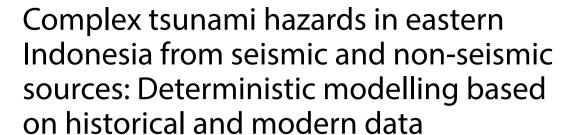
RESEARCH LETTER

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Abstract

Eastern Indonesia is one of the world's most complex regions in terms of tsunami hazards, as it accommodates numerous seismic and non-seismic tsunami sources with a history of deadly tsunamis. This study is an effort to enhance tsunami hazard knowledge in eastern Indonesia where limited data and analyses exist. We provide a brief understanding of eastern Indonesia's tsunami hazards by modelling selected deterministic tsunami scenarios from tectonic, submarine mass failure (SMF), and volcanic sources. To our knowledge, this is the first time that tsunami hazards modelling from such diverse sources in Indonesia has been performed. Our methodology is a deterministic tsunami hazard analysis considering credible tsunami sources from historical and contemporary data, modelling them using state-of-the-art simulation tools. We modelled two Mw7.8 tsunamigenic earthquake scenarios on the Flores back-arc thrust, one rupturing the basal fault (FBT-BF) and the other rupturing the splay fault (FBT-SF), showing that the two scenarios produce maximum tsunami amplitudes of \sim 5.3 m and \sim 4.2 m, respectively, which are comparable to the deadly 1992 Flores tsunami. We modelled potential SMF-generated tsunamis in the Makassar Strait with SMF volumes of 5 km³ and 225 km³ which yielded maximum tsunami heights of \sim 1.1 m and \sim 4.3 m along the eastern coast of Kalimantan Island and ~2.9 m and ~11.1 m along the west shore of Sulawesi Island, respectively. The 1871 Ruang volcanic tsunami is studied through existing historical documents and a source model is proposed comprising a flank collapse with volume of 0.10 km³. Such a source model successfully reproduced the 25 m runup reported in a historical account.

Keywords: Eastern Indonesia, Tsunami, Earthquake, Submarine mass failure, Volcano, Numerical simulations

Introduction

Because eastern Indonesia lies in a tectonically complex and seismically active region (e.g. Hamilton 1979; Milsom 2001; Nishimura and Suparka 1990) that is mostly covered by ocean, it accommodates a wide range of tsunamigenic sources—earthquake, submarine mass failure

(SMF), and volcanic (Fig. 1). Therefore, the region is regarded as subject to a high level of tsunami hazard (Horspool et al. 2014; Løvholt et al. 2012). Indonesia's tsunami hazard was the target of numerous studies following the 2004 Indian Ocean tsunami. However, the majority of these studies were focused on western Indonesia, from the Sumatra-Andaman to the southern Java subduction zones (e.g. Kennett and Cummins 2005; Muhammad et al. 2017; Mulia et al. 2019; Widiyantoro et al. 2020). Eastern Indonesia has experienced more historical tsunamis than the western Indonesia (Latief et al. 2000; Pranantyo 2020), but few tsunami hazard studies

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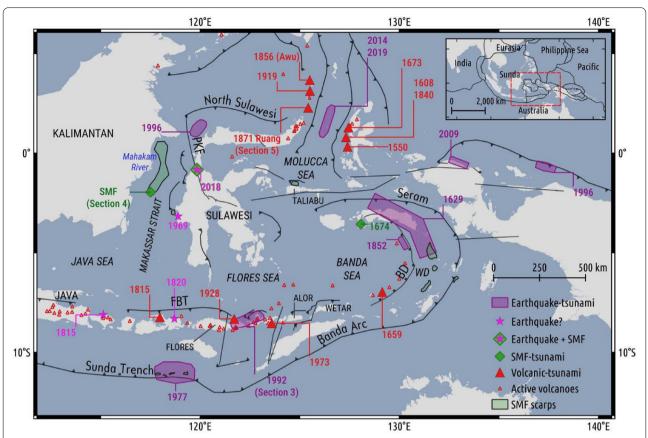


Fig. 1 Eastern Indonesia tectonic setting showing selected past major tsunamigenic events along with the type of the tsunamigenic source. Solid black lines show the tectonic plate boundaries of Bird (2003). Tsunamigenic sources are compiled from; earthquake-tsunami: Cummins et al. (2020); Gunawan et al. (2016); Gusman et al. (2009); Heidarzadeh et al. (2021); Liu and Harris (2013); Matsutomi et al. (2001); Pelinovsky et al. (1997); Pranantyo and Cummins (2019b); volcanic tsunamis are taken from Paris et al. (2013); SMF tsunami is from Pranantyo and Cummins (2019a), whereas SMF scarps are from Brune et al. (2009b, 2009a, 2010); Watkinson and Hall (2017); Pownall et al. (2016); Brackenridge et al. (2020) and Nugraha et al. (2020). FBT Flores Back-arc Thrust, BD Banda Detachment, PKF Palu-Koro Fault, WD Weber Deep, SMF Submarine Mass Failure

are available for this highly tsunamigenic zone (see, however, Cummins et al. 2020; Fisher and Harris 2016; Griffin et al. 2015; Liu and Harris 2013; Løvholt et al. 2012; Pranantyo and Cummins 2019a, b). While the majority of tsunami hazard studies in Indonesia were focused on tsunamis generated by megathrust earthquakes, two recent devastating tsunamis, in September 2018 (Palu) and December 2018 (Anak Krakatau), attracted attention to other types of tsunamis generated by SMFs and volcanoes, respectively (e.g. Grilli et al. 2019; Heidarzadeh et al. 2020; Liu et al. 2020; Mulia et al. 2020; Pakoksung et al. 2020; Takagi et al. 2019).

In recent years, there have been new findings on the seismotectonics of eastern Indonesia. For example, the Flores back-arc thrust (FBT in Fig. 1) was previously thought to consist of isolated segments of thrust faulting of the islands of Flores and Wetar (Silver et al. 1986). Recently, it has been recognized that it may extend all

along the southern margin of the Java Sea, from Alor in the east to eastern Java in the Java Sea to the west (Koulali et al. 2016; Pranantyo and Cummins 2019b; Supendi et al. 2020). Pownall et al. (2016) identified a major but previously unrecognised low-angle normal fault, called the Banda Detachment in the eastern part of the Banda Sea, which has formed a vast exposed scarp called the Weber Deep with massive SMF scarps along its margin (see BD and SMF scarps in Fig. 1). Watkinson and Hall (2017) compiled information on active faults that are likely to generate tsunamis in eastern Indonesia. Brackenridge et al. (2020) and Nugraha et al. (2020) identified evidence of SMFs in the Makassar Strait that may have generated large tsunamis (Fig. 1). Heidarzadeh et al. (2021) identified high potential for splay faulting in the Molucca Sea region. Such new data and findings in eastern Indonesia provide the opportunity to further develop the current understanding of regional tsunami hazards.

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In this research, we study the complex tsunami hazards posed in eastern Indonesia from seismic and non-seismic sources through numerical modelling. However, we did not intend to fully investigate all historical events. Rather, we focus on emphasising the diverse nature of tsunami sources in eastern Indonesia by investigating historical accounts and modern observations for selected events. We focussed on three regions, considering one type of tsunami source for each region. The reasons for choosing these three regions are twofold: these regions possess dominant tsunami hazards from a particular tsunami source, such as SMF or volcano; also, there are enough historical and modern data in these regions to enable our research and modelling efforts. First, we modelled two tsunamigenic earthquake scenarios from the FBT for the Flores Sea. Second, we assessed potential tsunami hazards in the Makassar Strait from SMF scenarios. Third, we studied the 1871 Ruang Volcano tsunami in the Molucca Sea.

Two main innovations of this research are that we consider tsunamis generated not only by earthquake but also by SMFs and volcano sources. Moreover, this is the first study for eastern Indonesia discussing tsunami hazards from SMF and volcano sources.

Data and methodologies

Tsunami sources

We considered three regions and one type of tsunami source (i.e. earthquake, SMF, or volcano) is assessed for each region. Coseismic earthquake deformation is calculated using the analytical dislocation formula of Okada (1985) which is then assumed to be equal to the initial sea surface displacement (Fig. 2a). We also included coseismic static deformation to the digital elevation model (DEM) that caused relatively small sea surface perturbations and might affect tsunami inundation (see Maumere tide gauge on Figs. 4c and 5, respecitively).

For SMF-tsunami modelling, we used the semi-empirical equations of Watts et al. (2005) to estimate maximum initial sea surface displacement (Fig. 2b). We assumed that the SMF has a Gaussian shape with submarine slump failure mechanism. This approach was successfully used in the past for modelling SMF tsunamis (e.g. Heidarzadeh and Satake 2017; Okal and Synolakis 2004; Synolakis et al. 2002; Tappin et al. 2008).

For the volcanic source, we assumed a flank collapse scenario to occur at Ruang Volcano. We estimated the initial tsunami wave by utilising a Gaussian displacement (Fig. 2c). We followed the approach by Heidarzadeh et al. (2020) that successfully reconstructed the December 2018 Anak Krakatau tsunami event. The details of all scenarios are given in Table 1 and are discussed in

more detail in Sects. "Flores back-arc thrust tsunami hazard", "Submarine mass failure in Makassar Strait", and "Tsunami generated by flank collapse of the 1871 Ruang Volcano".

Tsunami modelling

We used the JAGURS numerical package (Baba et al. 2015) to model tsunami propagation and coastal amplification. The code numerically solves the non-linear shallow water wave equations in 2D and in spherical coordinates. We utilised a nested grid domain comprising three levels of grids with various spatial resolutions for the Flores Sea and the Molucca Sea models (approximately 25 m to 450 m, Fig. 3). For the Makassar Strait, we used only a single grid with spatial model resolution of 225 m (Fig. 3). Simulations were conducted for a total time of 4 hours for each model. Given the availability of high-resolution topography, tsunami inundation modelling was performed only along the northern shore of Maumere, Flores Sea (Fig. 3).

As no high-resolution DEM is available for the Makassar Strait and the Molucca Sea models, we did not conduct inundation modelling. We therefore analysed maximum coastal tsunami amplitude. Rather than taking the offshore height then estimating the runup height using an amplification coefficient (e.g. Green's Law in Synolakis 1991), we directly extracted the maximum value at isobath 1 m depth, which is a reasonable representative of tsunami runup as per experience in tsunami modelling (e.g. Tinti et al. 2006; Satake et al. 2006).

The JAGURS code has been widely used to study and validate modern historical events, such as the 2011 Tohoku, Japan (Baba et al. 2015, 2017), the 2015 Illapel, Chile (Williamson et al. 2017), and the 1992 Flores, Indonesia (Pranantyo and Cummins 2019b) tsunamis. Moreover, the code was also used to investigate historical events prior to the instrumental period: the 1674 Ambon Island (Pranantyo and Cummins 2019a) and the 1852 Banda Sea (Cummins et al. 2020) events.

Digital elevation model

We prepared three sets of digital elevation models (DEMs, Fig. 3). First, we used the DEM of Pranantyo and Cummins (2019b) for the Flores Sea area. Pranantyo and Cummins (2019b) extended the DEM of Griffin et al. (2015) to the Palopo tide gauge, Sulawesi using a combination of data from a 90-m commercial nautical chart of TCarta Marine (https://www.tcarta.com), for depths shallower than 100 m, the General Bathymetric Chart of the Oceans (GEBCO, https://www.gebco.net), the 90-m Shuttle Radar Topography Mission (SRTM-90, https://srtm.csi.cgiar.org), and Airborne Interferometric Synthetic Aperture Radar - Digital Terrain Model (IFSAR

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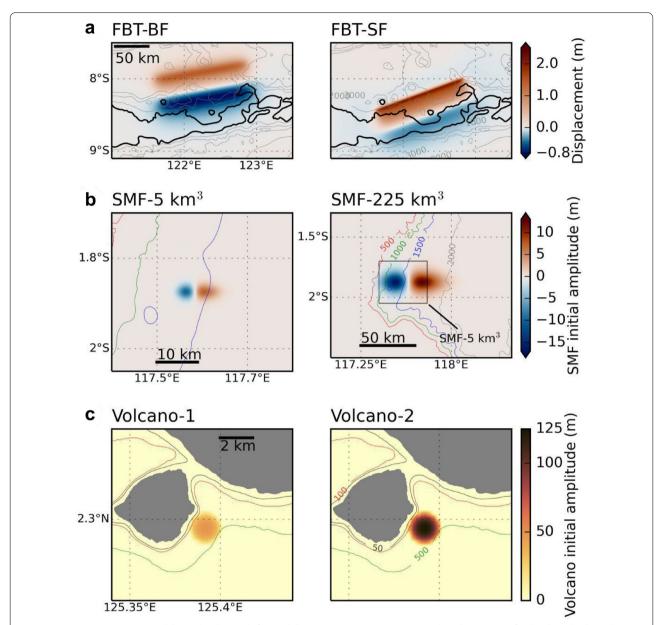


Fig. 2 Various tsunami source models used in this study for modelling tsunami scenarios. **a** Two earthquake scenarios for the Flores back-arc thrust basal fault (FBT-BT) and splay fault (FBT-SF). **b** Submarine mass failures (SMF) of volumes 5 km³ and 225 km³; black box shows location of SMF-5 km³ **c** Two volcano flank-collapse scenarios with volume of 0.10 km³ (Volcano-1) and 0.26 km³ (Volcano-2). Contours represent bathymetry depth in meters

DTM) around Mamuere, Flores (Fig. 3). Given the current shortage of high-resolution DEM available, application of IFSAR DTM is sufficient to produce preliminary understanding of tsunami inundation (Griffin et al. 2015).

For the DEMs of the Makssar Strait and the Molucca Sea, we combined the National Bathymetry grid (Batimetri Nasional), for depths greater than 500 m, contours of shallow coastal areas (Lembar Pantai Indonesia), and topography contours (Rupa Bumi Indonesia). These data are provided by the Government of Indonesia through the website: http://tides.big.go.id/DEMNAS and https://tanahair.indonesia.go.id (last accessed 11 September 2020). Then, we interpolated and resampled up to three different resolution levels (Fig. 3) using the surface module of the Generic Mapping Tools (Wessel et al. 2019).

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Table 1 Tsunami scenarios of earthquake, submarine mass failure, and volcano origins in eastern Indonesia

Scenario	Location	Source parameters	Coastal tsunami height
Earthquake-1: FBT-BF ^a	Top-right coordinate: 121.604°E and 8.011°S Depth = 10 km Strike = 80° Dip = 10°	Flores Sea Length = 140 km Width = 40 km Slip = 4 m Rake = 90° Mw = 7.8	$Max^e = 5.3 \text{ m}$ $Mean^e = 2.5 \text{ m}$
Earthquake-2: FBT-SF ^b	Top-right coordinate: 121.627°E and 8.535°S Depth = 2.7 km Strike = 70° Dip = 28°		$Max^e = 4.2 \text{ m}$ $Mean^e = 2.4 \text{ m}$
Submarine mass failure-1: SMF-5 km ³	Centroid = 117.610°E and 1.875°S Water depth = 1.5 km Slope = 12° Bulk density = 2300 kg/m ³ Slump failures mechanism	Length \times Width \times Thickness = 4.5 km \times 5 km \times 760 m Volume = 5 km ³ Travelled distance = 375 m	E Kalimantan ^f : Max = 1.1 m Mean = 0.1 m W Sulawesi: Max = 2.9 m Mean = 0.5 m
Submarine mass failure-2: SMF-225 km ³		Length \times Width \times Thickness $=$ 30 km \times 25 km \times 1000 m Volume $=$ 225 km ³ Travelled distance $=$ 2000 m	E Kalimantan ^f : Max = 4.3 m Mean = 0.8 m W Sulawesi: Max = 11.1 m Mean = 2.2 m
Volcano-1: 1871 Ruang ^c	Ruang Volcano, the Sangihe Islands, Molucca Sea Flank collapse at the eastern part	Radius = 2 km Volume = 0.1 km^3 Max amplitude = 50 m	Max = 28.0 m Mean = 18.4 m
Volcano-2: AK Type ^d		Radius = 2 km Volume = 0.26 km^3 Max amplitude = 125 m	Max = 54.2 m Mean = 35.3 m

 $[^]a$ Flores back-arc thrust from the basal fault; b Flores back-arc thrust from the splay fault;

Flores back-arc thrust tsunami hazard

The Flores Sea region, highlighted in Fig. 1, has a history of destructive tsunamis generated by SMF and volcanic activities as well as by earthquakes. The region experienced tsunamis in the past that have been documented in historical accounts, such as in 1815, 1818, 1820, and 1836 (Soloviev and Go 1974). However, the details of their generation mechanisms and source parameters are still unknown, as they occurred during the pre-instrumental era; only limited information can be obtained from the available historical accounts. In the modern era, the largest and most deadly tsunami was generated by the 1992 Mw7.8 Flores earthquake on the Flores back-arc thrust (FBT, Fig. 1). The detailed structure of the FBT is still poorly known, with past studies suggesting it consists of several segments as inferred from marine seismic data and historical events (Hamilton 1979; Koulali et al. 2016; McCaffrey and Nábělek 1984; Pranantyo and Cummins 2019b; Silver et al. 1983, 1986). Further, local tomography shows evidence of seismic velocity anomalies at shallow depth (<40 km) along the FBT that might be attributed to volcanic activity (Supendi et al. 2020). A similar anomaly was also seen on the west coast of Sumatra associated with a seamount that leads to earthquake segmentation along the Sumatra subduction zone (Singh et al. 2011).

Analysis of seismic and other data for the 1992 Flores (Pranantyo and Cummins 2019b), and the 2018 Lombok earthquakes that were also associated with the FBT, suggests two characteristics scenarios for large FBT earthquakes that differ in their tsunami-generating potential (Yang et al. 2020). One scenario, denoted here as FBT Basal Fault (FBT-BF), involves rupture confined to the basal fault and extending seaward toward the deformation front. The other scenario, denoted FBT Splay Fault (FBT-SF), involves rupture initiating on the basal fault at depth but diverting onto a more steeply dipping splay fault near the surface. FBT-SF earthquakes, such as the 2018 Lombok events, appear to be (Yang et al. 2020), ruptured beneath land and therefore generate relatively weak tsunamis. However, the 1992 Flores earthquake generated a large tsunami of 3-5 m height on the northern shore of Maumere (Tsuji et al. 1995), because it appears

 $^{^{\}rm c}$ Scenario for the 1871 Ruang Volcanic-tsunami event; $^{\rm d}$ The 2018 Anak Krakatau type scenario;

^e Between 121.6°E and 123.0°E on the northern shore of Flores Island;

^f By excluding coastal height at the Mangkalihat Peninsula

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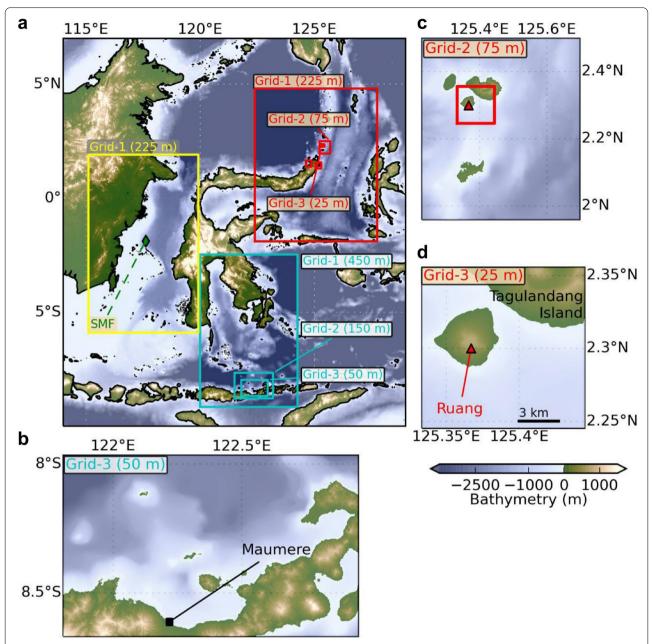


Fig. 3 Map of **a** digital elevation model (DEM) for tsunami modelling and its domain model. **b** DEM at Grid-3 for tsunamigenic earthquake scenario, **c** and **d** DEMs at Grid-2 and Grid-3 for the volcano-tsunami models, respectively

to resemble more an FBT-SF event that ruptures beneath the ocean.

Model set-up

Here we study the implications of the FBT-BF and the FBT-SF for tsunami hazards in the Flores Sea from two hypothetical earthquakes of Mw = 7.8 (Fig. 2a). Through a finite-fault source inversion study using teleseismic waveforms and coseismic displacement datasets,

Pranantyo and Cummins (2019b) reproduced an effective rupture model area of 140 km \times 40 km with two large-slip regions of up to \sim 20 m for the 1992 Flores earthquake and tsunami. The authors suggested that the best-fit dip and strike angles of the fault plane are 28° and 70°, respectively with the top depth of 2.7 km. We simplified this result into a homogeneous slip model of 4 m to represent the FBT-SF scenario. To create the FBT-BF scenario, the FBT-SF fault plane is shifted and rotated to

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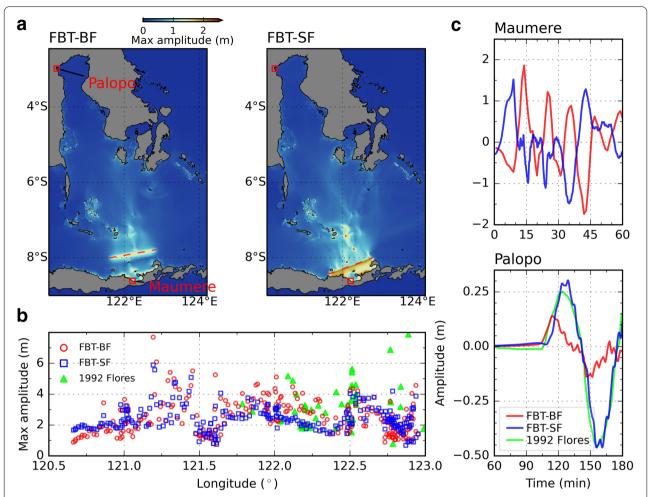


Fig. 4 Simulations of the tsunami generated in the Flores Sea from an Mw7.8 earthquake on the Flores back-arc thrust basal fault (FBT-BF) and splay fault (FBT-SF) scenarios. **a** Simulated maximum tsunami amplitude; the red dashed line shows top projection of the fault plane. **b** Coastal tsunami height along the northern shore of Flores Island at isobath 1 m. **c** Tsunami waveform at Maumere and Palopo gauges. Tsunami heights and waveform of the 1992 Flores event were obtained from Tsuji et al. (1995) and Hidayat et al. (1995), respectively

align with the plate boundary projection of Bird (2003). Then we used a gentle dip angle of 10° and the top depth is buried at 10 km depth. The complete source parameters of these two scenarios are given in Table 1.

Results and analysis

The FBT-BF scenario generates relatively larger tsunami heights along the northern shore of Maumere than the FBT-SF (Fig. 4). The maximum coastal tsunami height from the FBT-BF model is \sim 5.3 m whereas it is \sim 4.2 m for the FBT-SF. It appears that both scenarios produce relatively similar inundation distance, except at LOC-1 (Fig. 5). However, the maximum runup from the FBT-BF is somewhat higher than the FBT-SF. We note that the

coastal runup generated by the deadly 1992 Flores tsunami was 3–5 m (Tsuji et al. 1995, Fig. 4).

The FBT-BF model produces a high tsunami in the nearfield location Maumere (Figs. 4 and 5), because the majority of the deformation occurs in the sea and thus participates in generation of tsunami, whereas part of the FBT-SF coseismic deformation occurs on land where it does not contribute to tsunami generation. The effect these two deformation locations have on the tsunami inundation is clearly seen at LOC-1 (Fig. 5b). On the other hand, with the rupture occurring closer to the shoreline, the tsunami generated by the FBT-SF model arrives earlier in Maumere (Fig. 4c). Moreover, with a steeper dip angle, the FBT-SF generates higher tsunami with a shorter wavelength at Palopo compared to the FBT-BF (Fig. 4c). The FBT-BF might also occur at a

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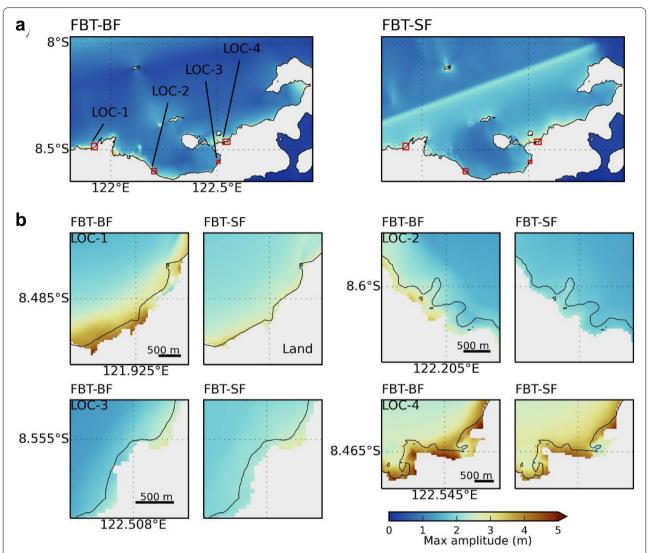


Fig. 5 Tsunami inundation result on the northern shore of Flores Island from the Flores back-arc thrust basal fault (FBT-BF) and splay fault (FBT-SF). a Maximum tsunami amplitude at the finest grid level; red boxes show locations of detailed inundation map shown in (b)

greater depth. In this case, the majority of the deformation would appear on land, which will reduce the tsunami hazard for the northern coast of Maumere. However, it would increase the seismic hazard for the island. The tsunami waveform resulting from the FBT-SF scenario at Palopo is comparable to the 1992 Flores event, after shifting the waveform by 8 minutes (discussed in Pranantyo and Cummins 2019b, Fig. 4).

Submarine mass failure in Makassar Strait

The Makassar Strait is located between the island of Kalimantan on stable continent crust, and the seismically-active island of Sulawesi (Fig. 1). Although all of the six tsunamis experienced in the Makassar Strait in the past

century have accompanied earthquakes near Sulawesi, the dominantly strike-slip fault regime suggests that at least some of these tsunamis were generated by earthquake-triggered SMFs (Prasetya et al. 2001; Takagi et al. 2019). Moreover, marine seismic reflection surveys have shown that SMFs have occurred offshore of Kalimantan at depths between 500 m and 1500 m with the largest estimated volume of $\sim\!600~{\rm km}^3$ located at the southeast of the Mahakam River (Brackenridge et al. 2020, Fig. 1). Another study revealed a SMF located southwest of Mamuju (Sulawesi) with a smaller aerial coverage of 150 km² at water depths between 1700 m and 1900 m (Nugraha et al. 2020, Fig. 1). It is not known whether these SMFs were due to a single failure or a series of

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failures. In terms of tsunamigenesis, frequent but smaller SMFs may lead to small or moderate tsunamis, while infrequent large SMFs could generate large tsunamis (Løvholt et al. 2015; Urgeles and Camerlenghi 2013). Here, we address the tsunami hazards from SMFs in the Makassar Strait by considering both a small and a large scenario.

Model set-up

It is not known whether the large SMF in the Makassar Strait reported by Brackenridge et al. (2020) occurred in a single event or a series of smaller failures, such as that during the 8200 BP Storegga Slide, Norway (Bryn et al. 2005). We therefore considered two SMF scenarios (Table 1).

The first scenario represents a small but frequent SMF. The SMF has a Gaussian shape with dimension of 4.5 km (length) \times 5 km (width) \times 760 m(thickness), resulting in a slide volume of 5 km³, with travel distance of 375 m, denoted here as SMF-5 km³. This scenario is comparable to the 1998 Papua New Guinea (PNG) event (Synolakis et al. 2002; Tappin et al. 2001; Watts et al. 2005). For the second scenario, we used a volume of 225 km³ (SMF-225 km³), about a third of the volume of the largest Makassar Strait SMF reported by Brackenridge et al. (2020) and moving as far as 2000 m. The SMF-225 km³ represents a large and infrequent scenario. These two SMFs are assumed to start at water depth of 1500 m with a slump failure mechanism. They are located in the southeast of the Mahakam River where the largest SMF was identified by Brackenridge et al. (2020).

Results and analysis

Tsunami modelling shows that SMF-225 km³ produces a larger tsunami than SMF-5 km³, as expected (Fig. 6). The maximum coastal amplitudes are \sim 1.1 m and \sim 4.3 m along the eastern coast of Kalimantan and ~2.9 m and ~11.1 m for the western shore of Sulawesi for the SMF-5 km³ and SMF-225 km³ scenarios, respectively. For comparison, the maximum coastal runup of the 1998 PNG event was up to 15 m (Synolakis et al. 2002; Tappin et al. 2001). Although a SMF as large as SMF-225 km³ might be expected to generate a higher tsunami than the 1998 PNG tsunami, we note that the maximum coastal amplitudes in these events are not directly comparable because of differences in bathymetry and coastline geometry between the two sites. The relatively smaller tsunami heights from the SMF-225 km³ tsunami in the Makassar Strait compared to the 1998 PNG event could be attributed to the bathymetry of the Makassar Strait. The SMF-225 km³ propagates across a wide (width=120 km) and shallow continental shelf (<500 m water depth) to reach the Kalimantan coast (Fig. 6a). Therefore, tsunami energy directed to the coast of Kalimantan dissipates fast as compared to the short source-to-shoreline distance (~20 km) and deep water (depth=50–2000 m) encountered by the 1998 PNG tsunami. We confirmed this by placing the SMF-5 km³ at a closer distance to the shoreline and noticed that the maximum tsunami height increases by a factor of four (Fig. 7a, d). The coastal geomorphology effect on tsunami heights is also seen at the Mangkalihat Peninsula (at ~1°N of northeast Kalimantan–Figs. 6 and 7). It focusses tsunami energy so that eastern Kalimantan has two amplitude maxima: the nearest shore to the SMF and at the Mangkalihat Peninsula.

Simulated tsunami waveforms at four locations are shown in Fig. 6b. It can be seen that the larger scenario generates maximum trough-to-crest wave heights of up to 7 m while the smaller SMF generates 0.5 m of wave height at Mamuju (MMJ, Fig. 6b). The waves generated by the smaller scenario are of much higher frequencies than those generated by the larger scenario. Tsunamis generated by SMFs typically have shorter wavelengths (higher frequencies) than those generated by earthquakes (Heidarzadeh et al. 2014). Because the SMF-5 km³ has a smaller size, it generates more high-frequency signals at all stations compared to SMF-225 km³ (Fig. 6b).

We note that we considered fixed values for the SMF dimensions and travel distance as well as neglected the kinematic process of the SMF-tsunami generation. These parameters would affect the initial sea surface produced from the semi-empirical equations of Watts et al. (2005). Understanding the possible ranges of these parameters and incorporating them in SMF-tsunami scenarios can be the subject of future studies.

Tsunami generated by flank collapse of the 1871 Ruang Volcano

The Molucca Sea region (Fig. 1) hosts a divergent double subduction zone with what is likely the highest concentration of active volcanic islands in the world. At least 17 such volcanoes are spread along the Sangihe Arc extending north from Sulawesi, and the Halmahera Arc, \sim 300 km to the east. While large earthquakes have generated destructive tsunamis in the Molucca Sea, historically the largest and deadliest tsunami was generated by volcanic activities (Latief et al. 2000; Paris et al. 2013). The 1871 eruption of Ruang volcano generated a tsunami that inundated the neighboring island of Tagulandang, penetrating 180 m inland with a runup of 25 m, and resulting in 400 deaths (Paris et al. 2013; Soloviev and Go 1974). Here, we develop a source model for the 1871 Ruang volcanic tsunami.

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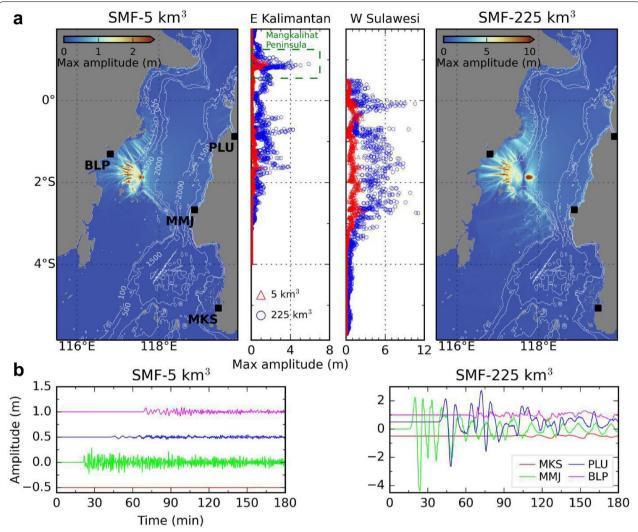


Fig. 6 Result of SMF-tsunami simulations in the Makassar Strait triggered by SMFs with volume of 5 km³ and 225 km³. **a** Maximum tsunami amplitude. **b** Simulated tsunami waveform at four virtual gauges: BLP (Balikpapan), MKS (Makassar), MMJ (Mamuju), PLU (Palu). SMF stands for Submarine Mass Failure

Historical accounts

According to Soloviev and Go (1974), enormous ground shaking, caused by the eruption of the Ruang Volcano, was felt on Tagulandang Island on 3 March 1871 (Fig. 8). Following the ground shaking, the south and west coasts of the island were inundated by sea waves that rose up to 25 m in height at the village of Haas (Fig. 8b). At least 400 people were killed. The tsunami generation mechanism and details of the tsunami source have not been studied previously.

Source analysis

A volcanic tsunami is a complex event which may involve multiple generation mechanisms, including pyroclastic flow, underwater explosion, caldera collapse, and flank collapse (Paris 2015). It appears that flank collapse is the most hazardous mechanism in volcanic tsunami generation, as demonstrated by the 1888 Ritter Island (e.g. Ward and Day 2003), and the 2018 Anak Krakatau (AK) volcanic tsunamis (e.g. Muhari et al. 2019; Putra et al. 2020; Heidarzadeh et al. 2020). At least six villages were destroyed in the 1888 Ritter Island event (Paris et al. 2013), and more than 400 deaths occurred in the 2018 AK event. Therefore, we assume a flank collapse mechanism for modelling the 1871 Ruang volcanic tsunami. By considering the location of historical reports of runup and examining the present-day aerial imagery of Ruang

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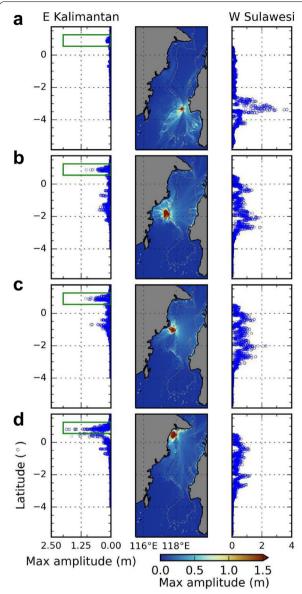


Fig. 7 Sensitivity study of the SMF distance from the coast when the SMF-5 km³ is moved from the south (**a**) to north (**d**) along the contour depth of 1,500 m. SMF stands for Submarine Mass Failure. Green box shows Mangkalihat Peninsula

Island, we assumed that a flank collapse occurred in the eastern side of the volcano (Figs. 2d, 8b).

By considering several initial tsunami source models with volumes in the range of $0.1{\text -}0.4\,\mathrm{km}^3$ and a trial-anderror approach, we found that a $^{\sim}0.1\,\mathrm{km}^3$ flank collapse, called the Volcano-1 scenario here (Table 1), is the best scenario to reproduce the tsunami height observed at Haas during the 1871 event (Fig. 8). The volcano source scenarios are static instantaneous sources which represent the status of the initial tsunami wave immidiately

after the generation phase. In this case, the complication of the generation phase is simplified. We consider a solitary-like wave as the initial wave which comprises only an elevation wave. The Volcano-1 scenario generates 15 to 25 m coastal tsunami height along the southern and western coast of Tagulandang (Fig. 8b, d). We note that the Volcano-2 scenario has the same initial length (2 km) and initial wave amplitude (125 m) as the 2018 AK tsunami model (Heidarzadeh et al. 2020). Fig. 8c-d reveal that an AK-type tsunami in the Ruang Volcano generates 30 to 35 m on the Haas coastline which is much larger than the historical record of 25 m (Fig. 8d). For comparison, the volume of the 2018 AK tsunami was estimated to be 0.175-0.326 km³ (Grilli et al. 2019; Heidarzadeh et al. 2020; Paris et al. 2020), while it is 0.1 km³ for our best source model of the 1871 Ruang volcanic tsunami (Volcano-1, Table 1). The tsunami waveform resulting from the Volcano-1 scenario also has a high-frequency signal

For validation of our modelling, we used the existing tsunami observation in Haas which involves only one observation point. In general tsunami simulation is validated using different data including historical runup data, paleotsunami studies, sensitivity analyses, historical tsunami waveform, and interviewing surviving eyewitnesses (e.g. Okal et al. 2002). For the 1871 event, the available observation data are very limited which limit our validation process. Future studies are encouraged to enhance tsunami modelling.

Discussion

Tsunamigenic sources in eastern Indonesia

In addition to the three potential tsunami sources discussed in the previous sections, we emphasise that there are numerous other potential tsunami sources in eastern Indonesia that we know little about. For example:

The Banda Detachment

The Banda Detachment is an extremely low-angle normal fault located above on the western side of the Banda Sea's Webber Deep, above the Banda slab (Pownall et al. 2016). It has not been considered as a major tsunami and seismic threat for eastern Indonesia until a recent investigation on the 1852 Banda Sea earthquake and tsunami by Cummins et al. (2020). Pownall et al. (2016) investigated the exposed structure of the detachment through geological field studies, supplemented by high-resolution multibeam bathymetry data. However, the detailed seismotectonics of the detachment beneath the Banda Islands are still poorly known.

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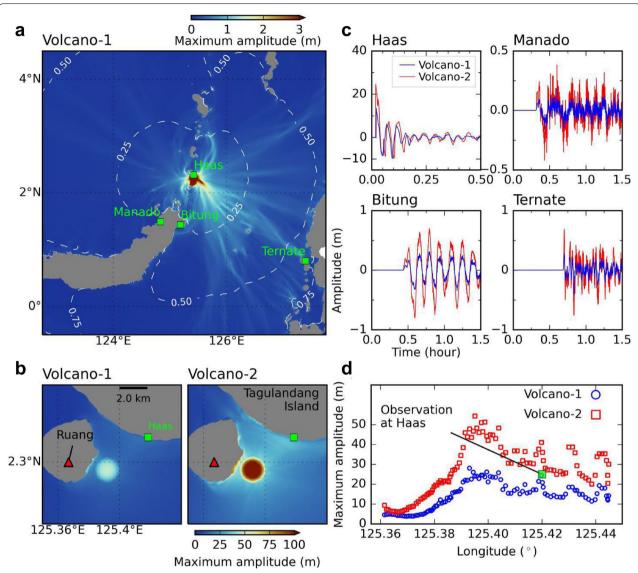


Fig. 8 Simulated tsunami heights from the 1871 Ruang Volcano eruption in the Molucca Sea, eastern Indonesia. **a** Maximum tsunami amplitude from Volcano-1 scenario with dashed white contours showing the tsunami travel times in hour. **b** Maximum tsunami amplitudes from Volcano-1 and Volcano-2 scenarios in the finest grid domain. **c** Tsunami waveforms at four locations shown in (**a**) and (**b**). **d** Maximum coastal tsunami amplitudes at along south coast of Tagulandang Island to validate the 1871 observation data

Potential SMF-induced tsunamis

SMF tsunami hazard is a complex process with large uncertainties regarding their locations, dimensions, mechanism, and occurrence probabilities (Grilli and Watts 2005; Harbitz et al. 2013; Løvholt et al. 2015; Watts et al. 2005). Some studies have been conducted for eastern Indonesia to identify past SMFs in the region; for example, Brune et al. (2009a, b, 2010); Pownall et al. (2016), and Watkinson and Hall (2017) used high-resolution bathymetry survey data to identify locations of underwater SMF scarps along the

Sunda Trench, the Banda Sea, and north of Taliabu Island, respectively (shown in Fig. 1). Brackenridge et al. (2020) and Nugraha et al. (2020) identified SMFs in the Makassar Strait from marine seismic data. Here, we modelled potential tsunamis from a few SMF scenarios in the Makassar Strait. More studies including probabilistic analyses and considering dynamic generation mechanisms are recommended to further address this topic.

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Volcanic tsunamis

With the presence of more than 130 active volcanoes in Indonesia (Katili 1975; Lavigne et al. 2008), this country is a hot spot for volcanic tsunamis. Awu volcano in Sulawesi, described in a recent study by Bani et al. (2020) as "among the deadliest volcanoes on Earth", generated a tsunami in 1856, which also has not been studied in terms of tsunami hazard (Fig. 1). To our knowledge, this study is the second volcanic tsunami study available for eastern Indonesia after Paris et al. (2013). Other historical volcanic tsunamis in this region from the 16th to 20th centuries have been listed by Latief et al. (2000) and Paris et al. (2013) (Fig. 1) and they are recommended to be subjects of further investigations.

Future works

More studies need to be done to better understand the tsunami hazard in eastern Indonesia. Our recommendations are:

Tsunami source reconstruction

To conduct comprehensive tsunami hazard assessment, understanding historical events, particularly their source mechanism is an important step to be taken. Tsunami catalogues, such as in the NGDC-NOAA, Latief et al. (2000), and Soloviev and Go (1974), do not neccesarily include detailed information for each event. For example, Pranantyo and Cummins (2019a) hypothesised a coastal landslide as the main source of the 1674 Ambon tsunami after re-analysing historical accounts. As another example, instead of the Tanimbar Trough megathrust earthquake (Fisher and Harris 2016), Cummins et al. (2020) suggested a moderate earthquake on the Banda Detachment triggered an SMF to generate the devastating 1852 Banda Sea tsunami event. With about two thirds of historical events occurring in eastern Indonesia (Pranantyo 2020), there are many events which are not studied in detail. Many historical events have occurred prior to the instrumental era; we encourage paleotsunami research to address this research gap. For example, Monecke et al. (2008) and Maselli et al. (2020) revealed a 1000-year old tsunami at northern Sumatra and East Africa, respectively. Rubin et al. (2017) found evidence for a 7,400 years old tsunami before the 2004 Indian Ocean tsunami in a paleotsunami study.

Probabilistic tsunami hazard assessment from multiple sources

The recent update of the national seismic hazard map of Indonesia (Irsyam et al. 2020) provides the basis to improve probabilistic tsunami hazard assessment (PTHA) for earthquake-generated tsunamis (see, e.g. Horspool et al. 2014). The non-seismic sources, discussed

in this study, can be adapted in the next generation of PTHA for Indonesia. Grezio et al. (2017) provides a framework to conduct a PTHA from multiple source types, which can be used as the first step.

Limitations and simplifications

Our numerical tsunami simulation is associated with some simplifications due to the complicated nature of tsunami generation from SMF and volcano sources. For example, we applied instantenous sources. Although such instantenous sources have been very helpful for tsunami hazard assessment and have provided reasonable and acceptable results, more advanced model including kinematic sources are encouraged to be applied in the future. However, such dynamic sources would require detailed DEM and knowledge on source dynamics which are currently unavailable.

Conclusion

Eastern Indonesia faces a complex tsunami hazard from seismic and non-seismic sources. We studied eastern Indonesia's diverse tsunami sources through modelling evidence-based credible scenarios based on historical and modern data from earthquakes, submarine mass failures (SMFs), and volcanic sources. Our main findings are:

- Volcanic and SMFs in eastern Indonesia are significant sources of tsunami hazard capable of generating tsunamis of scale and destructive potential similar to earthquake-generated tsunamis. They are discussed using historical accounts and modern observations and a map of areas at risk of tsunamis from SMFs is presented (see Fig. 1). We recommend potential tsunamis from SMFs and volcanoes to be included in any future tsunami hazard assessment for eastern Indonesia.
- As an example of tectonic tsunamis, we studied the Flores back-arc thrust (FBT) system by considering basal fault (FBT-BF) and splay fault (FBT-SF) possibilities. Two scenarios of Mw7.8 earthquakes on the FBT-BF and FBT-SF revealed that the maximum coastal tsunami heights are ~5.3 m and ~4.2 m, respectively. These results are comparable to the deadly 1992 Flores event.
- Modeling of two SMF tsunami scenarios in the Makassar Strait with volumes of 5 km^3 and 225 km^3 resulted in maximum coastal tsunami heights of $\sim 1.1 \text{ m}$ and $\sim 4.3 \text{ m}$, along the east coast of Kalimantan, and $\sim 2.9 \text{ m}$ and $\sim 11.1 \text{ m}$, along the west shore of Sulawesi, respectively.
- We studied the potential flank collapse responsible for the 1871 Ruang volcanic tsunami and proposed a source model for it through a trial-and-error

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approach. Our modelling showed that a flank collapse with volume of 0.1 km³ is capable of reproducing the 25 m tsunami runup height reported in historical accounts of inundation on Tagulandang Island.

We discussed several other locations in eastern Indonesia with potential for generation of seismic and non-seismic tsunamis. Further studies, including probabilistic assessments and their uncertainties, are required to provide a holistic understanding of complex tsunami hazards in eastern Indonesia and to further improve regional tsunami resilience.

Abbreviations

FBT: Flores back-arc thrust; FBT-BF: FBT basal fault; FBT-SF: FBT splay fault; SMF: Submarine mass failure; DEM: Digital elevation model.

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Authors' contributions

Conceptualization and draft preparation IRP, MH, PRC; Flores back-arc thrust tsunami hazard IRP, PRC; Submarine mass failure in Makassar Strait and Tsunami generated by ank collapse of the 1871 Ruang Volcano IRP, MH; Funding acquisition MH. All authors read and approved the final manuscript.

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Availability of data and materials

DEM for the Makassar Strait and Ruang Volcano cases were combined from Batimetri Nasional (https://tides.big.go.id/DEMNAS, last accessed 11 September 2020), Lembar Pantai and Indonesia and Rupa Bumi Indonesia (https://portal.ina-sdi.or.id/downloadaoi, last accessed 11 September 2020), whereas for the Flores Sea model was from Pranantyo and Cummins (2019b). DEM used in this study are available from the corresponding author on reasonable request. Tsunami modelling was conducted using the JAGURS software (https://github.com/jagurs-admin/jagurs, last accessed 11 September 2020).

Declarations

Competing interests

The authors declare that they have no competing interests.

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