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# Reassessment of the 1907 Sumatra "Tsunami Earthquake" Based on Macroseismic, Seismological, and Tsunami Observations, and Modeling

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*Abstract*—On 4 January 1907, an earthquake occurred off the west coast of Sumatra, Indonesia, with an instrumental surface-wave magnitude ($M_S$) in the range of 7.5–8.0 at periods of $\sim$ 40 s. The tsunami it generated was destructive on the islands of Nias and Simeulue, where it killed hundreds and gave rise to the legend of the S'mong. This tsunami was also observed in other parts of the Indian Ocean basin. Relative to its instrumented magnitude, the size of the tsunami was anomalous, qualifying the event as a "tsunami earthquake". However, unusually for a tsunami earthquake, the shaking on Nias was severe (7 EMS). We revisit the 1907 earthquake with a multidisciplinary approach by extracting evidence describing shaking effects or the tsunami from written documents and by acquiring new seismograms. Combining these, we discriminate two large earthquakes within an hour of each other with clear differences in seismological character. The first we interpret to be a tsunami earthquake with characteristic low levels of shaking, an estimated average seismic moment ($M_0$) of $2.5 \times 10^{28}$ dyn cm ($M_W \approx 8.2$) in the frequency band 6–8 mHz, and an epicentral location close to the front of the Sunda Megathrust. The seismograms we analyzed also document a regular growth of moment with period, approaching $M_W \approx 8.4$ at the longest resolvable period ($\sim$ 170 s). For the second earthquake that caused damage on Nias, we estimate $M_S \approx 7$ based on seismograms and phase data. We also identify two $M_S \approx 6$ aftershocks within 24 h of the mainshock. Additionally, we present a dataset of 88 locations within the Indian Ocean basin where the tsunami was observed. Using a subset of these, we forward modeled the tsunami to propose a seismic rupture model extending along the Sunda Megathrust for about 220 km ($\sim$ 94.7°E to $\sim$ 97°E) with a maximum modeled slip of $\sim$ 21 m. Our new rupture model provides an acceptable fit to our new dataset of tsunami runup and inundation values from 88 local and far-field locations in the Indian Ocean basin. We also urge caution against an over-reliance on the S'mong legend for tsunami evacuation as its premise, that a tsunami will only follow an earthquake with very severe ground motions, is rendered ineffective for tsunami earthquakes.

**Key words:** Tsunami, earthquake, Simeulue, Nias, Sumatra, Indonesia, Indian Ocean, 1907.

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## 1. Introduction

Numerous large earthquakes have occurred off the west coast of Sumatra, Indonesia, during the historical and instrumental eras (e.g., Newcomb and McCann 1987), and in particular since 2000. These events include a tsunamigenic earthquake on 4 January 1907 near the islands of Simeulue and Nias (Fig. 1), which Newcomb and McCann (1987) associated with shaking of such severity that "people on Nias could not stand". As many as 370 people were killed on Nias, and at least 1818 lives were lost on Simeulue (Koloniaal Verslag van 1907; Openbaar Verbaal 1908), including 1205 in Tapah (Tapak in Dutch) District, 431 in Simeuloeë Rajou District, 130 in Salang District, and 52 in Leuköon District on Simeulue (Bataviaasch Nieuwsblad, 12 February 1907). It was feared that 1000 people were killed at Koela-Deh in Tapah alone (Utrechts Nieuwsblad, 14 February 1907). This led to the disaster being embodied in myth and legend on the island of Simeulue (e.g., McAdoo et al. 2006; Syafwina 2014; Rahman et al. 2017). As discussed herein, the 1907 tsunami was also recorded in the far field, as far away as the island of La Réunion (Bertho 1910), which gives the event a clearly anomalous character in the context of the comparatively low "Pasadena" magnitude ($M_{PAS}$ = 7.6) assigned to the earthquake by

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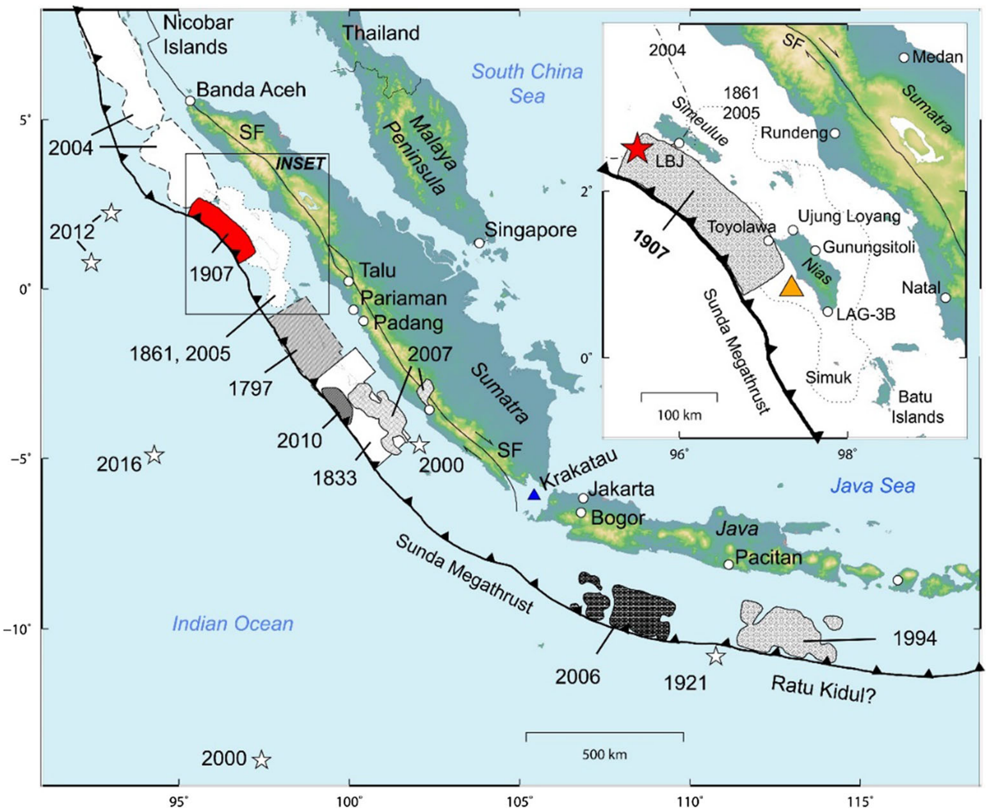


Figure 1

Generalized tectonic map of the Sunda Megathrust in Indonesia. First-order rupture of the 1907 earthquake (Event I, this study) indicated by a filled red polygon. Rupture areas for the 1797, 1833, 1861, 1994, 2004, 2006, 2007, and 2010 earthquakes are also shown (Bilek and Engdahl 2007; Chlieh et al. 2007; Konca et al. 2008; Hill et al. 2012). Location of the possible historical Ratu Kidul tsunami earthquake discussed in the text is labeled and appended by a question mark. Stars represent selected recent earthquakes. Inset box shows the islands of Simeulue and Nias with the first-order rupture of the 1907 earthquake (this study) indicated by a filled grey polygon, red star representing the epicenter of the 1907 earthquake (this study), and an orange triangle indicating the approximate location of Event II. Outlines of the 2004 (dot-dashed) and 2005 (dotted) lines are also displayed. Location of coral microatolls LBJ and LAG-3B from Meltzner et al. (2015) are also shown

Gutenberg and Richter (1954). Other estimates of conventional magnitudes for this earthquake have been presented by Abe and Noguchi (1983; $M_S$ = 7.6), and recently the ISC ($M_S$ = 7.8; Storchak et al. 2013). Duda (1965) proposed a figure of 7.8, but the nature of this magnitude was unspecified. More recently, Kanamori et al. (2010) conducted an extensive seismological study of the 1907 earthquake based on a number of historical seismograms. While they did not compute a seismic moment through waveform fitting, they measured a surface-wave magnitude $M_S = 7.8 \pm 0.25$ and estimated a moment magnitude $M_W$ = 7.8 by scaling time-domain amplitudes of body and surface waves of the 1907 earthquake to those of nearby modern earthquakes with known moment tensors. These results were obtained in the period range 40–50 s, but Kanamori et al. (2010) stress that the source was obviously longer, and thus the moment should be larger at longer periods, suggestive of a "tsunami earthquake".

The term "tsunami earthquake" was first used by Kanamori (1972) to discuss the sources of the 1896 Meiji Sanriku and 1946 Unimak (Aleutian Islands) earthquakes, both of which resulted in anomalously large tsunamis with respect to their instrumental magnitudes. This type of event can be distinguished based on disproportionate relationships between surface-wave magnitude ($M_S$) and seismic moment ($M_0$), from the observation of longer than expected process times despite small rupture areas (Sykes 1971; Kanamori 1972; Pelayo and Wiens 1992; Polet and Kanamori 2000), and from lower than anticipated macroseismic intensities (Kanamori 1972; Fukao 1979; Bourgeois et al. 1999). The longer process times result in red-shifting of the source spectrum, and in inconsistencies between deficient seismic magnitudes measured at short to moderate periods (thus relevant to macroseismic effects) and enhanced ultralong-period seismic moments (controlling the generation of tsunamis). The ruptures of tsunami earthquakes have been observed to propagate toward the trench axis (Polet and Kanamori 2000) on very shallow dipping faults or on splays (Fukao 1979; Pelayo and Wiens 1990, 1992) located in weakly coupled regions of aseismic convergence (Pelayo and Wiens 1990, 1992; Bourgeois et al. 1999), or at the very top of the plate interface under conditions of sediment starvation leading to a jagged rupture (Tanioka et al. 1997). Rupture velocities for such earthquakes are also less than expected for typical earthquakes owing to the low rigidity of materials proximal to the trench axis (Fukao 1979; Pelayo and Wiens 1990, 1992; Heinrich et al. 1998; Ihmlé et al. 1998). In addition, tsunami earthquakes can occur as mainshocks, which Okal and Saloor (2017) qualified as “primary tsunami earthquakes” (PTEs), or as “aftershock tsunami earthquakes” (ATEs), following a larger, regular megathrust event.

With the exception of the 2010 Mentawai event (e.g., Newman et al. 2011a; Hill et al. 2012), no other tsunami earthquakes have been conclusively identified off the Sumatran coast during the modern or historical period. Furthermore, in stark contrast to other natural disasters in the Dutch East Indies such as the 1883 eruption of Krakatau for which detailed official reports were written (e.g., Verbeek 1885), locating an official scientific report for the 1907 disaster was futile despite exhaustive efforts on our part. Szirtes (1912a, p. 5) carries cursory mention of a “detailed study” (*eingehende Untersuchung* in German) by T.H. Staverman, including possibly a study of its epicentral location, but without a complete citation. The scientific bibliography relating to geology in the Dutch East Indies between 1907 and 1912 (e.g., Verbeek 1912) has no record of this document, and its whereabouts remain a mystery, including at Strasbourg where Siegmund Szirtes was based (L. Rivera, personal communication 2017). In light of missing colonial investigative reports, and despite the conclusion in more general terms by Kanamori et al. (2010) that the 1907 Sumatra earthquake bore all the hallmarks of a tsunami earthquake, key aspects of this event remain unaddressed, including (1) conclusive, quantitative evidence of its nature as a “tsunami earthquake” and (2) an estimate of the geometry and slip parameters of the source supporting the reported distribution of the tsunami. In addition, perplexing observations clearly in need of further study include (3) the anomalously violent ground motions (Newcomb and McCann 1987; Kanamori et al. 2010) in comparison with other tsunami earthquakes, (4) the lack of aftershocks, and (5) the lack of land level changes comparable to those identified for other large earthquakes in the Simeulue–Nias region (e.g., Meltzner et al. 2012, 2015).

In this article, we employ a multidisciplinary approach to tackle these points. Through scrutiny of original macroseismic reports and systematic analysis of a number of seismograms, we separate the mainshock (henceforth Event I) from a previously unsuspected large aftershock that occurred only ~ 53 min later (henceforth Event II). Waveform analysis of digitized seismograms allows quantification of the mainshock at mantle wave periods up to 170 s and further demonstrates significant differences in source spectra between the mainshock and the large ~ 06:12 GMT aftershock. We also compile a set of 88 qualitative and instrumental observations of the tsunami in the Indian Ocean basin (including nil reports) and utilize a subset of these to prepare a slip model for the 1907 mainshock.

## 2. *Reassessing Macroseismic Intensities and the Discovery of Event II*

The earliest macroseismic study of the 1907 Sumatra earthquake by Newcomb and McCann (1987) is a dual-zoned intensity map (Fig. 2a) utilizing the Modified Mercalli Intensity Scale (MMI) to distinguish between what they defined as weak (MMI I–IV) and strong shaking (MM V–VII), for what was assumed to be a single event. We use the 1998

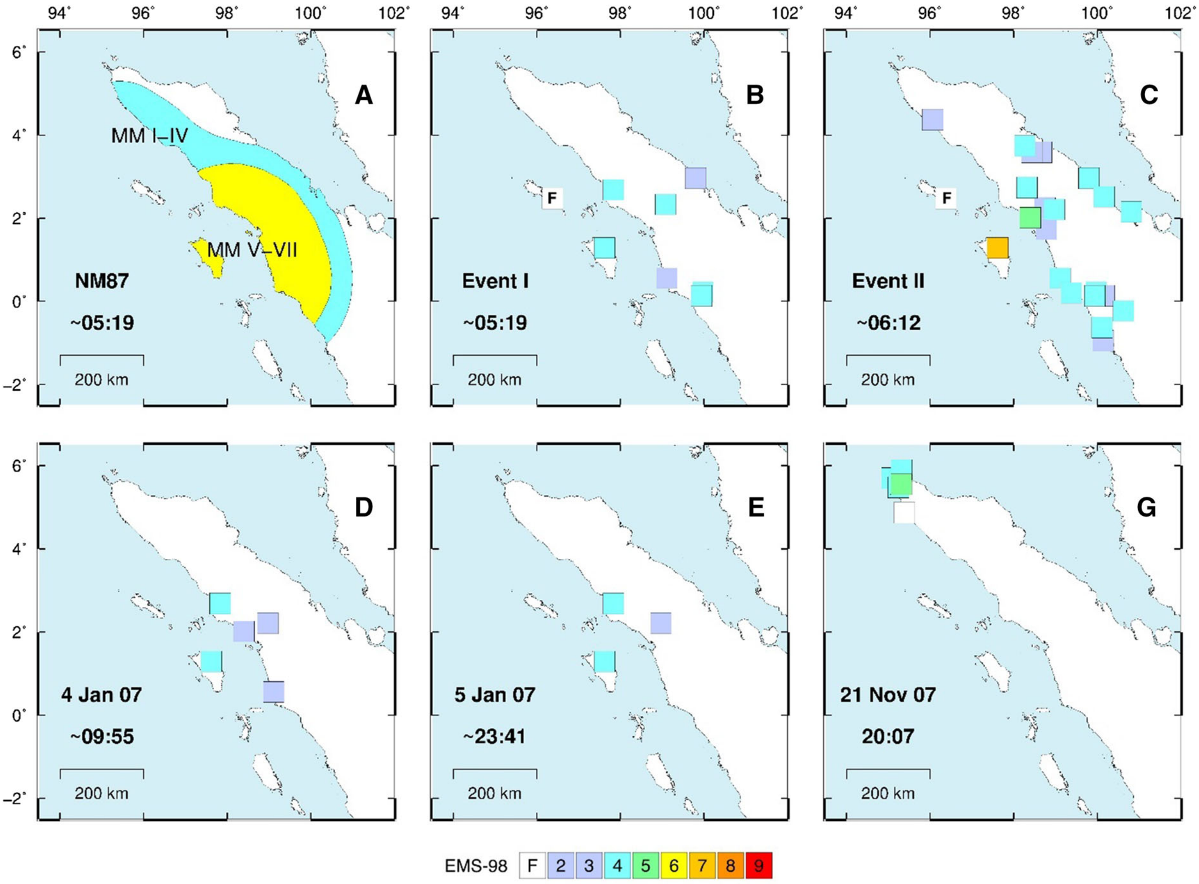


Figure 2
Intensity map (**a**) from Newcomb and McCann (1987) in comparison with intensities determined by our study for the mainshock at 05:19 GMT (**b**) and the largest aftershock at ∼ 06:12 GMT (**c**). Intensity for the largest known aftershocks on 4 January (**d**) and 5 January (**e**) are also shown along with the earthquake of 21 November 1907 (**g**) near Banda Aceh. White boxes marked with an "F" indicate that an earthquake was felt but macroseismic data were insufficient to assign an intensity

European Macroseismic Scale (EMS-98; Grünthal 1998) to assess intensity with our choice of macroseismic intensity assessment adhering to modern practice (e.g., Toppozada and Real 1981; Ambraseys and Douglas 2004; Martin and Szeliga 2010). The EMS-98 scale is equivalent to MMI (Musson et al. 2010); its merits and its suitability for use outside Europe are discussed by Hough et al (2016), and Martin and Hough (2016). In this and subsequent sections, non-English text appears in parenthesis (bh: Bahasa Indonesia, nl: Dutch; fr: French; de: German) accompanying the modern reformed Indonesian or English spelling, e.g., earthquake (nl: *aardbeving*). The same applies for place names in use during the colonial Dutch period, e.g. Jakarta (nl: Batavia). Our reassessment of intensity focuses on an annual summary of felt earthquakes in the Dutch East Indies (Anonymous 1909) by the Royal Magnetic and Meteorological Observatory (nl: Koninklijk Magnetisch en Meteorologisch Observatorium, KMMO) that was culled from official correspondence. This was supplemented with further accounts extracted from colonial newspapers published in Indonesia and in the Netherlands (see Online Appendices A and B).

Accurate timekeeping is vital to accurately associate reports with individual earthquakes. In this respect, the KMMO summary was invaluable as it printed the standard time in Jakarta (known as Batavia Time or BT) for seismic disturbances recorded instrumentally at Jakarta or Bogor

Table 1

*EMS-98 intensities for the 4 January 1907 mainshock (Event I)*

| Name | Lat. | Long. | EMS | Error | LT | BT | Account | References |
|---|---|---|---|---|---|---|---|---|
| Balige | 2.333 | 99.083 | 4 | 1 | 11:45 | + 31 | 30 seconden. N-Z. Drie vrij sterke schokken. | Anonymous (1909) |
| Gunungsitoli | 1.286 | 97.619 | 4–5 | 1 | ~ 12:00 | + 36 | ~ 60 seconden. O-W richting. Zwak golvende beweging. Gebouwen en boomen bewogen zichtbaar. | Anonymous (1909) |
| Natal | 0.557 | 99.113 | 3 | 1 | 11:49 | + 30 | 1 se. ZO-NW richting. 2 zwakke schokken. | Anonymous (1909) |
| Ophir Districts | 0.133 | 99.944 | 4 | 3 | ~ 12:00 | | Deze schokken zijn ook elders in de onderafdeeling Ophirdistricten meer of minder hevig gevoeld. | Het Nieuws van den Dag, 21 Mar 1907 |
| Rundeng | 2.685 | 97.834 | 4 | 4 | 11:55 | + 35 | 6 seconden. O-W. Drie sterke schokken | Anonymous (1909) |
| Sinabang | 2.479 | 96.379 | F | 4 | – | – | Den 4en dezer werden in den middag eenige elkander opvolgende schokken van aardbeving gevoeld, welke echter te Sinabang geene schade aanrichtten. | Het Nieuws van den Dag, 28 Jan 1907 |
| Talu | 0.225 | 99.976 | 4 | 1 | 12:15 | + 27 | 10 seconden. WZW–ONO. Vrij sterke schok. Waarnemer en diens schijver gevoelden zich onpasselijk door de beweging. Slingeren van lampen, bewegen van kasten, kraken van houtwerk in de kontroleurswoning, welke op een drassigen bodem in de Taloe-vallei staat en omringd in door sawah's. | Anonymous (1909) |
| Tanjung Balai | 2.964 | 99.800 | 3 | 1 | 12:09 | + 28 | 5 seconden. O-W. Lichte horizontale schok. | Anonymous (1909) |

*Lat* latitude (N°), *Long.* longitude (E°), *LT* local time, *BT* Batavia Time

(nl: Buitenzorg). BT was 7 h 7 min ahead of Greenwich Mean Time (GMT). It also published the difference in time at places outside Jakarta with respect to Batavia Time; For example, BT was 36 min ahead of local time at Gunungsitoli (nl: Goenoeng Sitoli) on Nias and 17 min behind local time at Pacitan (nl: Patjitan) in central Java. Thus, the local time was GMT + 06:31 at Gunungsitoli, GMT + 07:07 at Jakarta, and GMT + 07:24 at Pacitan.

A surprising result of our macroseismic reanalysis (Tables 1, 2) is the discovery of two distinctly separate earthquakes that were felt on Nias within an hour of each other on 4 January 1907 (Fig. 2b, c). A Milne seismograph in Jakarta (Anonymous 1909) recorded the first at 12:29 BT (05:19 GMT; Event I), and the magnetograph at Bogor detected the second at 13:24 BT (Event II). Engelbertus Schröder, the civil administrator (nl: kontrolleur) at Gunungsitoli on Nias (Online Appendix B), provided the strongest evidence with which to make this distinction; he described a weak but long-duration earthquake at about midday, followed by three "tidal waves" (nl: vloedgolven) at Toyolawa (nl: Tojolawa), which were later followed at 12:50 local time by a second violent earthquake at Gunungsitoli (Bataviaasch Nieuwsblad, 22 March 1907). His account appeared in several newspapers such as the Soerabaiasch Handelsblad (23 March 1907) and in the Nieuws van den Dag voor Nederlandsch-Indië (22 March 1907); the latter reported the time of the second earthquake to be "12:05". We believe this to be a typesetting error, as the identical account printed on the same day by the Bataviaasch Nieuwsblad (22 March 1907) states "12:50", and importantly 12:50 is also reported by Schröder (1917a) himself. The occurrence of two felt earthquakes separated by ~ 53 min is also corroborated by independent observers from Gunungsitoli (De Padanger, 26 January 1907), Natal, and Talu (nl: Taloe), as discussed in subsequent sections based on seismograms.

The weak, long-duration ground motions in the near field and the barely perceptible shaking at larger distances associated with Event I (Fig. 2b; Table 1) are characteristic of tsunami earthquakes (e.g., Kanamori 1972). In contrast, the descriptions of shaking and damage at Gunungsitoli from Event II

Table 2

*EMS-98 intensities for the 4 January 1907 aftershock (Event II)*

| Name | Lat. | Long. | EMS | Error | LT | BT | Account | References |
|---|---|---|---|---|---|---|---|---|
| Airbangis | 0.201 | 99.380 | 4 | 1 | 12:38 | + 29 | ~ 60 seconden. Hevige schok. | Anonymous (1909) |
| Bagan Si Api Api | 2.157 | 100.816 | 4 | 1 | 12:45 | + 23 | ~ 60 seconden. O-W. Vrij hevige schommeling. De waarnemer had een gevoel als werd hij duizelig. | Anonymous (1909) |
| Barus | 2.012 | 98.400 | 4–5 | 1 | 12:48 | + 33 | ~ 120 seconden. ZW-NO. Verscheidene kort op elkaar volgende vrij sterke schokken. De houten gebouwen kraakten. In de betonmuur van de verlaten benteng kwamen scheuren. | Anonymous (1909) |
| Gunungsitoli | 1.286 | 97.619 | 7 | 1 | 12:50 | + 36 | ~ 60 seconden. O-W richtung. Zeer zware golvingen. Het was onmogelijk op de been te blijven. Alles schommelde sterk heen en weer. Allerwege groote schade aan gebouwen. Richting horizontale scheuren in cementen vloer douanekantoor, Noord 20 Oost, Noord en Noord 340 Oost. Cementen vloer gevangenis Noord 305 Oost. | Anonymous (1909) |
| Kuala Bëë | 4.371 | 96.062 | 3 | 1 | 12:30 | + 42 | 45 seconden. N-Z. | Anonymous (1909) |
| Lambuhanbilik | 2.520 | 100.165 | 4 | 1 | 12:45 | + 26 | 10 seconden. O-W. Twee vrij sterke schokken. | Anonymous (1909) |
| Langkat Regency | 3.743 | 98.268 | 4 | 3 | 12:55 | | Een vrij sterke aardschock waargenomen in the richting Noord-Zuid. | Deli Courant, 4 Jan 1907 |
| Lubuksikaping | 0.137 | 100.167 | 3 | 1 | ~ 12:40 | + 26 | ~ 40 seconden. N-Z. Vele, zeer goed waarneembare golvingen. Een vrij zware golvende aardbeving waargenomen, die eenige seconden aanhield. | Anonymous (1909); Het Nieuws van den Dag, 21 Mar 1907 |
| Medan | 3.589 | 98.669 | 3 | 1 | 12:50 | | Hedenmiddag te 12.50 precies heeft hier terstede een duidelijk waarneembare aardbeving in noord-zuidelijke richting plaatsgehad. In het Medan-Hotel kwamen alle lampen, ook de zware in de groote zaal, in beweging, terwijl alle klokken er bleven stilstaan. Ook op het Postkantoor staakten de klokken den dienst. In den loop van den middag bereikten ons nog verschillende berichten, die met het bovenstaande overeenstemmen, en waaruit blijkt dat de aardbeving van vrij langen duur is geweest. | De Sumatra Post, 4 Jan 1907 |
| Natal | 0.557 | 99.113 | 4 | 1 | 12:42 | + 30 | 1 seconde. ZO-NW richting. 3 sterke schokken. | Anonymous (1909) |
| Padang Brahrang | 3.588 | 98.435 | 3 | 1 | 12:50 | | Ook uit Padang Brahrang wordt ons omtrent een aardbeving gemeld. Ze is daar bedenmiddag eveneens 12:50 waargenomen en de richting was Oost-west. Het was een soort golvende beweging, die de lampen flink aan het slingeren bracht. | De Sumatra Post, 4 Jan 1907 |
| Payakumbuh | –0.231 | 100.630 | 4 | 1 | 13:15 | +23 | 10 seconden. O-W. Een lichte schok. Vrij hevige schok werd gevoeld. | Anonymous (1909); Het Nieuws van den Dag, 21 Mar 1907 |
| Pulau Pandan | –0.949 | 100.140 | 3 | 1 | 12:55 | + 26 | 5 seconden. W-O. 5 lichte schokken. | Anonymous (1909) |
| Priaman | –0.628 | 100.116 | 4 | 1 | 13:02 | + 26 | ~30 seconden. O-W. Hevige horizonale bevingen. | Anonymous (1909) |
| Seribu Dolok | 2.252 | 98.748 | 2 | 1 | 12:40 | + 32 | Enkele seconden. 2 schokken. | Anonymous (1909) |
| Sibolga | 1.739 | 98.783 | 3 | 1 | 12:35 | + 31 | ~ 54 seconden. NW-ZO. Zacht golvende beweging. | Anonymous (1909) |
| Siborongborong | 2.210 | 98.972 | 4 | 1 | ~13:00 | + 30 | 10 seconden. Sterk. | Anonymous (1909) |

**Table 2** *continued*

| Name | Lat. | Long. | EMS | Error | LT | BT | Account | References |
|---|---|---|---|---|---|---|---|---|
| Sidikalang | 2.738 | 98.320 | 4 | 1 | 12:50 | + 33 | 10 seconden. NW-ZO. Zwakke schok. Beven der houten gebouwen, slingeren van lampen. | Anonymous (1909) |
| Talu | 0.225 | 99.976 | 4 | 1 | 13:05 | + 27 | 30 seconden. WNW-OZO. Hevige schok. Waarnemer kreeg een onpasselijk gevoel. Slingeren van lampen, bewegen van kasten, kraken van houten deelen van het gebouw. | Anonymous (1909) |
| Tanjung Balai | 2.964 | 99.800 | 4 | 1 | 12:53 | + 28 | ~120 seconden. O-W. Reeks opvolgende tamelijk sterke schokken. N-Z slingers klocken stopten. Lampen beschreven cirkels van 30 c.m. straal. Menschen kregen een gevoel van duizeligheid. Onmiddellijk na den schok brak een zware regenbui met donder los. | Anonymous (1909) |

*Lat.* latitude (N°), *Long.* longitude (E°), *LT* local time, *BT* Batavia Time

(Fig. 2c; Table 2) lead us to believe that it was responsible for the violent shaking on Nias that was misconstrued as the mainshock by Newcomb and McCann (1987) and flagged as anomalous by Kanamori et al. (2010). Countless houses were destroyed on Nias by Event II, and even weeks later many people were living under temporary canopy shelters (bh: pondok) put up near their dwellings (Bataviaasch Nieuwsblad, 22 March 1907). Unusually, neither earthquake was reported in an official summary of news and affairs for January 1907 from Aceh (nl: Atjeh) i.e. "Atjeh-verslag over Januari" (Java Bode, 16 April 1907). These earthquakes also do not appear in catalogues of felt earthquakes in Thailand (Nutalaya et al. 1985), nor were they reported from anywhere else in Southeast Asia.

Our research underscores the importance of meticulously collated and analyzed noninstrumental evidence that allows the study of historical earthquakes for which instrumental data are lacking or severely limited. The serendipitous discovery of Event II was an unexpected outcome borne out of careful scrutiny of macroseismic data that led us to look for seismological evidence (discussed in subsequent sections) to support it. The absence of this event from earthquake catalogues (e.g., Gutenberg and Richter 1954; Storchak et al. 2013) is very conspicuous but not unusual, as with other recently discovered large early-instrumental earthquakes (Hough et al. 2005). This results from the limited number of seismograms at hand for early instrumental earthquakes, and the inadequacy (or simple inexistence) of proper algorithms to associate reported phase times, not to mention the adjustment of local times before implementation of standard time zones.

## 3. *Location of the Mainshock (Event I)*

The earliest published locations for Event I come from Turner et al. (1912) and Szirtes (1912a), who used arrival times from over 66 stations. As summarized by Kanamori et al. (2010), and not surprising for an event at the beginning of the 20th century, epicentral estimates are poorly constrained and significantly scattered (Fig. 3). Gutenberg and Richter's (1954) solution (2°N, 94½°E) is on the outer rise and slightly west of the solution (2°N, 95°E) by Turner et al. (1912), but both are very unlikely locations for a tsunami earthquake. By contrast, Szirtes (1912a) reports a location by T.H. Staverman (2°N, 96¼°E) in the immediate vicinity of the trench. In their recent compilation of relocations for early instrumental earthquakes, Storchak et al. (2013) locate the event at (1.87°N, 94.21°E), near the Turner et al. (1912) and Gutenberg and Richter (1954) epicenters, and with a remarkably small error ellipse (semi-axes: 28 km and 16 km). The most recent version (5.0) of the ISC-GEM catalog moves the epicenter north by 61 km, to

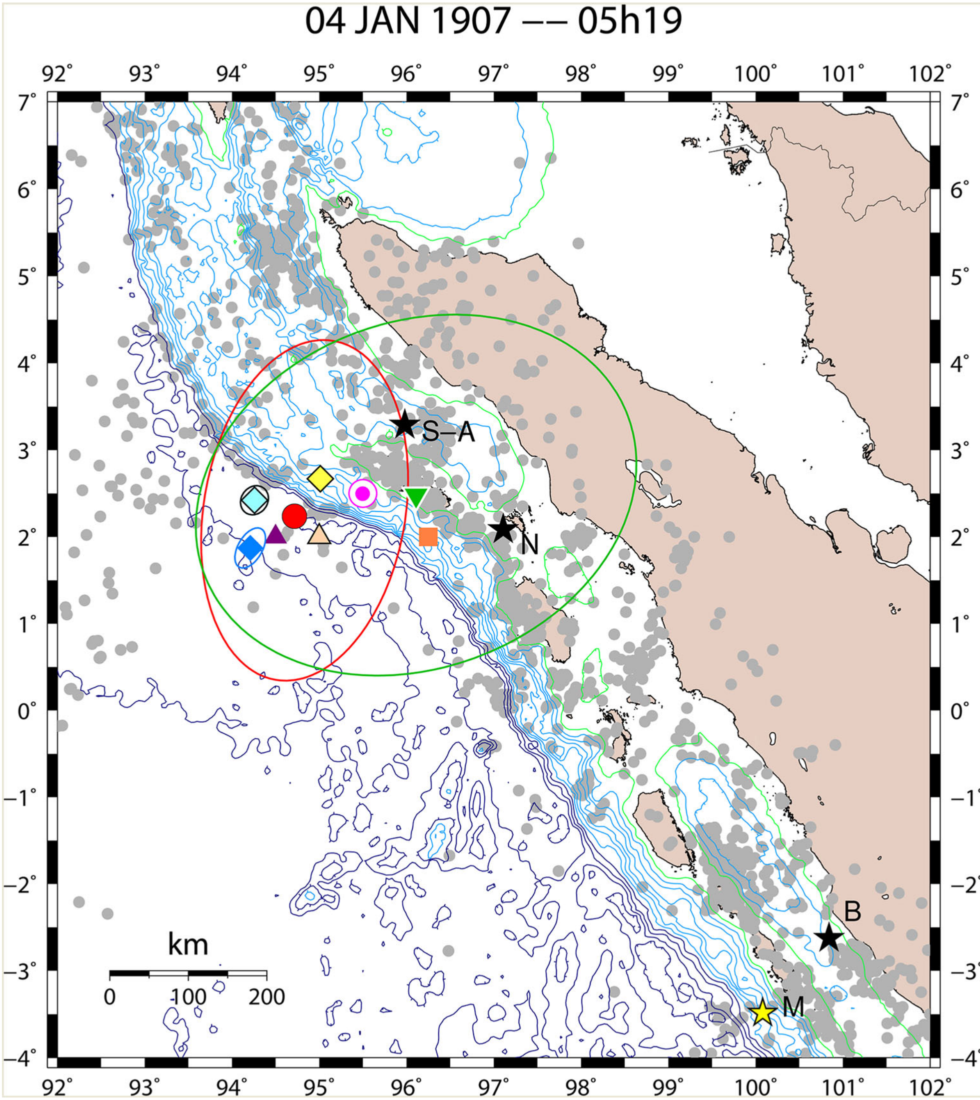


Figure 3
Relocations of the 1907 Sumatra event. The red dot shows our solution, with associated Monte Carlo ellipse. The green inverted triangle is the epicenter from Kanamori et al. (2010), with the confidence ellipse described in their online appendix shown in green. The dark-brown upward triangle is Gutenberg and Richter's (1954) epicenter, and the orange square T. Staveman's (Szirtes 1912a). The blue diamonds (with respective confidence ellipses) are the ISC solution by Storchak et al. (2013; solid, bright), and from the ISC-GEM (5.0) catalog (outlined, light blue); note that the ellipses do not intersect, suggesting that they are deceptively small. The yellow diamond is the best estimate from a grid search (D. Di Giacomo, pers. comm., 2017), and the preferred location is shown as the purple bull's eye symbol. The light-brown triangle is Turner et al.'s (1912) location. The black stars show the epicenters of the megathrust events of 2004 (Sumatra–Andaman, "S–A"), 2005 (Nias, "N"), and 2007 (Bengkulu, "B"), and the yellow star ("M") the 2010 Mentawai tsunami earthquake. Background seismicity (1970–2015; h < 100 km; M ≥ 5) shown as light-grey dots. Isobaths are at 500-m intervals (green at 500 m; dark blue at 4000 m and deeper)

(2.422°N, 94.258°E). It is noteworthy that the very small confidence ellipse (20 km by 17 km) of the ISC-GEM solution does not overlap with the solution from Storchak et al. (2013) (Fig. 3). This casts doubt on the reliability of both locations, since they are supposed to be derived from the same algorithm. On the other hand, a systematic grid search of the same dataset confirms a large scatter of possible solutions but proposes a best-fitting epicenter at 2.67°N, 95.01°E (D. Di Giacomo, personal communication 2017), 125 km NE and across the plate boundary from the Storchak et al. (2013) solution.

Kanamori et al. (2010) relocated event I based on travel times listed in Gutenberg's personal notepads (Goodstein et al. 1980), with an emphasis on differential S – P times, to minimize errors due to clock uncertainties. Their solution (2.48°N, 96.11°E; Fig. 3) is located approximately 60 km closer to the trench than the 2004 and 2005 epicenters, at the seaward limit of the zone of interplate seismicity (Pesicek et al. 2010). This configuration is reminiscent of the 2010 Mentawai tsunami earthquake (Newman et al. 2011a; Hill et al. 2012). However, the 95 % confidence ellipse defined by Kanamori et al. (2010, p. 371) extends $\sim$ 500 km, from the outer rise, beyond the Gutenberg and Richter (1954) and Storchak et al. (2013) locations, all the way to inland Sumatra.

We perform an independent relocation using the dataset listed by the ISC, and the interactive method of Wysession et al. (1991), which includes a Monte Carlo algorithm injecting Gaussian noise into the data. For an event in the 1900s, we give the noise a standard deviation $\sigma_G = 12.5$ s. Our solution converges to (2.24°N; 94.72°E: O.T. 05:19:13 GMT), a location on the outer rise, in the vicinity of the Storchak et al. (2013) and Gutenberg and Richter (1954) epicenters, but our confidence ellipse extends across the trench and grazes the solution from Kanamori et al. (2010); it is essentially contained inside these authors' ellipse. While all these relocations have very large uncertainties [we regard the Storchak et al. (2013) confidence ellipse as deceptively small], the emerging general pattern (Fig. 3) is that Event I was probably significantly displaced updip and trenchward with respect to the main seismogenic zone at the interplate contact on the Sunda Megathrust, to the general area located between the ISC grid-search solution and that of Staverman (in Szirtes 1912a), in a tectonic environment reminiscent of that of the Mentawai tsunami earthquake of 25 October 2010 (Newman et al. 2011a; Hill et al. 2012). This is our preferred location for the epicenter of Event I (2.5°N, 95.5°E) and is indicated by a red star on Fig. 4.

Our preferred location lies within an east-facing reentrant on the Sunda Megathrust (Franke et al. 2008) that indicates a zone of low seismic productivity between 1918 and 2007, and adjacent to, but not within, the rupture and aftershock zones of the 2004 and 2005 earthquakes (Chlieh et al. 2007; Engdahl et al. 2007; Konca et al. 2008; Pesicek et al. 2010). In this region, seismic reflection surveys (Franke et al. 2008) and three-dimensional (3-D) active source tomography (Tang et al. 2013) have identified a ridge of oceanic basement (Fig. 1b) that projects into the Wharton Basin, coinciding with a mapped fracture zone (Singh et al. 2011; Jacob et al. 2014). Onshore on Simeulue, this coincides with the Simeulue Saddle (Sieh et al. 2006), which has served as a persistent barrier to rupture in the past (Meltzner et al. 2012). Further downdip and beneath the Simeulue Saddle (Sieh et al. 2006), this morphological high can be associated with a region of strong coupling beneath central Simeulue (Tsang et al. 2015), and has been inferred as a structural control for local seismicity and the rupture dimensions of modern earthquakes under central Simeulue (Morgan et al. 2017). The dimensions of this morphological feature are debated (Franke et al. 2008; Tang et al. 2013; also see Fig. 4b in Morgan et al. 2017). Although our best-fit epicentral location lies slightly to the west of this feature, its uncertainty ellipse overlaps the western ramp of this morphological high, which we believe played a crucial role in rupture propagation and tsunami generation.

## 4. *Event II and Later Aftershocks*

Our study is the first to identify several aftershocks associated with the 1907 Sumatran earthquake. For the newly discovered large earthquake (Event II), waveforms were far fewer than for the mainshock, but we identified it in new records from Manila (Masó 1907) and Shimla (Patterson 1909), and the Osaka record scrutinized by Kanamori et al. (2010). Station bulletins from Manila (Masó 1907), Osaka (Anonymous 1931), and Shanghai (de Moidrey 1912) also list it. Masó (1907) interpreted the Manila records as requiring two events but pointed out the lack of evidence for Event II at Zikawei (Shanghai) and in Europe; we believe this to be partially incorrect, as Event II appears in the Zikawei bulletin (de Moidrey 1912). Anonymous (1909)

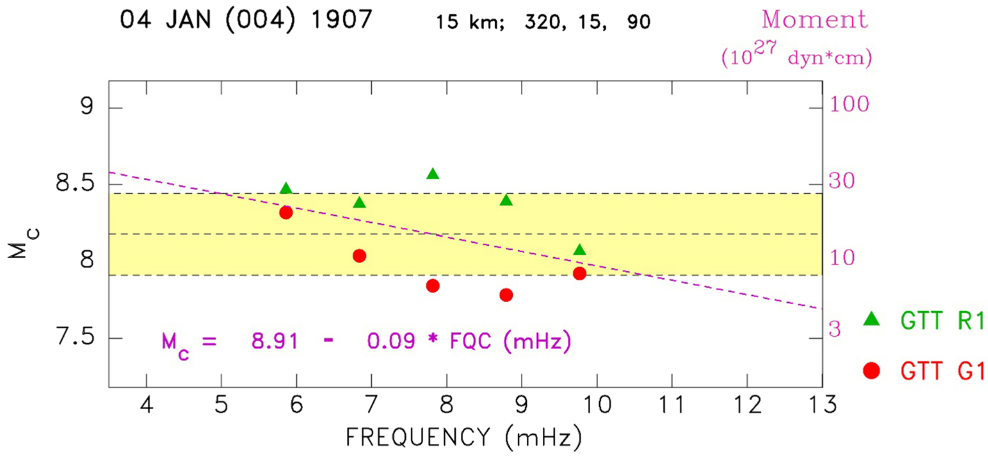


Figure 4

Spectral amplitudes of Rayleigh and Love waves at Göttingen, interpreted as corrected mantle magnitudes $M_c$ (Okal and Talandier 1989), computed in the geometry $\phi$ = 320°, $\delta$ = 15°; $\lambda$ = 90°, in the frequency band 6–10 mHz. The black dashed lines and yellow band show the average value and standard deviation of the full dataset, while the purple dashed line shows its best linear regression. Note the strong increase of moment with period

provides the time a magnetograph at Bogor detected this shock as 13:24 BT ($\sim$ 06:18 GMT), which gives an origin time of 06:15 GMT correcting for travel time to Bogor. We note, however, that the arrival time of the mainshock at this instrument is unknown. The difference in arrival time between the P waves from Event II and those of the mainshock at Osaka (Anonymous 1931), the difference in arrival time between the S waves from both events at Manila (Masó 1907) and Shanghai (de Moidrey 1912), and inspection of the waveform recorded at Manila (Masó 1907) suggest a $\sim$ 53 min interval between the two. We therefore estimate an origin time of $\sim$ 06:12 GMT, which is also supported by the first-hand account by Schröder (1917a) of two shocks $\sim$ 50 min apart.

The paucity of instrumental records prevents an instrumental location for Event II, but an epicentral distance (5420 km) to Osaka has been previously published (Anonymous 1931). Unfortunately, this datum is of little help, since Osaka is essentially equidistant (within 10 km) from the preferred locations of Events I and II. Finally, an epicenter in the region of Nias for Event II is further supported by the damage at Gunungsitoli (Table 2) and the destruction of buildings elsewhere on Nias (Bataviaasch Nieuwsblad, 22 March 1907). It is also likely, as discussed in more detail below, that uplifts inferred to have occurred in the Hinako Islands (Bataviaasch Nieuwsblad, 22 March 1907) and documented from a fossil coral microatoll on southern Nias (Meltzner et al. 2015) were related to Event II. This would suggest a source region in south–central Nias or off its south–central coast.

Two strongly felt aftershocks (Anonymous 1909) at $\sim$ 09:55 GMT on 4 January (Fig. 2d; Table 3) and $\sim$ 23:52 GMT on 5 January (Fig. 2e; Table 4) could be correlated with sparse regional and teleseismic recordings (Levitski 1909; Pechau 1907; Geiger 1909; Szirtes 1912b; Turner and Milne 1908a, b); origin times for both are corrected with respect to travel time to Jakarta from the Simeulue–Nias region. We estimated $M_S$ = 5.8 for the 5 January event using phase data from Göttingen (Geiger 1909) and Jena (Pechau 1907). We also compute Milne magnitudes ($M_M$) of $\sim$ 6.1 to $\sim$ 6.2 for both events assuming an instrumental gain of 5 (Abe and Noguchi 1983); however, we emphasize that these values are very poorly constrained, and are associated with uncertainties of up to ±0.5 (1$\sigma$).

In addition to the above, 19 felt aftershocks were counted on Simeulue on 4 January (Bataviaasch Nieuwsblad, 12 February 1907). Earthquakes were felt daily (Nieuws van den Dag voor Nederlandsch-Indië, 24 January 1907) with rarer aftershocks experienced after 15 January 1907 (De Sumatra Post, 1 February 1907). Earthquakes were also felt at Sinabang on Simeulue at 23:45 LT on 19 January 1907 (Bataviaasch Nieuwsblad, 12 February 1907) and on 8 July 1907 (Het Nieuws van den Dag, 20 September 1907), while on Nias,

Table 3

*EMS-98 intensities for the 4 January 1907 aftershock at 9:55 GMT*

| Name | Lat. | Long. | EMS | Error | LT | BT | Account | References |
|---|---|---|---|---|---|---|---|---|
| Gunungsitoli | 1.286 | 97.619 | 4 | 1 | 16:20 | + 36 | NO-ZW. Meerdere sterke schokken. Slingeren van lampen | Anonymous (1909) |
| Natal | 0.557 | 99.113 | 2 | 0 | 16:27 | + 30 | 1 second. ZO-NW. Zwakke schok. | Anonymous (1909) |
| Barus | 2.012 | 98.400 | 3 | 0 | 16:27 | + 33 | 15-seconden. ZW-NO. Enkele kort op elkaar volgende lichte schokken. | Anonymous (1909) |
| Siborongborong | 2.210 | 98.972 | 3 | 0 | ~ 17:00 | + 30 | N-Z. Zwak. | Anonymous (1909) |
| Rundeng | 2.685 | 97.834 | 4 | 0 | 16:25 | + 35 | Sterke schok. | Anonymous (1909) |

*Lat.* latitude (N°), *Long.* longitude (E°), *LT* local time, *BT* Batavia Time

Table 4

*EMS-98 intensities for the 5 January 1907 aftershock at 23:52 GMT*

| Name | Lat. | Long. | EMS | Error | LT | BT | Account | References |
|---|---|---|---|---|---|---|---|---|
| Gunungsitoli | 1.286 | 97.619 | 4 | 0 | 06:15 | + 36 | 2-seconden. Z-N. Korte sterke schok | Anonymous (1909) |
| Siborongborong | 2.210 | 98.972 | 3 | 0 | 06:00 | + 30 | N-Z. Zwak | Anonymous (1909) |
| Rundeng | 2.685 | 97.834 | 4 | 0 | 06:00 | + 35 | Een sterke schok | Anonymous (1909) |

*Lat.* latitude (N°), *Long.* longitude (E°), *LT* local time, *BT* Batavia Time

aftershocks were felt continuously until 17 January (Bataviaasch Nieuwsblad, 29 January 1907). Aftershocks occuring later than 5 January 1907 were only reported from Nias (Anonymous 1909). Well-timed felt earthquakes are almost absent from Simeulue except for a shock that was quite heavy (nl: vrij hevig) at Sinabang around midday (~ 12:42 BT) on 4 January 1907 (Utrechts Nieuwsblad, 14 February 1907) without causing any damage (De Sumatra Post, 1 February 1907). We suspect this shock could be related to Event I or a strong local aftershock, neither of which we can definitively rule out. Another large earthquake was felt in the Banda Aceh region on 21 November 1907 (Fig. 2g; Anonymous 1909), but this was probably unrelated to Event I.

## 5. Reassessment of Long-Period Seismic Moment and Source Slowness

Kanamori et al. (2010) inferred a seismic moment ($M_0$) of about 6 $\times$ $10^{27}$ dyn cm for Event I at periods of ~ 50 s, through a comparison of time-domain amplitudes of body waves at Göttingen with those obtained at the nearby Black Forest Observatory (BFO) during the earthquake of 2 November 2002. This method, which assumes the same focal geometry for both events [strike ($\phi$) = 297°, dip ($\delta$) = 16°, slip angle ($\lambda$) = 73°], is confined to the time domain and, as such, tacitly assumes that Event I had a source spectrum similar to that of the reference event, and hence followed scaling laws. However, those are expected to be violated precisely by tsunami earthquakes, whose source spectrum is red-shifted towards lower frequencies with respect to a more traditional source, such as the 2002 event for which we have verified a totally regular energy-to-moment parameter ($\Theta = -4.92$). For this reason, it is necessary to further explore the source spectrum of Event I in the frequency domain to constrain its seismic moment at periods typical of mantle waves.

In addition to the waveforms interpreted by Kanamori et al. (2010), we revisit the record from Göttingen (GTT), and locate three previously unused waveforms from Pulkovo, Russia (Golitsyn 1908), Shimla, India (Patterson 1909), and Manila, Philippines (Masó 1907). The Pulkovo record only features a partial, single component for Event I, and none for its aftershocks (Golitsyn 1908), while the Shimla seismogram clipped during Event I (Patterson 1909). The Manila record was written on a Vicentini mechanical seismometer with a period $T = 1.4$ s, which makes it the only short-period recording available to us of the 1907 Sumatra earthquakes; its crucial importance to our study is discussed in a subsequent section.

We use the first passages of Rayleigh ($R_1$) and Love ($G_1$) waves at Göttingen (GTT) for which precise metadata are available, with records hand-digitized at a sampling rate of 1 s. Our results are presented (Fig. 4) in the mantle range of frequencies (6–10 mHz), expressed as a mantle magnitude corrected for focal mechanism ($M_c = \log_{10} M_0 - 20$ with $M_0$ in dyn cm) in the formalism of Okal and Talandier (1989). We use a slightly adapted focal mechanism ($\phi = 320°$, $\delta = 15°$; $\lambda = 90°$), rotated only 8° in the formalism of Kagan (1991) from Kanamori et al.'s (2010), in order to reduce the scatter between Love and Rayleigh spectral amplitudes. Note that this new mechanism is also closer to the geometry of the nearby 2005 Nias megathrust earthquake ($\phi = 333°$, $\delta = 8°$; $\lambda = 118°$). Our results (Fig. 4) suggest an average moment $M_0 \approx 2.5 \times 10^{28}$ dyn cm ($M_c \approx 8.2$) at periods between 100 and 160 s; at the largest resolvable period ($\sim$ 170 s), the magnitude estimate approaches $M_c \approx 8.4$. This value of the seismic moment is about four times larger than proposed by Kanamori et al. (2010) from an estimate of time-domain amplitudes of S waves around 50 s and demonstrates slowness in the source of the 1907 mainshock, in clear agreement with its nature as a "tsunami earthquake". In addition, Fig. 4 documents a growth of moment with period, with a regression slope for $M_C$ versus frequency of $-0.09$ logarithmic units per mHz. This number is comparable to values obtained for documented tsunami earthquakes (e.g., Java, 2006: $-0.11$; Mentawai, 2010: $-0.08$; Manzanillo, 22 June 1932: $-0.14$; Hikurangi, 1947: $-0.07$ and $-0.08$); by contrast, traditional subduction events feature lower slopes (in absolute value) that do not exceed $-0.05$ (e.g., Maule, 2010: $-0.05$; Illapel, 2015: $-0.05$; Manzanillo, 3 June 1932: $-0.01$; see Okal and Saloor 2017). This property provides a quantitative confirmation of the nature of Event I as a tsunami earthquake in conjunction with its anomalously low felt intensities.

## 6. *Ratio of Estimated Energies between Events I and II*

In the case of Event II, we recompute conventional magnitude estimates from those reports of ground amplitude for which associations could be made, using established formulæ and guidelines (Kárník et al. 1962; Geller and Kanamori 1977; Ambraseys and Douglas 2000). Our best estimate of $M_S$ is $\sim$ 7.1 based on phase data from Osaka.

We also reproduce in Fig. 5 a copy of the Manila seismic record from Masó (1907). The seismogram in the top frame (Fig. 5a) was written on a Vicentini mechanical seismometer with a period $T = 1.4$ s. The distance to Manila is $\Delta = 29°$. Even though the orientation of this horizontal seismogram (NNW–SSE or 337°–157°) is pure transverse (the back-azimuth at Manila being $\beta = 247°$), this record clearly shows the P waves from two earthquakes separated by $\sim$ 53 min, corresponding to the two shocks identified on the basis of macroseismic data. We align the traces of the two events vertically to ease comparison of their waveforms (Fig. 5a, b). The body waves have a dominant recorded period of $\sim$ 4 s. The P waves of the mainshock are both much weaker and of longer duration than those of the aftershock. Note also that the mainshock P wavetrain consists of several subevents, lasting a total of about 2 min, while the aftershock waveform features two main packets, each lasting about 3 s. By contrast, we show in the lower frame a record (Fig. 5b) written on a longer-period Omori system with a natural period $T = 6.4$ s, oriented ENE–WSW, which this time is purely orthoradial. On that record, the amplitudes of the P waves from the two events become very comparable, and the main shock displays prominent Rayleigh waves featuring a period of $\sim$ 9 s at their maximum amplitude (probably reflecting the peaked response of the instrument), while the surface waves from the aftershock are much weaker.

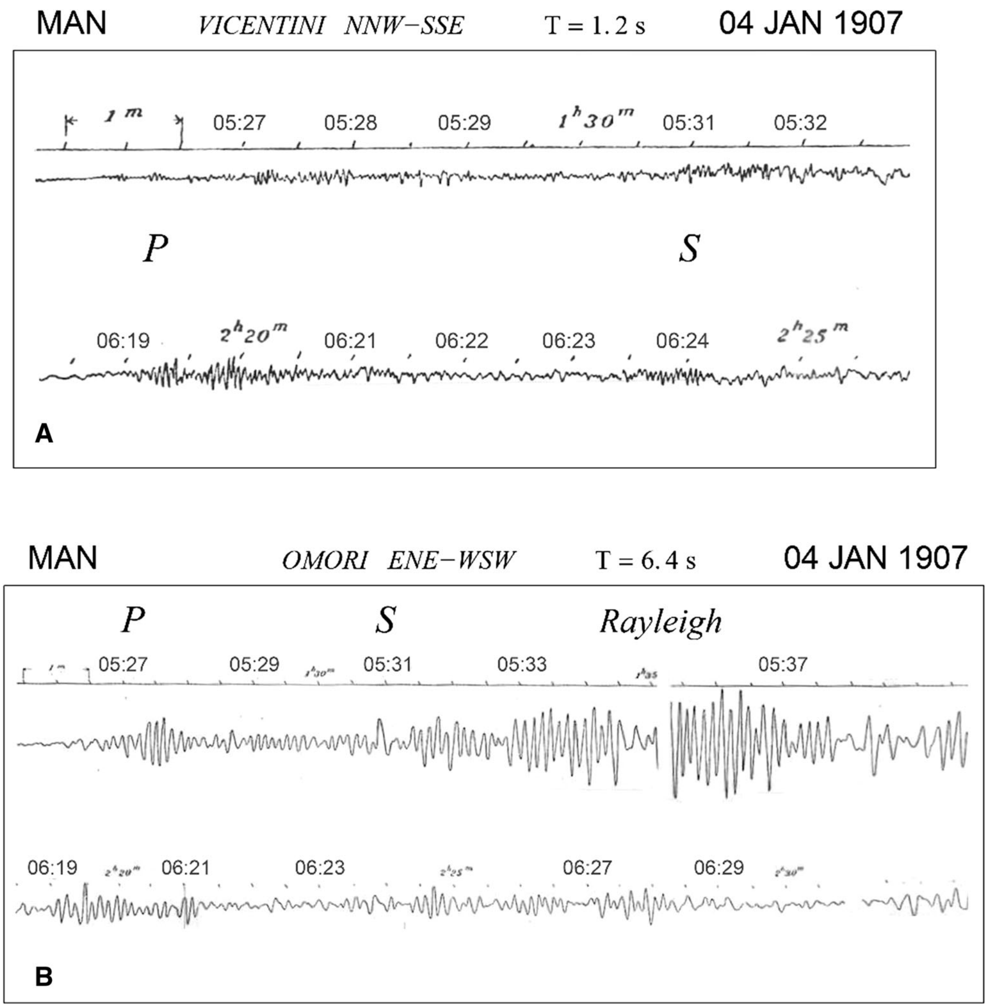


Figure 5
Seismic recordings at Manila (distance 29°; back-azimuth 247°), reproduced from Masó (1907), clearly showing the two events, separated by ~ 53 min. **a** Short-period Vicentini seismograph; **b** Omori seismograph. In both instances, the records are offset to align corresponding phases vertically. Time marks are at 30-s intervals, with original times given as local p.m. times (GMT + 8). Standard times (GMT) are overprinted in dark blue. These records dramatically illustrate the different characteristics of the two events

In an attempt to quantify these observations, we enlarged the Vicentini records (Fig. 5a) and digitized them at a time sampling $\delta t = 0.1$ s. Unfortunately, the Vicentini instrument was undamped (Masó 1907), which means that it would, at least theoretically, have an infinite response at its natural period. In this context, it would not be possible to formally compute an energy-to-moment ratio and a slowness parameter ($\Theta$) as defined by Newman and Okal (1998). This is further compounded by the fact that the photographic magnification of the figure by Masó (1907) is unknown. Under these circumstances, we use the model of a very weakly damped instrument ($\varepsilon = 1.1$) and obtain a ratio of estimated energies between the mainshock (Event I) and aftershock (Event II) of $E_I/E_{II} \approx 0.2$. Furthermore, we obtain an estimate of $M_S \approx 7.1$ for the classical surface-wave magnitude of Event II as described in the previous section, which would correspond to a maximum moment of $\sim 4 \times 10^{26}$ dyn cm, assuming that it follows scaling laws. However, the strong intensities reported may suggest that its source is blue-shifted towards higher frequencies, in which case the moment could be lower. Given the long-period moment estimated above for the mainshock ($2.5 \times 10^{28}$ dyn cm), this would suggest a factor of 300 between the energy-to-moment ratios of Events I and II, amounting to a difference of $\sim 2.5$ units in their parameters $\Theta$. While this value is not unreasonable, it comes close to the maximum range of $\Theta$ values that we have documented [see Okal and Saloor (2017) for an extensive dataset] and could be explained using both a very low value of $\Theta \approx -6.5$ for the mainshock, and a high value, $\Theta \approx -4$, for Event II. The former value is within the range of observed $\Theta$ for tsunami earthquakes [El Salvador 2012: −6.42; Hikurangi 1947 (II, 17 May): −6.51 (Okal and Saloor 2017)], while the latter would be typical of a "snappy" earthquake (Okal and Kirby 2002) occurring inside the overriding plate, such as the main normal faulting aftershock of the 2011 Tohoku earthquake (−4.12) or the 1939 Chillán earthquake (−4.04) (Okal and Kirby 2002; Okal et al. 2016). The jagged nature of the P waves of the mainshock at Manila would also be in line with observations during the 1992 Nicaragua event (Polet and Kanamori 2000) and the resulting model by Tanioka et al. (1997).

## 7. *Indian Ocean Tsunami Observations*

We were able to compile 88 observations of the tsunami generated by Event I across the Indian Ocean (Table 5; Fig. 6; Online Appendix B). They were obtained from individual accounts (e.g., Schröder 1917a), as well as from reports published in local newspapers. Most of the Dutch news reports were corroborated by later official Dutch correspondence (Openbaar Verbaal, 23 April 1908). First- and second-hand accounts from a few locales in the near and far field are available (e.g., Anonymous 1909; Visser 1922), and some were repeated by Solov'ev and Go (1974). We also extracted eyewitness or second-hand accounts appearing in contemporary anthropological (e.g., Baumwoll 2008; Rahman et al. 2017) and scientific studies (Yogaswara and Yulianto 2006; Whitlow 2008; Fujino et al. 2014).

The impact of the tsunami was greatest on the southern coast of Simeulue, and on the northern and western coasts of Nias (Fig. 6a, b). Without providing additional location details, news and official reports from Simeulue suggest the tsunami struck after Friday afternoon prayers, the sea flooding inland as much as 600–800 m with isolated inundations of 1200 m, or to the foot of the hills, sweeping coral boulders and marine fauna inland (Bataviaasch Nieuwsblad, 12 February 1907; Utrechts Nieuwsblad, 14 February 1907; Openbaar Verbaal, 23 April 1908; Yogaswara and Yulianto 2006). Better numerical constraint is forthcoming from Nias (Fig. 6a, c), for example, from Afulu (nl: Afoeloe), where the sea washed inland for over a kilometer (nl: ongeveer een paal)[1] as far as the foot of the hills, where it deposited debris that included human remains and large uprooted trees (Bataviaasch Nieuwsblad, 22 March 1907). Schröder (1917a) noted that a part of the bay at Afulu was filled with sand and other material (nl: Vermelding verdient de opvulling van een deel de baai van Afulu met zand en ander materiaal) at the time of his visit. Schröder (1917a) also reports that Hulo Uma near Afulu was "robbed of all life" (nl: van alle leven beroofd). Southwest of Toyolawa, only the west coast of the island of Pulau Mausi (nl: Ma'uso or Maoesi) was impacted by the tsunami (Schröder 1917a). However, to the south, the tsunami appears to have rapidly diminished in character at Lagundi (Fig. 6b; Bataviaasch Nieuwsblad, 22 March 1907).

The island of Simeulue Cut (nl: Simeuloeë Tjoet or Simaloer Tjoet) off the southern coast of Simeulue (Fig. 6a) "was lost" or "disappeared" (nl: is verdwenen) with only the hill at the center of the island above the water (Fig. 6b), suggestive of extreme tsunami erosion or, possibly, subsidence. West of Nias, on Pulau Wunga (Fig. 6b), the tsunami swept the island from the west (Schröder 1917a), destroying three-fourths of it including numerous coconut trees, with debris and victims swept into the lagoon at the center of the island (Bataviaasch Nieuwsblad, 22 March 1907). The height of the tsunami at Pulau Wunga is estimated at between 6 m and 15 m (Schröder 1917a; De Padanger, 25 February 1907), and in 2005, modern residents told one of the authors

[1] The old Dutch measure "een paal" used in colonial Indonesia is equivalent to 1507 m (Staring 1871).

Table 5

*Tsunami observations for the 1907 tsunami extracted from newspaper reports and other publications from 88 locations (including nil reports) from the Indian Ocean basin*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 1 | Aden | YE | 12.802 | 45.018 | – | – | "The tidal wave was not perceptible at this port" (Erskine 1909) |
| 2 | Afulu | ID | 1.263 | 97.245 | – | 1507 | Tsunami went inland about "een paal" (1507 m, *see text*) almost to the base of the hills where debris and skeletons of those killed were left; at least 50 killed (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 3 | Ayer | ID | 2.591 | 95.968 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 4 | Alafan | ID | 2.824 | 95.756 | > 8 | – | Local history preserved by word of mouth recalls corpses left in the branches of durian trees, and make note to point out that the 2004 tsunami (that was 8-m high at this location) did not reach the height of the branches of durian trees (*Kompas*, 20 August 2014) |
| 5 | Angkë | ID | 2.509 | 96.165 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 6 | Apollo Bandar | IN | 18.922 | 72.834 | 0.0508 | – | "The effect of the tidal wave is noticeable between 7 P.M. on 4th, and 9 P.M. on 5th January, the oscillations of the pencil occurring only at or about the time of slack water at low and high tides. The greatest movement of the pencil out of the normal was 2 inches at 2-50 A. M. on 5th" (Erskine 1909) |
| 7 | Awe Ketjil | ID | 2.436 | 96.252 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 8 | Awe Sebal | ID | 2.433 | 96.271 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 9 | Bahoe | ID | – | – | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 10 | Baie du Courrier | MG | −12.265 | 49.059 | – | – | No record of the tsunami available (*see text*) |
| 11 | Barus | ID | 2.012 | 98.339 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 12 | Boeman/Serie Boenon/Boenon Siri | ID | 2.519 | 96.150 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 13 | Cape Tolojawa | ID | 1.404 | 97.062 | – | – | Village almost completely destroyed; two killed; water leapt with great force landward but was broken by the coral reefs (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 14 | Colombo | SL | 6.979 | 79.870 | – | – | "It was observed as a disturbance, or tidal wave, at the mouth of the Kelani river, and by the villagers on the banks for some miles upstream" (*Ceylon Observer*, 10 January 1907) |
| 15 | Diego Suarez (Antsiranana) | MG | −12.289 | 49.302 | – | – | No record of the tsunami available (*see text*) |
| 16 | Doemala | ID | 1.171 | 97.304 | – | – | Partially destroyed; the cape to the north–west broke the tsunami; three fatalities (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |

**Table 5** *continued*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 17 | Galle | SL | 6.031 | 80.231 | – | – | "A great deal of excitement was caused in the Fort today when those assembled on the jetty noticed that the sea had receded in the harbor, the whole coast round the bay being high and dry some 25 or 35 feet. The lighters and other boats moored near the jetty were left on dry land. The hull of the wrecked "Dalswinton" was exposed to view. The coolies near the jetty secured a good deal of fish, lobsters, etc. The sea receded seven times at intervals of half-an-hour. After each recession the in-coming flow of water was very heavy. On the third occasion it was nearly level with the jetty. The sea was perfectly calm, and no waves were noticeable, but the current with the in-coming swell was very strong. The B. I. steamer "Loodiana" was in harbor discharging rice, and was affected by the movement of the seas, being moved backwards and forwards. Several lighters laden with rice were on their way from the steamer to the jetty, and were in danger of being dashed against the rocks owing to the heavy inflow" (*Ceylon Observer*, 10 January 1907; Also see Online Appendix B) |
| 18 | Guhanaga (Geni) | ID | 4.683 | 95.686 | – | | An eyewitness claimed the Krueng Sabe river overflowed until Desa Geni i.e. modern Guhanaga (*Aceh Post*, 10 April 2013) |
| 19 | Gunungsitoli | ID | 1.286 | 97.619 | 0.70 | – | "At Gunungsitoli seawater, dark brown in colour, leapt against the beach to a height of about 70 cm (7 dM)" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 20 | Hambantota | SL | 6.123 | 81.122 | – | – | "The first big wave was probably unrecorded and occurred, Mr. Barnard thinks, at about 1:30 p.m. The second great wave occurred at 3 p.m. and the third at 3:05 p.m. The waves are not always quite exact, which accounts for the time between the waves at which No. 7 wave occurred, and also at 4:05 p.m., when one was possibly unrecorded, or spoilt by the interfering waves. A wave after rushing up the beach recoiled and met the succeeding one, making its force diminished, and it might happen that one retiring wave just met an incoming small one and spoilt it…… between greatest rise and fall 14 feet measured at Jetty" (*Ceylon Observer*, 10 January 1907; Also see Online Appendix B) |
| 21 | Hulo Uma | ID | 1.252 | 97.236 | – | – | Hulo Uma near Afulu was "robbed of all life" (Schröder 1917a) |
| 22 | Île Amsterdam (*questionable*) | FR | −37.834 | 77.556 | – | – | La même marée sismique a été observée aux Îles Saint-Paul, Amsterdam, Rodriguez, la Réunion, Maurice et enfin aux Seychelles (Bertho 1910) |
| 23 | Île Saint-Paul (*questionable*) | FR | −38.724 | 77.515 | – | – | La même marée sismique a été observée aux Îles Saint-Paul, Amsterdam, Rodriguez, la Réunion, Maurice et enfin aux Seychelles (Bertho 1910) |
| 24 | Inoel/Inoer | ID | 2.483 | 96.195 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 25 | Karachi | PK | 24.833 | 66.992 | 0.0762 | – | "The disturbance commenced at 5 P.M. on 4th January, about the time of slack water at low tide and lasted till 10 A.M. on 5th. It was distinctly noticeable between 11 P.M. on 4th and e P.M. on 5th; at 1–15 A. M. at slack water at high tide on the 5th, the pencil showed an abnormal movement of the wave of 3 inches" (Erskine 1909) |
| 26 | Kayu Menang | ID | 2.306 | 97.741 | – | – | Possibly affected by flooding in 1907 causing residents to move to Singkil (Aceh Post, 10 April 2013) |
| 27 | Kidderpore | IN | 22.548 | 88.320 | – | – | "There is no trace of the tidal wave on the diagrams, at the river ports of Rangoon and Kidderpore" (Erskine 1909) |

**Table 5** *continued*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 28 | Koela Deh | ID | n/a | n/a | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 29 | Kota Ladang | ID | n/a | n/a | – | – | Disappeared (*Utrechts Nieuwsblad*, 14 Feb 1907) |
| 30 | Kota Tinggi | ID | 2.399 | 96.475 | – | 600–900 | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 31 | Kuala Bhee | ID | 4.371 | 96.062 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 32 | La-eion | ID | 2.547 | 96.108 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 33 | Lahalos | ID | n/a | n/a | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 34 | Lahoebang (Lakubang) | ID | 2.586 | 95.989 | – | 2000–3000 | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907). Dolphins (bh: ikan lumba-lumba) and whales (bh: ikan paus) carried inland up to distances of 2–3 km from the coast (Yogaswara and Yulianto 2006) |
| 35 | Lafu | ID | 1.401 | 97.213 | – | ~ 100 | "A few houses damaged; tidal wave ran about 100 m inland; damage minor" (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 36 | Lagundi | ID | 0.582 | 97.737 | – | – | "Weak tsunami" (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 37 | Lamajan (Cape) | ID | 2.572 | 95.996 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 38 | Laokeh | ID | n/a | n/a | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 39 | Lasingaloe | ID | 2.442 | 96.232 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 40 | Lessihan | ID | 2.407 | 96.324 | – | – | "Disappeared" (*Utrechts Nieuwsblad*, 14 February 1907) |
| 41 | Lebang | ID | 2.433 | 96.283 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 42 | Leukoën (Lukon) | ID | 2.609 | 95.867 | – | – | 65 killed (Utrechts Nieuwsblad, 14 Feb 1907). On the (small) islands of Simeuloee Tjoet, Linggang and Leukoën most the houses were destroyed. (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 43 | Linggang | ID | 2.610 | 95.868 | – | – | On the (small) islands of Simeuloee Tjoet, Linggang and Leukoën most the houses were destroyed. (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 44 | Madras (Chennai) | IN | 13.091 | 80.298 | – | – | "Oscillations due to the tidal wave are traceable on the tidal diagram between midnight of 4th and midnight of 5th January. They are insignificant" (Erskine 1909) |
| 45 | Matara | SL | 5.942 | 80.543 | – | – | "The sea receded as far back that the sunken ridge of rocks a quarter of a mile from the shore became visible. This happened two or three times" (*Ceylon Observer*, 10 January 1907) |
| 46 | Mauritius | FR | −20.285 | 57.573 | – | – | La même marée sismique a été observée aux Îles Saint-Paul, Amsterdam, Rodriguez, la Réunion, Maurice et enfin aux Seychelles (Bertho 1910) |
| 47 | Meulaboh (Analabu) | ID | 4.143 | 96.128 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 48 | Moedil | ID | 2.466 | 96.217 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 49 | Nantjalla | ID | 2.450 | 96.227 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |

**Table 5** *continued*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 50 | Naibos | ID | 2.489 | 96.187 | 8–10 | ~ 1000 | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907); Sharks (bh: ikan hiu), whales (bh: ikan paus), and coral boulders were transported inland; marine fauna was swept inland as much as a kilometer at Naibos in south Simeulue where local narratives also allege human corpses and dead livestock such as buffalo were found in the tops of coconut trees at heights of 8–10 m (Yogaswara and Yulianto 2006) |
| 51 | Natal | ID | 0.557 | 99.113 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 52 | Oejong | ID | 2.688 | 95.776 | – | – | 87 killed (*Utrechts Nieuwsblad*, 14 Feb 1907) |
| 53 | Oedjoeng Lojang | ID | 1.530 | 97.352 | – | – | "All houses except one flattened to the ground" (*Bataviaasch Nieuwsblad*, 29 Jan 1907). *Note*: Uncertain if damage is from the earthquake of the tsunami |
| 54 | Oedjoeng Oesoej (Ujung Gossong?) | ID | – | – | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 55 | Padang | ID | −1.003 | 100.379 | | – | Recorded by the automatic tide gauge in Teluk Bayur (nl: Emmahaven) (Anonymous 1909; also see text) |
| 56 | Pointe des Galets | FR | −20.940 | 55.305 | – | – | "Le 4 janvier 1907, à 4h20 m de l'après-midi, au moment de la pleine mer, on vit l'eau monter assez rapidement dans le port, atteignant 60 mm à 70 mm au-dessus du niveau des marées de syzygies, puis tout à coup se retirer lentement bien au-dessous du niveau des plus basses mers. Cette élévation et cet abaissement se répétèrent avec un rythme parfait, de 10 en 10 min, ainsi que l'a bien indiqué le marégraphe. La mer, au large, était calme et belle, sans houle. La dénivellation, toutes les 10 min, était de lm, 70. Le phénomène continua jusqu'au 6 janvier au soir, avec des recrudescences d'intensité" (Bertho 1910) |
| 57 | Port Blair | IN | 11.675 | 92.761 | 0.127 | – | "The first disturbance appeared to have commenced at 1-45 P.M., on 4th January 1907; the oscillations of the pencil due to the tidal wave, were slight up to 2-40 P.M., after which they increased in frequency and in height up to 6-30 P. M., the time of slack water at low tide, when the wave was greatest, the height being 5 inches. After this the curve showed a diminishing of the wave until it ceased at 10-20 P.M. on 6th instant. The oscillations were most marked at each slack water at low and high tides" (Erskine 1909) |
| 58 | Pulau Mausi | ID | 1.355 | 97.101 | – | – | The west coast of the island of Pulau Mausi was impacted by the tsunami (Schröder 1917a) |
| 59 | Pulau Raja | ID | 4.869 | 95.382 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 60 | Pulau Tello | ID | −0.066 | 98.264 | – | – | "For the tidal wave, which destroyed the island of Simaloer on 4 January 1907, reports were received from Gunungsitoli, Nias, Pulau Wunga, Natal, Barus, Meulaboh, Kuala Bhee, Pulau Raja and Pulau Tello" (Anonymous 1909) |
| 61 | Pulau Woenga (Pulau Wunga) | ID | 1.207 | 97.091 | 7–5 | – | All houses washed into the lagoon with at least 100 killed. 120 coconut trees destroyed; estimated to have been 7 m–15 m high (Schroeder, 1912a; *De Padanger*, 25 Feb 1907; *Bataviaasch Nieuwsblad*, 22 Mar 1907) |

**Table 5** *continued*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 62 | Rangoon | MY | 16.768 | 96.159 | – | – | "There is no trace of the tidal wave on the diagrams, at the river ports of Rangoon and Kidderpore" (Erskine 1909) |
| 63 | Rodrigues Island | FR | −19.711 | 63.448 | – | – | "The officer in charge of the Eastern Extension Telegraph office, Barrack Street, stated last night that at 8:35 p.m. the Company's office at Cocos Island had been informed by the Rodrigues manager that the sea was boiling, and that small tidal waves were being experienced. At about 9 o'clock information came to hand that the tide, which should have been at its lowest ebb, was rising rapidly, and that a small reef which was ordinarily visible standing out of the water was being covered. The tide was higher than it had ever been before. Half an hour later the tide was reported to be still rising, and the residents were hauling their boats up out of danger. Shortly before 11 p.m. the Rodrigues station reported that the tide was falling" (*The West Australian*, 5 January 1907) |
| 64 | Salang | ID | 2.637 | 95.864 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 65 | Saloer Ilir | ID | 2.443 | 96.238 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 66 | Saint-Benoît | FR | −21.044 | 55.717 | – | – | "Le phénomène était bien marqué, et complètement visible de la « Batterie » , où beaucoup de personnes ont l'habitude de prendre le frais dans les journées chaudes vers le soir. Il était 4 h. ½. Tout à coup, les lames qui de tout temps déferlent à cet endroit, disparaissent, la mer se retire calme, laissant à sec un fond d'une centaine de mètres de large environ. Les eaux se retirent derrière la chaine de Caps, qui forme le récif de St-Benoit, caps qui n'émergeaient jamais quelque temps qu'il fît, mais que la retraite de la mer laisse entièrement à nu. Parmi les spectateurs du phénomène, des jeunes garçons, attirés par l'appât, se précipitent sur les poissons surpris, que l'eau a abandonnés. Mais à peine quelques minutes s'étaient écoulées, que les gens restés sur le rivage signalent à ces jeunes imprudents, une houle d'une hauteur extraordinaire venant de très loin. Ceux-ci n'eurent que le temps d'abandonner leur butin et de gagner la côte. Bien leur en prit : la houle est venue déferler et envahir la terre ferme à une limite que n'atteint pas d'ordinaire le niveau de la mer, le ressac balayant et entraînant tout : poissons et galets. Plusieurs vagues semblables se sont succédé à différents intervalles. A neuf du soir la mer a commencé à reprendre son niveau ordinaire, puis tout est rentré dans l'ordre normal" (*Journal de l'île de La Réunion*, 8 January 1907) |
| 67 | Saint-Gilles-de-Bain | FR | −21.053 | 55.224 | – | – | "Peut-être quelques uns de nos érudits nous donneront-ils l'explication de ce phénomène qui a fortement impressionné la population saint gilloise et même les quelques baigneurs en villégiature" (*Journal de l'île de La Réunion*, 8 January 1907) |
| 68 | Saint-Marie | FR | −20.893 | 55.508 | – | – | "….et qu'à Ste Marie des rochers qui n'émergent jamais, ont été complètement mis à découvert" (*La Patrie Créole*, 8 January 1907) |
| 69 | Saint-Pierre | FR | −21.334 | 55.471 | – | – | "Il paraît que dans le port de St-Pierre, il a été relevé une différence de niveau de près de deux mètres, produisant, au retrait de l'eau, de véritables cascades descendant des hauts fonds non dragués" (*La Patrie Créole*, 8 January 1907) |

**Table 5** *continued*

| # | Name | CN | Lat. | Long. | HT (m) | IN (m) | Description |
|---|---|---|---|---|---|---|---|
| 70 | Seychelles | SC | −4.712 | 55.491 | – | – | La même marée sismique a été observée aux Îles Saint-Paul, Amsterdam, Rodriguez, la Réunion, Maurice et enfin aux Seychelles (Bertho 1910) |
| 71 | Si Linggas | ID | – | – | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 72 | Si Toeboeh | ID | – | – | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 73 | Sifahandro | ID | 1.504 | 97.353 | – | – | A few houses destroyed (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 74 | Sibolga (*questionable*) | ID | 1.731 | 98.782 | – | – | "It is worth mentioning that in the past 50 years, (at the time) when a strong earthquake destroyed Hinako (Nias), the sea at Sibolga rushed forth and a tidal wave was formed, the city was flooded. Now when people see the sea ebb and flow, they fear a tidal wave (report from the controller of Sibolga). More than likely that this report is related to the earthquake of 4 January 1907" (Visser 1931) |
| 75 | Simueloee Tjoet (Simuelue Cut) | ID | 2.531 | 95.940 | – | – | "Half lost" (*Bataviaasch Niewsblad*, 23 Jan 1907) or "partially lost in the sea" (De Sumatra Post, 1 Feb 1907). Barely the (little) top of the (little) hill was visible out of the water (*Utrechts Nieuwsblad*, 14 Feb 1907; *De Padanger*, 25 Feb 1907; Most of the houses destroyed (*Bataviaasch Niewsblad*, 12 Feb 1907). Also see main text |
| 76 | Sinabang | ID | 2.479 | 96.379 | 0.5 | – | 0.5 m oscillations of harbor (*Utrechts Nieuwsblad*, 14 February 1907) |
| 77 | Siriwaoe/Saroeng Baroeng | ID | 1.700 | 97.448 | – | – | "Flooded" (*Bataviaasch Nieuwsblad*, 10 Jan 1907). Temporarily underwater (*Bataviaasch Nieuwsblad*, 29 Jan 1907) |
| 78 | Sirombu | ID | 0.951 | 97.418 | – | – | Deaths reported (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |
| 79 | Sosoh | ID | 3.721 | 96.825 | – | – | "Went under water" (*Bataviaasch Nieuwsblad*, 12 Mar 1907) |
| 80 | Soea-Soea | ID | 2.421 | 96.314 | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 81 | Taloe Siaba | ID | 1.510 | 97.378 | – | – | "Lost" (*De Padanger*, 26 Jan 1907) |
| 82 | Tamatave (Toamasina) | MG | | | – | – | No record of the tsunami available (*see text*) |
| 83 | Tanjung Gossong | ID | 2.395 | 96.336 | – | – | The newly established field or agricultural land (bh: ladang) was destroyed (*Bataviaasch Nieuwsblad*, 12 Feb 1907); Coral boulder carried inland supposedly in 1907 (Fujino et al. 2014) |
| 84 | Tangalle | SL | 6.022 | 80.801 | – | – | "The sea ebbed and flowed in the same manner, exposing the sea bottom as far as the rock which lies to the east of the Resthouse…". (*Ceylon Observer*, 17 June 1909) |
| 85 | Tapah (island) | ID | 2.355 | 96.240 | – | – | "As good as without coconut trees" and on this island about 200 people were killed (*Utrechts Nieuwsblad*, 14 Feb 1907); One account says 1000 people were killed at Kuala Deh (on Tapah) alone (*Utrechts Nieuwsblad*, 14 Feb 1907); All villages completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 86 | Tapak Tuan | ID | 2.357 | 97.180 | – | – | "Ebb and flood observed thrice" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 87 | Titi Kapoer | ID | – | – | – | – | Village completely "lost" (*Bataviaasch Nieuwsblad*, 12 Feb 1907) |
| 88 | Toerelaoeja | ID | 1.532 | 97.532 | – | – | "A fisherman was killed" (*Bataviaasch Nieuwsblad*, 22 Mar 1907) |

See Online Appendix B for verbatim newspaper reports. Country name code (CN): France (FR), India (IN), Indonesia (ID), Madagascar (MG), Pakistan (PK), Seychelles (SC), Sri Lanka (SL), and Yemen (YE); Lat. = latitude, Long. = longitude, height (HT), and inundation distance (IN) of tsunami in meters (m) as best as can be estimated from available material

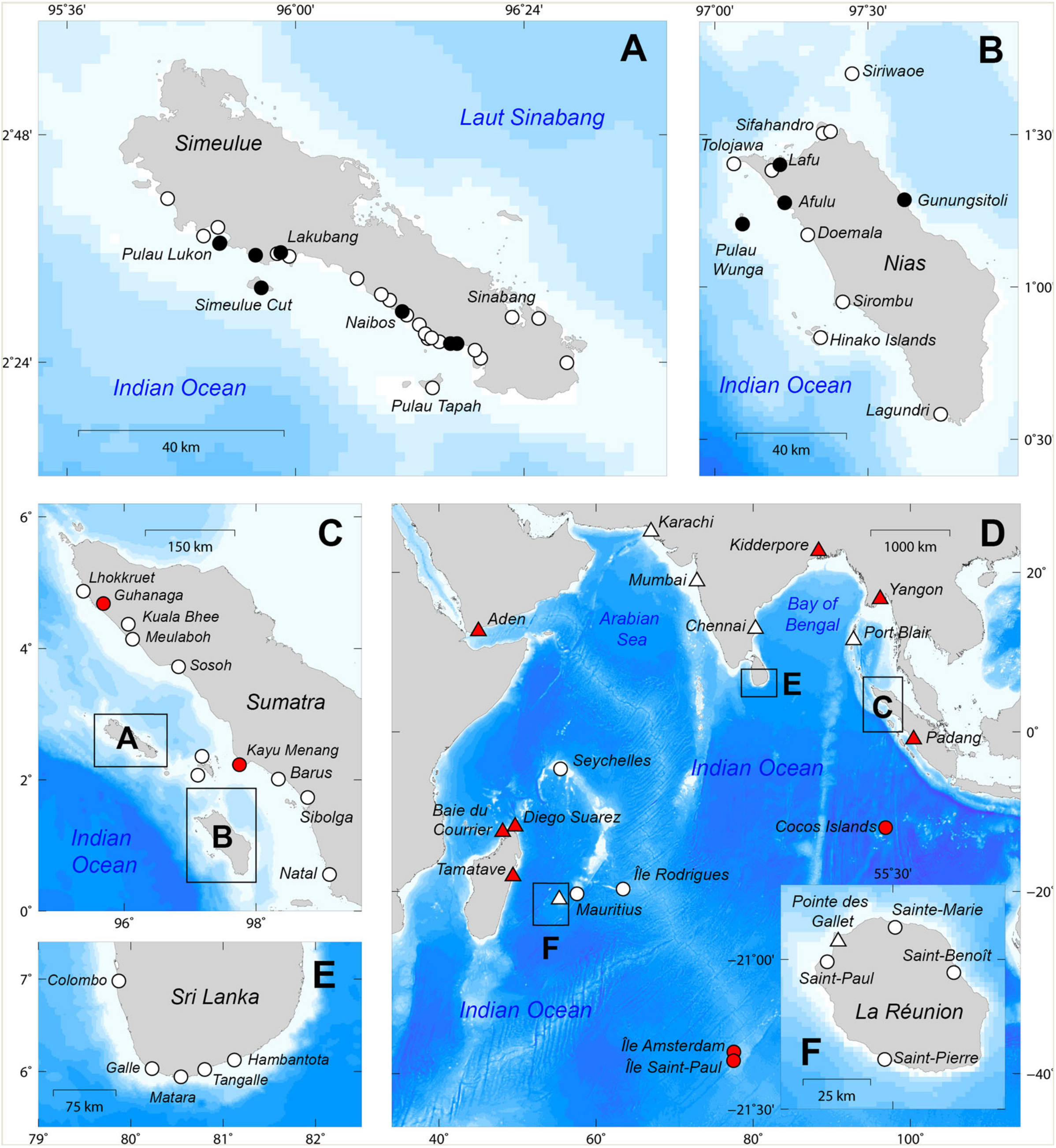


Figure 6
Tsunami observations on Simeulue (**a**), Nias (**b**), and northern Sumatra (**c**), and in the Indian Ocean basin (**d**) including Sri Lanka (**e**) and La Réunion (**f**), also tabulated in Table 5. White circles show locations where the tsunami was observed, and black circles indicate sites used to forward model the tsunami. Red circles mark questionable or false reports. White triangles show tide gauges where readings were available, and red triangles show tide gauges in operation in 1907 where either data were unavailable, the tsunami was unrecorded, or records were incomplete

(K.S.) that corpses were stranded in coconut trees in 1907. The only photographic evidence of this disaster that we found is from Pulau Wunga (Schröder 1917b; Fig. 7a, b); how representative these are of damage elsewhere on the island is unknown, but the similarity of the post-tsunami landscape to that of Pulau Sibigau

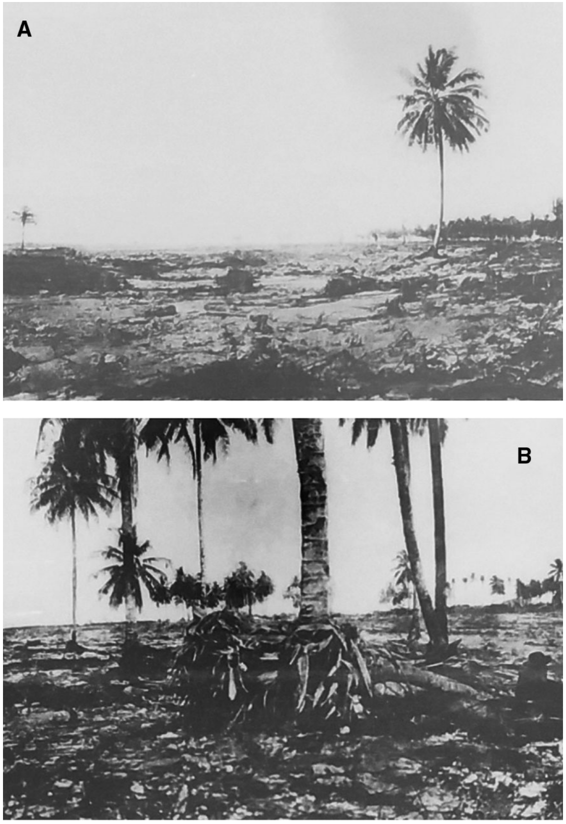


Figure 7
The northern (**a**) and western part (**b**) of the island of Pulau Wunga (Schröder 1917b)

(Hill et al. 2012) following the 2010 Mentawai tsunami earthquake is striking.

On the Sumatran mainland (Fig. 6a), vague accounts suggest Kayu Menang (Aceh Post, 10 June 2013) and Sibolga (Visser 1931) were possibly flooded. At Guhanaga (formerly Geni), a flood in the Krueng Sabe River (Aceh Post, 10 June 2013) was attributed to the tsunami by an eyewitness, but we consider this account cautiously as the date associated with it is unreliable. The tsunami was reportedly recorded by a tide gauge in the harbor at Padang (Anonymous 1909), but this record has been lost. Monecke et al. (2008) suggest that a sand sheet (unit A) deposited on the Sumatran coast to the north of Meulaboh was related to the 1907 tsunami. While accounts at our disposal from the west coast of Sumatra are sparse, we doubt a tsunami that flooded several kilometers inland would go unnoticed, and despite a heavy colonial military presence in the region at the time, there is no record of damage to towns on the coast (Koloniaal Verslag van 1907; 1908). We believe there is a higher likelihood that this sand sheet was instead deposited by the tsunami that destroyed Bubon, Meulaboh (formerly Analabu) and Singkel, following the 16 February 1861 Nias earthquake (Padangsch nieuws- en advertentie-blad, 2 March 1861; Pinang Gazette, 16 March 1861).

On the Indian Subcontinent in erstwhile British India and her dependencies, tide gauges operated by the Survey of India at Port Blair (Andaman Islands), Apollo Bandar (in Mumbai), Chennai (Madras), and Karachi provide the only instrumental readings from this tsunami (Erskine 1908, 1909; Fig. 6d), but maregrams were unavailable to us. Similar instruments at Kidderpore (Kolkata), Yangon (Rangoon, Myanmar), and Aden (Yemen) did not record the disturbance (Erskine 1908, 1909). In Sri Lanka, it was observed at points on the southern coast in particular at Galle, where the harbor filled and emptied seven times at half-hour intervals, but water did not overflow the jetty (Ceylon Observer, 10 January 1907).

In the Southern Indian Ocean (Fig. 6f), the tsunami was observed at Mauritius (Erskine 1909) and on Rodrigues (The West Australian, 5 January 1907). La Réunion (Bertho 1910; Sahal et al. 2011), supported by readings on a maregraph, reports an "oscillation" (presumably peak-to-peak) of 1.7 m at Pointe des Galets, about 1/3 (if meant to represent a peak-to-peak amplitude) of the runup observed in 2004 at nearby (and vastly developed) Le Port (Okal et al. 2006a), starting at 16:20 local time (which before 1911 was GMT + 3:42), in perfect agreement with the 7.5 h propagation time observed in 2004. Bertho (1910) also mentions observations in the Seychelles and on the French islands of Amsterdam and Saint Paul; however, the remoteness of the latter two islands, whose settlement at the time is not proven beyond doubt, lead us to question the veracity of the corresponding reports. Curiously, this event is missing from the French national tsunami database (Lambert and Terrier 2011).

As for Madagascar, historical tide gauge data available from Service hydrographique et océanographique de la Marine (SHOM) for Diego-Suarez (now Antsiranana; SHOM Shelfmark: SHD R

7JJ2384) have no entries for 3–6 January 1907 (Garnier-Loussaut, personal communication 2014). Observations of high and low water levels are missing for January 1907 from Tamatave (now Toamasina), and diurnal visual observations made with a tide staff are only available for 15 February until 2 March 1907 from Baie du Courrier (Ferret, personal communication 2014). No reports could be found in the several French-language newspapers published in Madagascar at the time.

## 8. Tsunami Modeling Methodology

We choose a subset of 12 locations with reliable geographic coordinates on the islands of Simeulue and Nias (Fig. 6a, b), at which either runup, wave heights, or inundation distances could be determined (Table 5). These also include islands such as Lukon, Pulau Wunga, Simeulue Cut, and Tapah that were completely or partially overtopped (Table 5). These sites extend approximately parallel to the northern Sunda Trench, along strike from Simeulue to Nias, for a distance of about 220 km. Their spatial distribution and their proximity to the Sunda Trench (60–80 km), along with the effect of directivity (e.g., Miyoshi 1955; Kajiura 1972) then allow a causal relationship between field observations and the parameters of the rupture, with each site serving as a control point to estimate and constrain slip on a corresponding segment of a model of the parent seismic source.

Our tsunami simulations use the Cornell Multi-grid Coupled Tsunami Model (COMCOT), a fully validated finite-difference algorithm solving the nonlinear shallow-water approximation of hydrodynamics (Liu et al. 1998). COMCOT simulates tsunami wave propagation in the deep ocean by solving linear, shallow-water equations in a spherical coordinate system (Wang 2009), while depth-averaged nonlinear, shallow-water equations are used to simulate near-shore wave propagation and onshore inundation (Wang 2009). It has been used to investigate both historical and modern tsunamis (e.g., Li et al. 2015; Wang and Liu 2006). We use three nested layers or grids (Grid 01–Grid 03) to simulate the tsunami at different scales, with the resolution of the grids varying from $\sim$ 2000 m in the source region near the Sunda Trench to 100 m in the coastal areas of Simeulue and Nias. Our setup of computational grids is shown in Fig. 8. A 30 arc-second grid (ca. 925 m) from the General Bathymetric Chart of the Oceans (GEBCO) digital bathymetry dataset (see "Data and Resources") is used to create the computational Grids 01 and 02. Three sublayers, each with a resolution of 100 m, are used for Grid 03 to cover the 12 selected sites on Simeulue and Nias. The topography in the innermost Grid 03 is the "bare-earth" digital elevation model (DEM), in which vegetation biases are removed from Shuttle Radar Topography Mission (SRTM) data using a multisensor approach (O'Loughlin et al. 2016). We derived nearshore bathymetry and topography by combining depth contours digitized by us from hard-copy maps, with digitally available topographic contours and the 30 arc-second GEBCO dataset (see "Data and Resources"). We also specify a constant Manning's roughness of 0.013 for the ocean floor and 0.025 for the inland area in the innermost grids.

The extremely limited nature and quality of the available seismological data preclude the use of commonplace modern methods (e.g., Kikuchi and Kanamori 1982, 1986, 1991) to constrain the parameters (fault length and width, seismic slip) necessary to compute a field of initial conditions for the simulation of the tsunami. As documented in a recent study (Ebel and Chambers 2016) seismicity occurring in the vicinity of past large ruptures in eastern North America and California shows a tendency to concentrate its largest events at the edges of past ruptures. They went on to show that this geographical trend can be used to map the rupture area of historical events predating the development of modern (and especially digital) data necessary to conduct detailed source tomography. In this context, and assuming that Ebel and Chambers' (2016) paradigm can be extended to the case of large subduction interfaces, we use our preferred epicentral location, and catalogues of relocated seismicity before and after the 2004 Sumatra–Andaman and 2005 Nias earthquakes (Engdahl et al. 2007; Pesicek et al. 2010), to define a zone of presently low seismic productivity in the uppermost part of the interface of the Sunda Megathrust, extending roughly 250 km

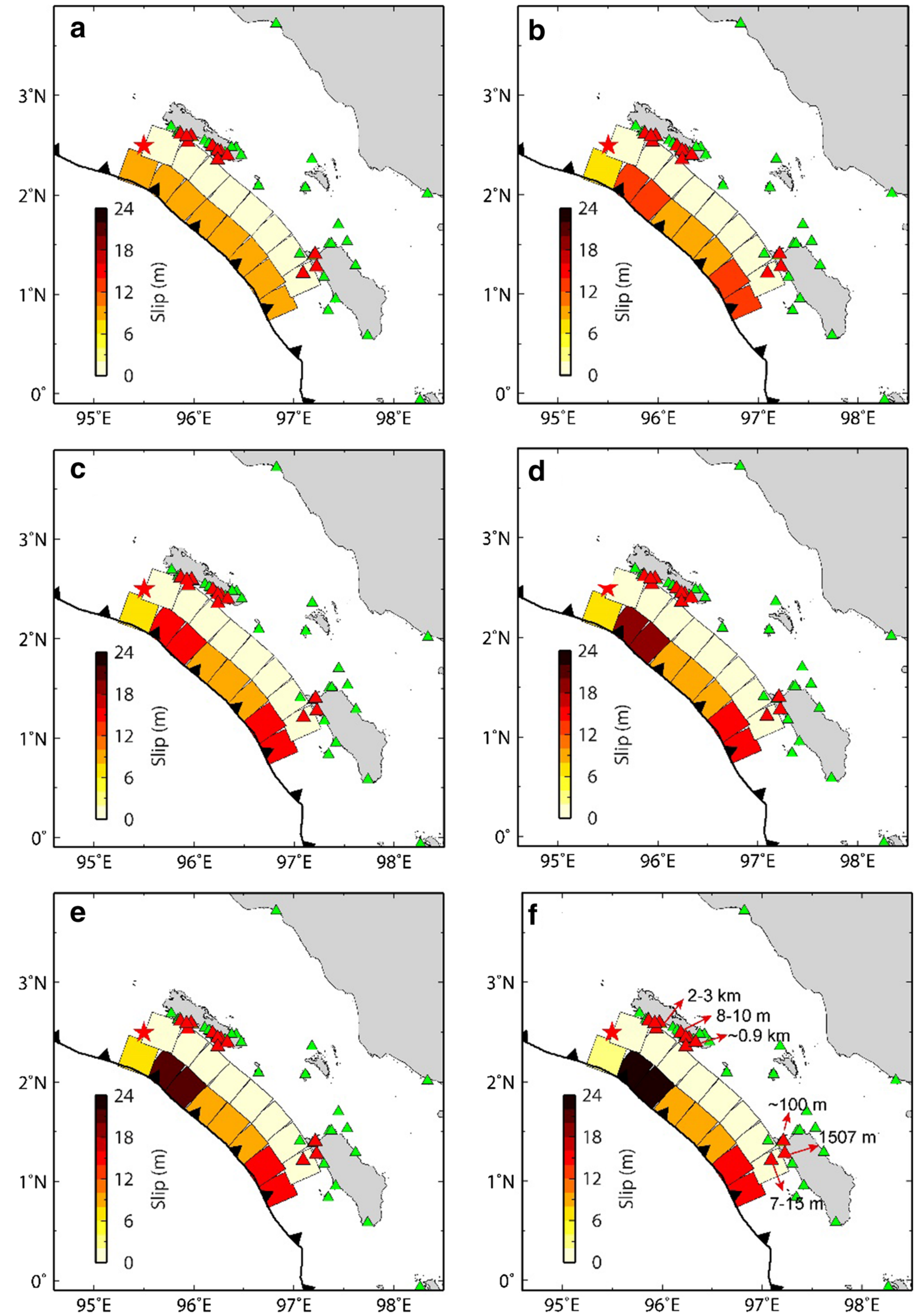


Figure 8

Hypothetical slip models utilized by us to reproduce the 1907 tsunami. Slip is initially assumed to be 9 m (**a**), but we increase this value incrementally to 24 m (**b**–**f**). Green triangles represent locations where the tsunami was reported, and red triangles represent locations used in the tsunami model (Table 5). Inundation distances estimated from documentary evidence are indicated in **f** with updip segments along the trench (from west to east) are **A** (light yellow), **B** (black), **C** (orange) and **D** (red) between 94.7°E and 97°E. In this general area, we then envision a number of scenarios for seismic rupture along the shallow updip plate interface of the Sunda Megathrust, which we divide into 16 elementary subfaults, themselves regrouped into four segments labeled A to D. The 16 patches, each measuring 30 km × 40 km, are distributed in updip–downdip pairs (Fig. 8), their exact geometry following Slab 1.0 (Hayes et al. 2012).

Given the slowness we have documented in the source of the 1907 earthquake, we use slip estimates departing from the classical scaling laws applicable to subduction events (Geller 1976; Blaser et al. 2010) and consider models with variable rigidity ($\mu$). We begin by assuming that the rupture was limited to the shallowest portion of the interface; conventional crustal material would feature a typical value $\mu = 3 \times 10^{11}$ dyn/cm$^2$, which using the moment $M_0 = 2.5 \times 10^{28}$ dyn cm obtained from mantle waves, would result in a slip ($\Delta u$) $\approx$ 7 m on each of the updip subfaults. We then model a tsunami earthquake by varying the rigidity on each segment between 0.7 and 2.0 × $10^{11}$ dyn/cm$^2$, which increases the slip to between 9 and 24 m (Fig. 8; S1–S6) in 3-m increments. These values of $\mu$ fall in the range proposed in the context of tsunami earthquakes by a number of investigators (Ide et al. 1993; Satake 1995; Bilek and Lay 1999; Geist and Bilek 2001; Hill et al. 2012; Li et al. 2015). For each of these models, we then compare the simulated tsunami amplitudes with those estimated from documentary material (Fig. 6).

Incidentally, the largest inferred slip in 1907 on the interface of the Sunda Megathrust coincides with a morphological high. As discussed previously, this feature has been associated with a region of strong coupling beneath central Simeulue (Tsang et al. 2015), and inferred as a structural control for local seismicity and for the rupture dimensions of modern earthquakes under central Simeulue (Sieh et al. 2006; Morgan et al. 2017). This pattern is very similar to that of other tsunami earthquakes and associates both event nucleation and the largest slip with the subduction of subsurface topography along strongly coupled interfaces (e.g., Tanioka et al. 1997; Abercrombie et al. 2001; Newman et al. 2011b; Bell et al. 2014). This remark is also supported by the jagged nature of the Omori waveform at Manila discussed above. Another morphological feature to the south in the vicinity of the Batu Islands (Natawidjaja et al. 2006; Fig. 1b) represents another barrier to rupture (Philibosian et al. 2014) and demarcates an important segment boundary on the Sunda Megathrust near the Batu Islands (Meltzner et al. 2015). The weaker tsunami amplitudes on southern Nias suggest that the 1907 rupture did not extend to the Batu Islands segment barrier or terminated in the neighborhood of this southern segment boundary near the likely rupture of a deadly tsunamigenic earthquake near the island of Simuk (Fig. 1b) to the south of Nias on 9 March 1861 (Reiche 1863). Since our rupture is only constrained by tsunami observations, further research would also be required to refine the western limit of the 1907 rupture in the region of the morphological high identified by Franke et al. (2008) and Tang et al. (2013), to determine whether the rupture stopped at, or propagated through, this segment boundary.

## 9. *Observed and Modeled Tsunami Impacts*

The tsunami impacts documented on Simeulue (Fig. 6a) were best replicated by more than 21 m of slip on segment B, which is our preferred rupture model (Fig. 9); For example, at Lakubang, the inundation distance is thought to have approached 3 km (Yogaswara and Yulianto 2006; Fig. 9b). At this location, despite slip greater than 21 m on segment B, the inundation remains underpredicted and we suspect that the inundation distance reported by Yogaswara and Yulianto (2006) is strongly controlled by local drainage that is known to allow tsunamis to travel much farther inland following the channels of natural and manmade drainage features (e.g., Mori et al. 2011). In the region of Nias to the south (Fig. 9c), we find that a slip of 15 m is required on segment D to reproduce the wave heights reported from Pulau Wunga (Fig. 9c). Our constraints on the amount of slip on segments A and C (Fig. 9) are weaker due to the lack of quantitative records from northern Simeulue and the Banyak Islands, respectively (Fig. 6a–c). However, we infer that the noticeable tsunami impacts on the west coast of Sumatra (Fig. 6c) such as the flooding at Susoh (Bataviaasch Nieuwsblad, 12 February 1907),

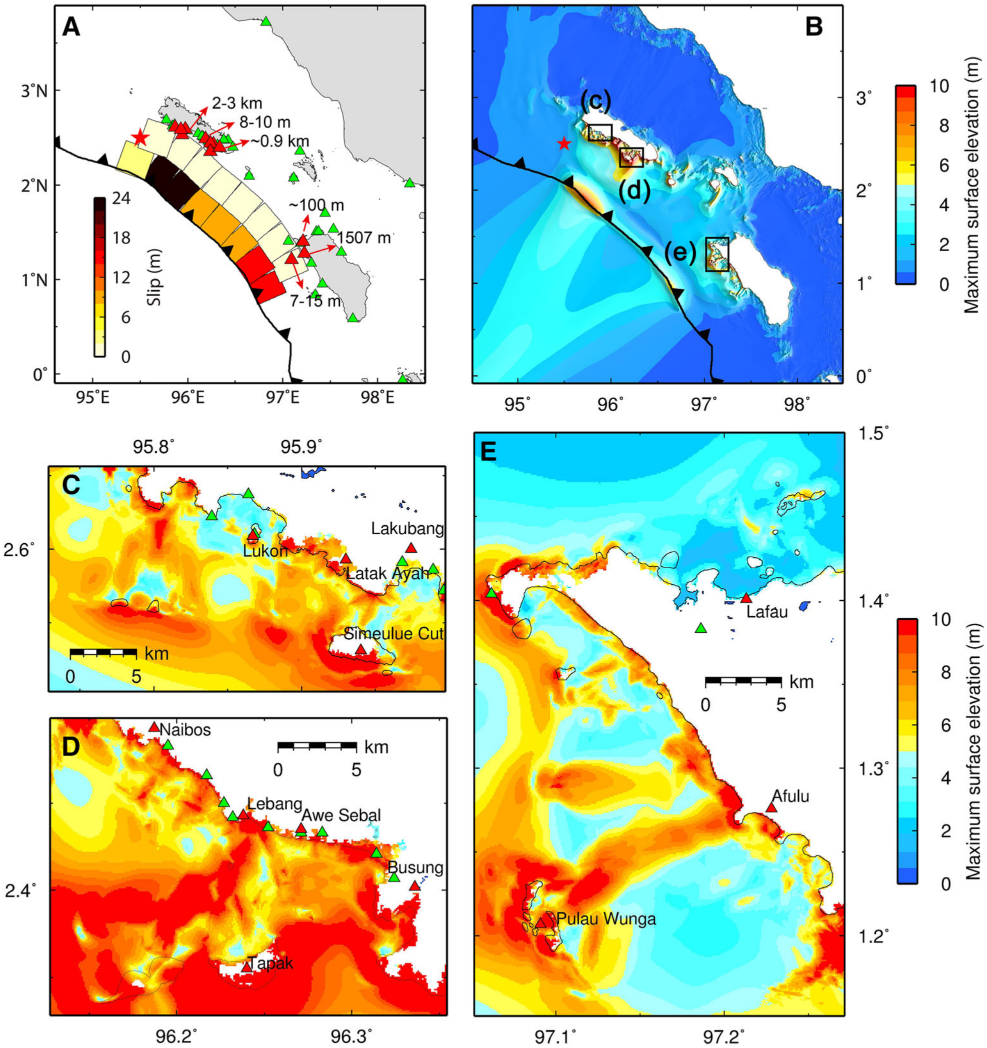


Figure 9
Hypothetical rupture geometry and slip parameters for the 1907 mainshock (**a**) estimated in this study off Simeulue (**c**, **d**) and Nias (**e**). Green triangles represent locations where the tsunami was reported (Table 5), and red triangles represent locations used in the tsunami model

Tapaktuan (Anonymous 1909), and possibly Kayu Menang (*Aceh Post*, 10 June 2013), are probably indicative of slip of 6–9 m on those segments.

In conclusion, our simulation experiments indicate that the values of runup and inundation estimated from the documentary material require seismic slips varying from 6–9 m on segments A and C to as much as 15 m on segment D, and probably more than 21 m on segment B. These values are greater, by factors ranging from 1.3 to 5, than expected under scaling laws (e.g., Geller 1976) for an earthquake of $M_0 = 2.5 \times 10^{28}$ dyn cm. This provides an additional argument for the anomalous properties of the 1907 event, and quantifies its character as a “tsunami earthquake”, as defined in Kanamori’s (1972) landmark study.

Our preferred rupture model satisfactorily predicts tsunami heights at all but one location, i.e., Afulu on Nias (Figs. 6b, 9b). We note that the modern village is located near a semicircular bay (Telok Afulu) opening to the south and sheltered on the west by a small island called Hulo Uma (1.251°N, 97.236°E); further, a review of topographic data (see “Data and Resources”) indicates steep relief (≥ 20 m) close to

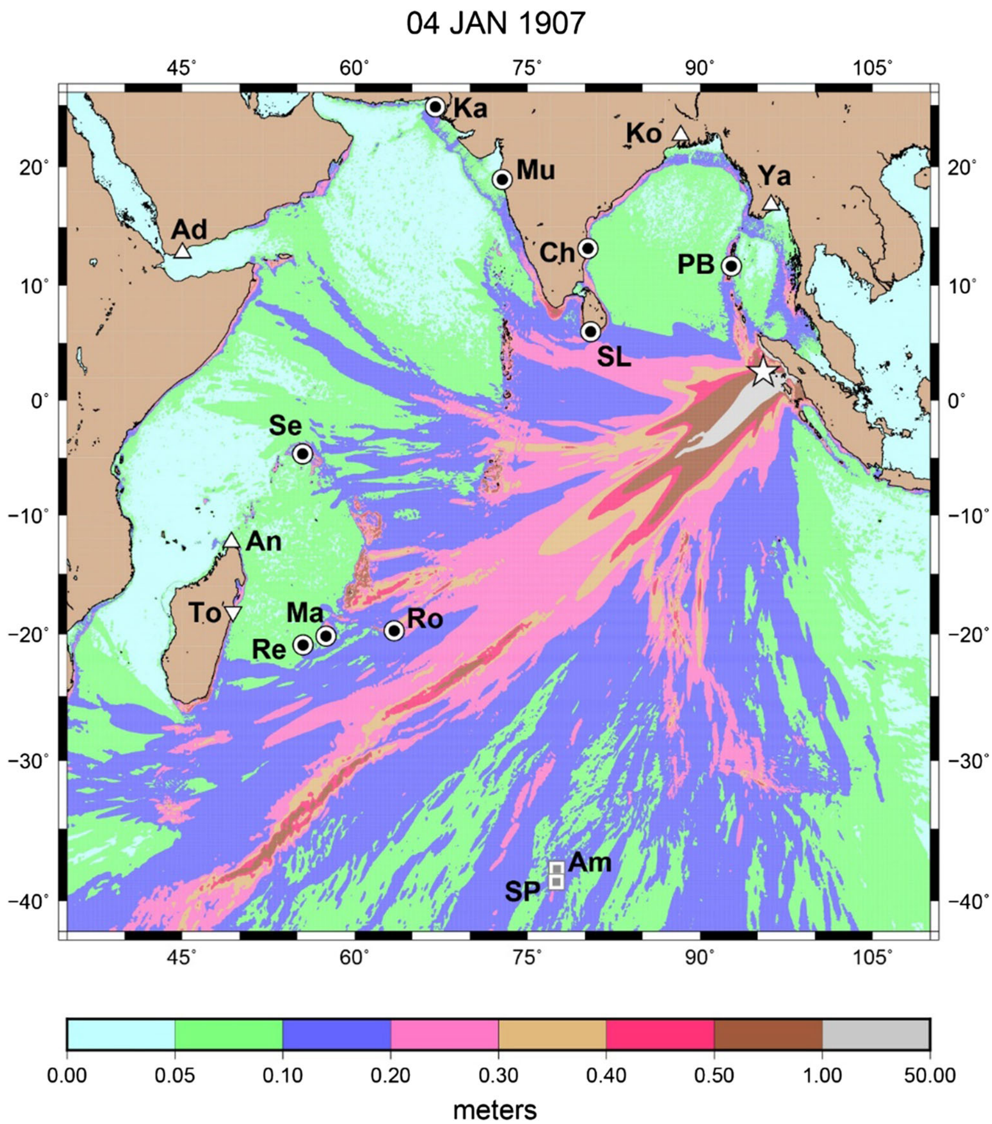


Figure 10

Maximum tsunami amplitude simulated in deep water using our preferred model of rupture for the 1907 mainshock, whose epicenter is shown as the large star. Locations with tsunami effects either instrumentally recorded or simply reported, are shown as black bull's eye symbols (Ka: Karachi; Mu: Mumbai; Ch: Chennai; SL: Sri Lanka; PB: Port Blair; Ro: Rodrigues; Se: Seychelles; Ma: Mauritius; Re: La Réunion). Instrumented locations not reporting the event are shown as open triangles (Ad: Aden; Ko: Kolkata; Ya: Yangon; An: Antsiranana/Diego Suarez). The port of Toamasina (Tamatave), Madagascar (To), discussed in the text, is shown as an inverted triangle. Amsterdam (Am) and Saint Paul (SP) islands, sites of questionable reports, are shown as grey-centered squares

the shore, and a drainage channel extending inland for $\sim 1$ km from the northwestern shore of Telok Afulu. Such features can cause highly localized amplification of tsunami waves (e.g., Shimozono et al. 2014), while a small island can also amplify tsunami waves in its lee, a scenario known as the "Babi effect" (e.g. Briggs et al. 1995). Localized extreme inundation could also be due to an aerial or subaerial landslide, possibly triggered by the snappier Event II (e.g., Tsuji et al. 1995; Pflaker 1997). We also cannot rule out the possibility of a separate, local tsunami caused by Event II, especially given the lack of arrival times in the accounts of the tsunami at Afulu.

Figure 10 contours the maximum amplitudes simulated in deep water (i.e., not including the interaction of the wave with coastlines) in the far field, throughout the Indian Ocean basin. As expected, our results are generally similar to previous simulations for scenarios of large earthquakes on the Sunda Megathrust, as presented, for example, by Okal et al. (2009), the main pattern being the combination of a major lobe of directivity in the direction perpendicular to the strike of the trench (Ben-Menahem and Rosenman 1972), and of the focusing effect of the shallow bathymetry along the Southwest Indian Ocean Ridge.

Owing to the limited nature of the available far-field reports, it is only possible to compare them qualitatively with our simulations. We first note that reports of the tsunami at Karachi and Mumbai, on the western coast of the Indian Subcontinent, are generally compatible with the development of a probable edge wave hugging the broad continental shelf present in the area, while the river port sites at Kolkata and Yangon, with no tsunami reported on existing tide gauges, appear relatively sheltered in our simulations. In the Southwest Indian Ocean, the Mascarene Islands (Seychelles, La Réunion, Rodrigues, and Mauritius) all feature deep-water amplitudes on the same order (20–30 cm) as simulated for the 2004 tsunami (Okal et al. 2006a). On the other hand, the Mascarene Plateau, arcing from La Réunion to the Seychelles, clearly screens the Mascarene Basin in its lee, thus protecting the northern half of Madagascar, and explaining the lack of tsunami reports from the maregraph at Diego-Suarez. This would also explain the lack of observations at Tamatave, which was already the main trading port of the island and whose activity was at the time well described in the local press. By contrast, stronger amplitudes, potentially comparable to those at the Mascarene Islands, would be expected on the southern part of Madagascar, the site of the highest runup values in 2004 (Okal et al. 2006b); the absence of reports in the press may reflect poor communications and possibly an ongoing state of insurgency. Finally, regarding the islands of Amsterdam and Saint Paul, deep-water amplitudes in the range of 0.2 m and an individual simulated value reaching 0.9 m within 5 km of the coast of Saint Paul would give some veracity to the report of an observable wave (Bertho 1910), but the presence of a settlement at the time on the island of Saint Paul remains unproven.

The value of maximum slip in our rupture model is obtained in the model of a simple planar rupture, but we also recognize the possibility of a complex rupture involving splay faults within the overlying accretionary wedge. Seismic reflection profiles indicate the presence of frontal folds and pop-up structures south (Franke et al. 2008) and west (Singh et al. 2008) of Simeulue. The relation between splay faults and unexpectedly large seafloor displacements has been numerically proven (e.g., Wendt et al. 2009) and proposed for other tsunami earthquakes (e.g., Fan et al. 2017). However, given the uncertainties in the near field associated with both quantifiable numeric observations, i.e., runup and inundation distances, as well as the largely unknown local arrival times of the tsunami, we restrict this study to a simple planar model. In conclusion, despite the largely qualitative nature of the available dataset of observations, simulations based on our preferred rupture model correctly predict the main features of the tsunami in the far field.

## *10. Discussion*

Our study resolves many unaddressed aspects of the 1907 Sumatra earthquake sequence but leaves unanswered the question of whether any subsidence was associated with this sequence. In this context, we note Hodgson's (1934) remark that "the south coast was partially submerged by an earthquake", which could be interpreted as coseismic subsidence (Meltzner et al. 2010, 2015) or as tsunami inundation, in the semantics of the 1930s. Reports from the southern coast of Simeulue are limited, and none of the available Dutch accounts mention land level changes associated with the 1907 earthquake, except in brief descriptions from Simeulue Cut (Haagsche Courant, 14 February 1907; Fig. 6a) and the Hinako Islands (Bataviaasch Nieuwsblad, 22 March 1907; Fig. 6b). We model subsidence (Figs. S7, S8) of $\leq$ 50 cm on Simeulue Cut and at the south coast of the island of Simeulue due to a dislocation in an elastic half-space (Okada 1985), and calculate even smaller values of subsidence ($\leq$ 15 cm) at the Hinako Islands. The accounts at our disposal do not state whether the writer visited the island of Simeulue Cut, viewed it from a distance, interviewed direct witnesses, or simply derived this information second-hand. If taken at face value, the description from Simeulue Cut might be inferred as coseismic subsidence or extreme tsunami erosion. The other perplexing detail comes from the Hinako Islands (Fig. 6b), where the seabed was reportedly exposed (uplifted?) for up to 2 h (Bataviaasch Nieuwsblad, 22 March 1907). Coral microatolls have been well studied on Simeulue and have contributed to our understanding of the rupture extents of great medieval earthquakes (Meltzner et al. 2015), as they are natural long-term indicators of changes in relative sea level, but these are often subject to preservation issues that can undermine temporal completeness (Meltzner et al. 2012). In this regard, and pertinent to our study, Meltzner et al. (2012) investigated a coral microatoll at Ujung Lambajo (LBJ; Fig. 1b) at a distance of $\sim$ 6 km northeast of Simeulue Cut but found that the paleorecord at this site only extended to 1955. Much further south, Meltzner et al. (2015) record the death of a microatoll (LAG-3B; Fig. 1b) near Lagundri on Nias and suggest this could either be related to the 1907 earthquake or had “nothing to do with tectonics or relative sea level (RSL) change”. Unlike the locations of many tsunami earthquakes that are devoid of offshore islands, Simeulue and Nias lie within 100 km of the trench axis and therefore increase the likelihood that the coseismic signature of land level changes from tsunami earthquakes could be recorded in the paleorecord of microatolls. It is also entirely plausible that the inferred land level changes on Simeulue Cut and the Hinako Islands are indicative of a rupture that extended further downdip than in our first-order model. Also, they could have been, both or independently, associated with the aftershock, or with postseismic after-slip; the alleged Hinako uplift (Bataviaasch Nieuwsblad, 22 March 1907) could have occurred concurrently with the death of a coral microatoll (LAG-3B) previously documented by Meltzner et al. (2015), and thus could possibly represent coseismic uplift from Event II. Bearing in mind the uncertainties in all of the above, we do not incorporate these in our rupture model but suggest that further work is required in this unique physiographic environment to uncover the paleorecord of previous tsunami earthquakes near Simeulue.

Owing to its size and location, the identification of the 1907 Sumatra earthquake as a tsunami earthquake has a number of implications which must be discussed in a global perspective. Table 6 compiles characteristics of 21 known such events, including estimates of seismic moments and, when available, of the slowness parameter $\Theta$ introduced by Newman and Okal (1998). At $M_0 = 2.5 \times 10^{28}$ dyn cm, the 1907 earthquake ranks as the third largest documented “tsunami earthquake”, after the 2004 Sumatra–Andaman earthquake and the 1946 Aleutian Islands earthquake. Note that the list in Table 6 may not be exhaustive since the origin of some historical destructive waves remains debated, such as the tsunami of 26 February 1902 in El Salvador (Cruz and Wyss 1983; Ambraseys and Adams 1996). Some evidence would also characterize the 1700 Cascadia megathrust event as a tsunami earthquake (Obermeier and Dickenson 2000; Okal 2011). We also speculate that the 16th century disaster on the south coast of Java relating to the Javanese and Sundanese legend of Ratu Kidul and recently interpreted as a tsunami based on surviving indigenous Babads and written Dutch sources (Reid 2014) could have been another tsunami earthquake, owing to the lack of reported shaking effects preserved in these materials. However, we emphasize that the brief nature of these documents warrants further work to confirm our assertions, as these could also be related to traditional earthquakes, seismically or gravitationally triggered turbidity currents, or meteorological phenomena. Paramount among remaining questions of primary importance is the relationship between PTEs and ATEs as defined by Okal and Saloor (2017) with traditional megathrust earthquakes, namely: (1) Does the distribution of PTEs bear a regional signal? (2) Does the occurrence of PTEs along a subduction zone rule out regular (and possibly larger) megathrust earthquakes? (3) Can a subduction zone be considered immune to tsunami earthquakes, either PTEs or ATEs?

A systematic study by Okal and Newman (2001) in the regions of the three 1990s PTEs (Nicaragua

Table 6

*List of documented tsunami earthquakes since 1896*

| # | Date (D M Y) | Region | Type* | Moment ($10^{27}$ dyn cm) | $\Theta$ | Notes |
|---|---|---|---|---|---|---|
| 1 | 15 June 1896 | Meiji Sanriku, Japan[a] | PTE | ~ 12 | NA | Tanioka and Satake (1996) |
| 2 | 4 January 1907 | Northern Sumatra | PTE | ~ 25 | −6.5? | This study |
| 3 | 13 April 1923 | Kamchatka | ATE (L) | 1.2 | | Saloor and Okal (2018) |
| 4 | 23 June 1932 | Manzanillo, Mexico | ATE | 5.2 | −6.18 | Okal and Borrero (2011) |
| 5 | 21 July 1934 | Santa Cruz Islands | ATE | 10 | −6.10 | Okal and Saloor (2017) |
| 6 | 1 April 1946 | Aleutian Islands[a] | PTE (L) | 85 | −7.03 | López and Okal (2006) |
| 7 | 25 March 1947 | Gisborne, New Zealand | PTE | 4 | −5.94 | Okal and Saloor (2017) |
| 8 | 17 May 1947 | Gisborne, New Zealand | [b] | 3 | −6.51 | Okal and Saloor (2017) |
| 9 | 20 November 1960 | Northern Peru | PTE | 2.7 | −6.13 | Okal and Newman (2001) |
| 10 | 20 October 1963 | Kuril Islands | ATE | 7.5 | −6.42 | Fukao (1979) |
| 11 | 13 August 1965 | Vanuatu | ATE | 2 | −5.88 | Okal and Saloor (2017) |
| 12 | 10 June 1975 | Nemuro-Oki, Japan | ATE | 0.8 | −6.43 | Fukao (1979) |
| 13 | 19 December 1982 | Tonga | PTE | 2.0 | −5.76 | Newman and Okal (1998) |
| 14 | 2 September 1992 | Masachapa, Nicaragua | PTE | 3.4 | −6.30 | Newman and Okal (1998) |
| 15 | 2 June 1994 | South of East Java | PTE | 5.3 | −6.01 | Newman and Okal (1998) |
| 16 | 21 February 1996 | Chimbote, Peru | PTE | 2.2 | −5.94 | Newman and Okal (1998) |
| 17 | 26 December 2004 | Sumatra–Andaman | PTE | 1200 | −6.40 | Stein and Okal (2007), Choy and Boatwright (2007) and Okal (2011) |
| 18 | 17 July 2006 | South of Central Java | PTE | 4.6 | −6.13 | Saloor and Okal (2018) |
| 19 | 25 October 2010 | Mentawai Islands | ATE | 6.8 | −6.22 | Saloor and Okal (2018) |
| 20 | 27 August 2012 | El Salvador | PTE | 1.3 | −6.42 | Saloor and Okal (2018) |
| 21 | 6 February 2013 | Santa Cruz Islands | PTE | 9.4 | −5.94 | Okal and Saloor (2017) |

**PTE* primary tsunami earthquake, *ATE* aftershock tsunami earthquake (Okal and Saloor 2017), *L* tsunami enhanced by ancillary landslide

[a]Charter events from Kanamori (1972)

[b]While #8 is smaller than its predecessor (#7), the moment ratio (3/4) is too close to qualify the second event as an aftershock of #7

1992, Java 1994, and northern Peru 1996) found no systematic trend for slowness in background seismicity but identified an older event in northern Peru in 1960 as a PTE, 340 km from the 1996 Chimbote source, thus suggesting a lateral coherence in the updip properties of the interface governing the occurrence of PTEs. Following their study, the 2006 Java earthquake provided a confirmation of this trend, occurring 580 km from the 1994 epicenter. Similarly, the 2012 El Salvador PTE occurred only 175 km from the site of the 1992 Nicaragua earthquake; should the 1902 event (Cruz and Wyss 1983; Ambraseys and Adams 1996) be confirmed as a PTE, then it would earmark a 350-km section of the Central American subduction zone as prone to PTEs. In this context, the 1907 event provides some limited new insight. It was indeed followed, 98 years later, by a slow megathrust earthquake, but the origin of their slow character may not be comparable: based on its location near the trench, the 1907 event's slowness was rooted in its shallow source, whereas in 2004, it emanated from a relatively slow and jagged propagation along its exceptionally long fault length (Ishii et al. 2005; de Groot-Hedlin 2005; Tolstoy and Bohnenstiehl 2005). More comparable are the events of 1907 and 2010, both of which took place along the shallowest, probably structurally similar, portions of the plate interface, and were separated laterally by 900 km. However, the 2010 Mentawai earthquake was clearly an ATE of the 2007 Bengkulu megathrust event, while the 1907 earthquake was primary: there is no concrete evidence in the known historical record for an immediately preceding mainshock which would have been significantly larger (Newcomb and McCann 1987).

Whether or not the occurrence of PTEs along a subduction zone rules out regular (and possibly larger) megathrust earthquakes is particularly critical along the south coast of Java, where two PTEs featuring very similar source characteristics took place in 1994 and 2006, and where no truly gigantic earthquake is known in the admittedly short historical record (Newcomb and McCann 1987). Our assertion would also apply to the Hikurangi subduction zone, off the North Island of New Zealand, where the historical record is even shorter and where the only large interplate thrust earthquakes since 1917 are the 1947 tsunami earthquakes (Doser and Webb 2003; Okal and Saloor 2017), although Cochran et al. (2006) inferred prehistoric tsunamis from an analysis of wetland sediment cores. Our assertion would also extend conceivably to Cascadia if indeed the 1700 event had a slow source. In this context, the proximity of the 1907 and 2005 epicenters would suggest a negative answer, namely that PTEs and regular megathrust events may occur along neighboring subduction segments (or even along the same one at different depths along the interface). Note that this conclusion might be supported by the case of the 1946 Aleutian PTE, in comparison to the nearby 1938 and 1957 megathrust earthquakes which did not exhibit source slowness, the former even generating a deceptively small tsunami (Stover and Coffmann 1993); however, this analogy remains tentative in the presence of the Shumagin gap between the 1946 and 1938 ruptures, where no large events are known since at least 1787 (Davies et al. 1981), which leaves the question of its potential for a PTE wide open until the next large earthquake fills it.

Tsunami earthquakes have not yet been documented in a number of subduction zones having produced large tsunamigenic earthquakes during the era of instrumental seismology (e.g., Southern Peru, Northern Chile, Makran), or during preinstrumental, historical times (e.g., Hellenic Arc, Ryukyu). A small-scale study in Vanuatu by Okal and Saloor (2017) documents a lateral, along-strike, variation of the slowness parameter $\Theta$, in conjunction with the subduction of submarine structures, on a scale of only a few hundred kilometers. The underestimation of the magnitudes of great earthquakes prior to instrumentation (Hough 2013), the largely random nature of the fragmentation of rupture at subduction zones (Ando 1975), and the gross temporal undersampling of tectonic cycles by modern seismology which resulted in unexpectedly large events such as the 2004 Sumatra–Andaman and 2011 Tohoku earthquakes, have led to the demise of otherwise promising paradigms (Stein and Okal 2007; McCaffrey 2007). Thus the only prudent answer to this question must remain negative. The 1907 earthquake provides no new insight, however, on whether any subduction zone can be considered immune to tsunami earthquakes, either PTEs or ATEs.

In the absence of definitive evidence of aseismic slip, tremor, or slow-slip earthquakes updip (Feng et al. 2015; Tsang et al. 2015), and based on newly modeled estimates of convergence of 46 mm year$^{-1}$ at 1°N, 96°E (Bradley et al. 2017), we believe that the rupture patch identified in this study could host a future $M_W \geq 7.7$ tsunami earthquake, updip and trenchward between the rupture patches of the 2004 and 2005 earthquakes with dimensions and physical properties similar to our preferred model (Fig. 8), and with lower than anticipated ground motions to elicit self-evacuation. We recall that, on Simeulue, the local legend of the S'mong associates strong earthquakes with tsunami hazard and elicits self-evacuation to high ground upon feeling strong shaking (McAdoo et al. 2006; Baumwoll 2008; Syafwina 2014), which turned out particularly effective in preventing heavy loss of life on Simeulue during the 2004 Sumatra–Andaman and 2005 Nias tsunamis, both preceded by damaging shaking (Martin 2005; McAdoo et al. 2006). It has been proposed (e.g., Syafwina 2014) that the S'mong is based on memories from 1907 preserved in verse or in stories passed down by older generations [we note, however, that Yogaswara and Yulianto (2006) record versions of the legend, both with and without severe shaking]. If so, the exact role played, in the S'mong legend, by the weak shaking due to Event I, and the presumably stronger one from Event II, remains unclear; at any rate, shaking from Event II, estimated to lag Event I by $\sim$ 53 min, may not have occurred before the tsunami attacked Simeulue; this is further suggested by E. Schröder's account of the second shock felt on Nias (located farther from Event I than Simeulue) after flooding by the tsunami (Bataviaasch Nieuwsblad, 22 March 1907). While the S'mong tradition may have saved many lives in 2004 and 2005, it is clear that it is not adapted to the particular challenge of tsunami earthquakes, as illustrated by the case of the 2010 Mentawai tsunami earthquake, 600 km southeast of Simeulue (Figs. 1, 3), a typical ATE following the 2007 Bengkulu megathrust earthquake. Some interviewed witnesses reported that the 2010 shaking on the Mentawai Islands was both weak and long, lasting as much as “several minutes” or was even not felt at some locations in the Pagai islands (Hill et al. 2012). This is an important observation, since source slowness is expected to both decrease high-frequency ground motion (and hence the level of shaking) and increase the duration of seismic wavetrains; the comparison of these two properties has been earmarked by Convers and Newman (2013) and Okal (2013) as a means of identifying tsunami earthquakes from the analysis of first-arriving P wave shapes. Yet, the ensuing 2010 tsunami attained runup heights of 17 m and killed more than 500 people. In this case, local villagers did not immediately evacuate as the shaking was weaker than during the seismologically much larger 2007 Bengkulu mainshock (Borrero et al. 2009) and during the 2009 intraplate Padang earthquake (McCloskey et al. 2010), both of which did not produce significant tsunamis in the Mentawai Islands. Accordingly, we end by reiterating the recommendation made by Hill et al. (2012) to include the duration of felt shaking as a warning for spontaneous evacuation, in a sense to implement a variant of Convers and Newman’s (2013) algorithm based on human perception. This constitutes a formidable challenge, since our experience gathered from a large number of post-tsunami surveys (e.g., Synolakis and Okal 2005) is that the perception of relatively short time durations (seconds, minutes) by lay individuals in a situation of emergency and panic is even less accurate than that of distance.

## *11. Conclusions*

The main conclusion of our study is the confirmation and quantification of the slowness of the 1907 mainshock (Event I), which we achieve from a broad range of seismological observations. By computing its seismic moment from the spectral amplitude of surface waves measured at mantle periods (up to 170 s), we obtain a value significantly greater (by a factor of about 4) than previously derived around 50 s by Kanamori et al. (2010). The identification of Event II, occurring only 53 min after the mainshock, clearly resolves the paradox of an event bearing many hallmarks of a “tsunami earthquake” but being felt at surprisingly high intensities. Although it must remain qualitative in the absence of instrumental metadata, the comparison of amplitudes and duration of body and surface waves at Manila clearly documents the difference in source properties between Events I and II, hence the slowness of the mainshock. We also propose a seismic rupture model which provides an acceptable fit to a new dataset of tsunami runup and inundation values from local and far-field locations in the Indian Ocean basin. Our preferred model extends from $\sim$ 94.7°E to $\sim$ 97°E along the Sunda Megathrust with as much as 21 m of slip. We also note that while the S’mong tradition may have prevented heavy loss of life on Simeulue in 2004 and 2005, both of which were preceded by severe shaking, it will be ineffective for future tsunami earthquakes that do not generate shaking violent enough to elicit societal concern, and in turn, to warrant spontaneous evacuations.

## *12. Data and Resources*

We present a list of all newspaper titles and dates consulted including libraries and online databases (free and subscription-based) where these are currently available (Online Appendix A) with transcriptions of selected newspaper reports in Online Appendix B. We consulted official mail reports (nos. 88, 91, 179, 202, 258, and 1134) which include telegrams sent by the Governor of Atjeh and the Resident at Tapanoeli to the Governor-General in Batavia (Jakarta). These are stored in the Openbaar Verbaal (23-05-1908, no. 11) for “Atjeh en Onderhorigheden” belonging to the collection “Ministerie van Koloniën: Politieke Verslagen en Berichten uit de Buitengewesten” (2.10.52.01), inventory number 16 at the National Archives of the Netherlands, The Hague. “Handelingen der Staten-Generaal” which contains the “Koloniaal Verslag” for 1907 and 1908 can be found via the Staten-Generaal Digitaal (https://www.statengeneraaldigital.nl/). Figures were created using freely available Generic Mapping Tools (Wessel and Smith 1991) and QGIS software (http://download.qgis.org/). Bathymetry was digitized for Nias and Simeulue from AMS T503 series maps (1:250,000; sheets NA 47-5, NA 47-8, NA 47-9, NA 47-13, NA 47-14, NA 46-8) available via the Perry-Castañeda Map Collection at the University of Texas at Austin (http://www.lib.utexas.edu/maps/ams/indonesia/, last accessed July 2017). We also used the General Bathymetric Chart of the Oceans (GEBCO) digital bathymetry dataset (http://www.gebco.net/, last accessed in October 2014). Digital topographic contours (1:5000) are available from Badan Informasi Geospasial (http://tanahair.indonesia.go.id; last accessed 27 November 2017). The topographic data used in the tsunami simulations are bare-ground Shuttle Radar Topography Mission (SRTM) data downloaded from https://data.bris.ac.uk/data/dataset/10tv0p32gizt01nh9edcjzd6wa (last accessed, April 2018). For some key locations including Lakubang, Lukon, and Simeulue Cut, we replace the SRTM data with 4-m-resolution digital terrain data purchased from the Nippon Telegraph and Telephone (NTT) Data Corporation. Topographic maps (1:50,000) prepared by the 653rd Topographic Engineering Battalion of the United States Air Force for Simeulue (Series HIND 605 Sheet 5; NLA shelf mark: MAP G8082.S5 s50) and by the British War Office for Nias (Series HIND 614 Sheet 9; NLA shelf mark: MAP G8082.N5 s50) were procured from the National Library of Australia (NLA).

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