9.0 Tohoku earthquake, which should favor Rayleigh wave triggering in both cases. Additionally, the Rayleigh wave period of the M_w 8.2 Indian Ocean earthquake and the M_w 7.6 Philippines earthquake is about 40 s, producing very similar seismic waves. However, the triggering earthquakes induced a PGV of at least 1 mm/s while the M_w 7.6 Philippines event induced a PGV of only 0.6 mm/s. We conclude that this places a triggering threshold for tremor beneath Sumbawa of about 1 mm/s PGV (or alternatively 8 kPa of dynamic stress), which is of the same order of magnitude as reported for Taiwan [*Chao et al.*, 2012a].

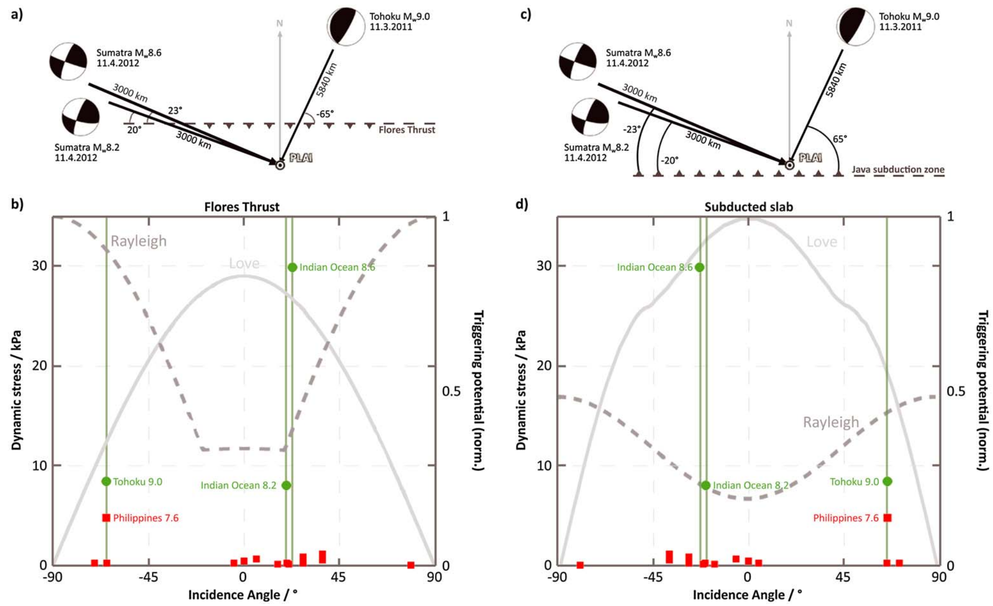

Figure 4. Analysis of the triggering potential. Illustration of the wave incidence angle for the three triggering earthquakes with respect to a hypothetical E-W striking fault plane that estimates either the (a) Flores Thrust or the (c) Java subduction zone. Note the change in sign due to different dip orientation. Triggering potential for Love and Rayleigh waves on the (b) Flores Thrust and the (d) subducted slab compared to incidence angle and peak dynamic stress of all earthquakes that were studied. Parameters used: Reverse fault, 60° Dip for Flores Thrust, 25° Dip for Java subduction zone, μ=0.2, 20 s period waves at 20 km (Flores) and 45 km (subducted slab) depth (compare *Chao et al.* [2012a] and *Chao et al.* [2013]). Green dots represent the triggering events, and red squares denote the nontriggering events. See the list in Table 1 for event details. Only four events induced dynamic stresses in the kPa range. The two markers at ±65° represent the 2011 Tohoku and the 2012 Philippines events (the latter did not trigger any tremor), the two markers at ±23° represent the 2012 strike-slip sequence in the Indian Ocean.

Our results are consistent with triggering factors suggested elsewhere [*Peng et al.*, 2009; *Guilhem et al.*, 2010; *Chao et al.*, 2012a] such as ground motion, incidence angle, and surface wave periods. While *Chao et al.* [2012a] report triggering predominantly for intermediate periods (10–30 s), *Guilhem et al.* [2010, and references therein] show that long-period (greater than 30 s) surface waves have a greater potential for triggering tremor. Here we note that the Rayleigh waves triggering tremor are in the long-period 45–65 s range, while the (nontriggering) Love waves show periods from 55 to 110 s. In the specific case of the M_w 8.6 Indian Ocean event, triggered tremor emerges only toward the end of the dispersive Love wave train, when periods are in the 50–60 s range, despite the fact that ground motion is already above the apparent 1 mm/s threshold. Thus, our observations suggest that long-period (45–65 s) surface waves are optimal for triggering tremor at Sumbawa.

To establish the triggering potential of the surface waves (following *Hill* [2012], *Chao et al.* [2012a], and *Chao et al.* [2013]), we assume that tremor originates from a fault plane striking E-W, which approximates the Flores Thrust or the Java subduction zone. The observations (see Figure 2a) of Rayleigh wave triggering from the Tohoku earthquake is consistent with the calculated triggering potential on the Flores Thrust (Figure 4b) and reasonable for the subduction zone scenario (Figure 4d). However, for the two 2012 Indian Ocean earthquakes, Love wave triggering potential is large and Love wave-induced ground motion is more than twice that of the Rayleigh waves, yet tremor correlates better with the Rayleigh waves, especially for the M_w 8.2 event. This observation adds to other studies [*Miyazawa and Brodsky*, 2008; *Chao et al.*, 2012a] that report Rayleigh wave favored triggered tremor for strike-parallel incidence in Nankai, Japan, and the Central Range, Taiwan. While *Miyazawa and Brodsky* [2008] and *Chao et al.* [2012a] favor tremor triggering by simple Coulomb shear failure promoted by the transient stresses, alternative explanations for the observed preferred Rayleigh wave triggering include higher frictional strength of the tremor hosting fault or mixed-mode failure by local fluid transport. In our case, the low-triggering thresholds that we observe beneath Sumbawa implicate very low effective stresses and hence favor tremor generation by a mechanism based of fluids which are likely associated with nearby arc volcanism.

5. Conclusion

We observed surface wave triggered tremor beneath Sumbawa, Indonesia, induced by the M_w 9.0 2011 Tohoku and the two M_w 8.6 and M_w 8.2 2012 Indian Ocean strike-slip events. Tremor amplitudes scale with ground motion and peak at 180 nm/s ground velocity on the horizontal components. A comparison of ground motion of the three triggering events and a similar (nontriggering) M_w 7.6 2012 Philippines event constrains an apparent triggering threshold of approximately 1 mm/s ground velocity or 8 kPa dynamic stress. Surface wave periods of 45–65 s appear optimal for triggering tremor at Sumbawa. Tremor is triggered predominantly by Rayleigh waves, even when Love waves produced higher ground motion and triggering potential. Rayleigh wave triggering, low-triggering amplitudes, and the tectonic setting all favor a model of tremor generated by localized fluid transport.

Nonvolcanic tremor is typically associated with low-frequency earthquakes and slow-slip events. Expanded broadband station coverage should be pursued in search of episodic tremor and slow-slip phenomena, and this first-reported observation of triggered tremor beneath Sumbawa should initiate follow-on targeted studies of ETS in this important tectonic region of the Sunda Arc.

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