

Age determination of paleotsunami sediments around Lombok Island, Indonesia, and identification of their possible tsunamigenic earthquakes

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Abstract Age determination of paleotsunami sediment from Lombok Island, Indonesia, and surrounding area has been carried out using the ^{210}Pb method in BATAN Jakarta. The basic theory of this method assumes that weathering of sediments, including paleotsunami sediments, will result in ^{210}Pb enrichment. The principle of this method is to calculate ^{210}Pb contents accumulation in a particular sedimentation interval from the surface to the deeper buried sediments. The results are then converted into age or depositional time in years ago unit. The dating results from the paleotsunami sediments of the Gawah Puduk ($8^{\circ}46'2.91''$, $115^{\circ}56'34.23''$) and Gili Trawangan areas ($8^{\circ}21'1.38''$, $116^{\circ}2'36.6''$) indicate the Gawah Puduk sediments were deposited 37 years ago (c. in 1977) and 22 years ago (c. in 1992). Three paleotsunami sediments from Gili Trawangan were deposited 149 years ago (c. in 1865), 117 years ago (c. in 1897) and 42 years ago (c. in 1972). These results are then compared to the available Indonesian earthquake catalogue data. This study reveals that paleotsunami sediments around Lombok Islands, from older to younger, were caused by the 1857 earthquake (epicentre in Bali Sea; $M7$; $8^{\circ}00'09.45''$, $115^{\circ}29'56.41''$), 1897 earthquake (epicentre in Flores Sea; $M5.5$; $8^{\circ}47'59.62''$, $120^{\circ}48'03.5''$ or Sulu Sea

earthquake; $M8.5$; 70 km NW of Basilan Island), the 1975 earthquake (Nusa Tenggara; $10^{\circ}6'16.61''$, $123^{\circ}48'09.39''$), 1977 earthquake (in Waingapu, Sumba; $M8.0$; $11^{\circ}5'39.34''$, $118^{\circ}27'50.86''$) and the 1992 earthquake (Flores; $M7.8$; $8^{\circ}28'52.11''$, $121^{\circ}53'44.3''$).

Keywords Age · Paleotsunami · Sediment · ^{210}Pb · Earthquake

1 Introduction

Currently, research on paleotsunami sediment is developing in Indonesia, especially since the events of tsunami 2004 in Aceh and tsunami 2006 in Pangandaran. The term paleotsunami sediments in this study is defined as a sedimentary deposits formed as a result of the tsunami that occurred before 50 years ago. This research was carried out along the coast of Lombok island; however, since the age of tsunami deposits that can be determined is limited, tsunami deposits derived from Gawah Puduk ($8^{\circ}46'2.91''$, $115^{\circ}56'34.23''$) and Gili Trawangan ($8^{\circ}21'1.38''$, $116^{\circ}2'36.6''$) were discussed (Fig. 1). Lombok Island has been selected for this research due to its flat beach morphologies in general; therefore, it is possible to obtain paleotsunami sediments. Lombok Island is also one of the most popular tourist destinations in Indonesia, so the research is necessary to be aware of the tsunami hazards in the future.

This paper discusses age determination of paleotsunami sediments found in the study area in order to determine the earthquake event that was related to the tsunami. The age determinations have been carried out using the ^{210}Pb method in BATAN Jakarta. The basic theory of this method assumes that the ^{210}Pb is enriched during the weathering of sediments including paleotsunami

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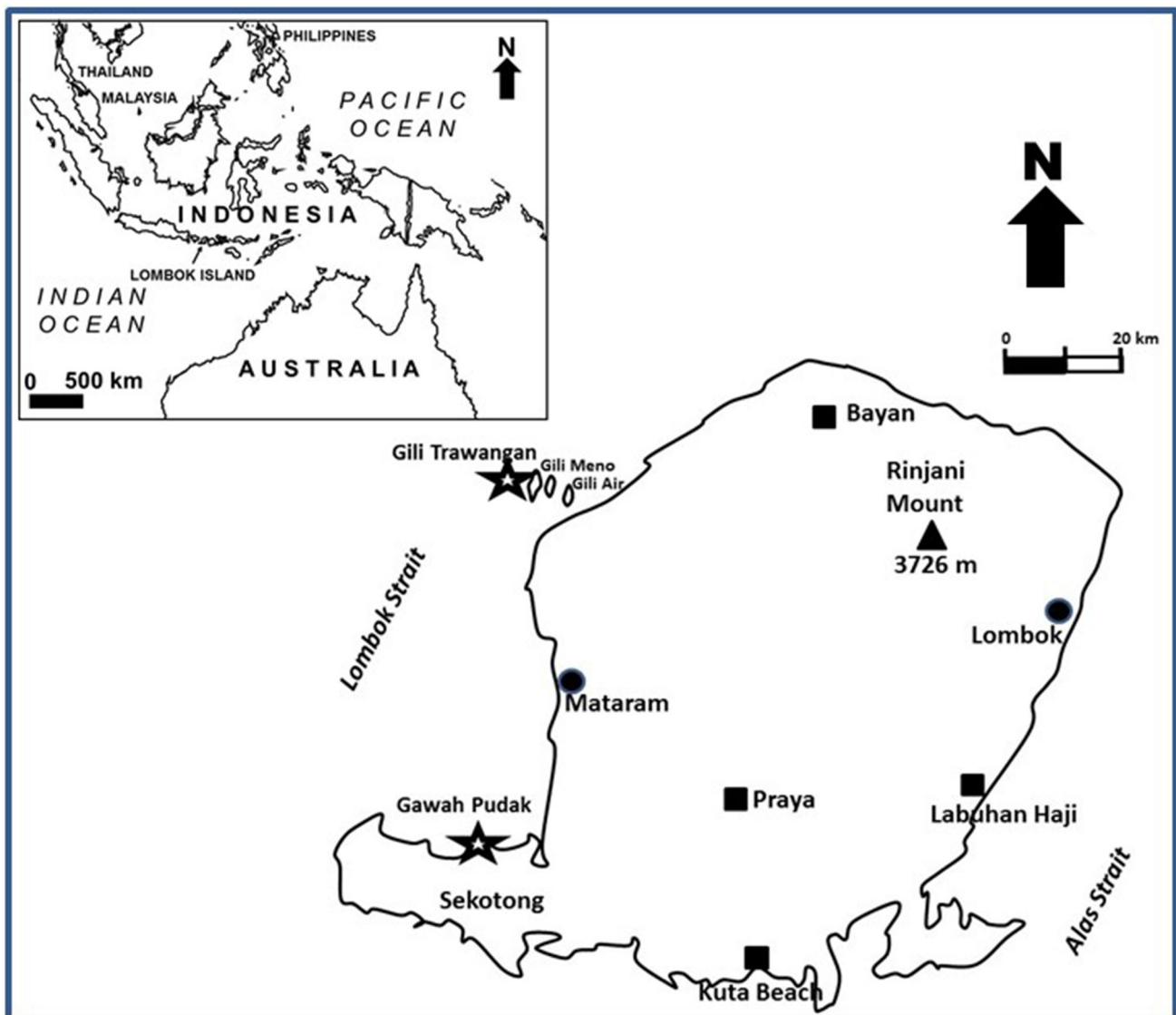


Fig. 1 Map showing observation and sampling locations (star signs; Gawah Pudak and Gili Trawangan) of the paleotsunami sediments in Lombok Island. The *star* is for sampling location, the *circle* is for big city, the *square* is for small city and the *triangle* is for volcano

sediments. The paleotsunami deposits in this study were deposited as a beach deposits from tidal to shallow marine environment. The principle of this method is to calculate the ^{210}Pb contents accumulation of any particular sedimentary interval and convert them into age or depositional time in years ago unit. The ^{210}Pb calculation starts from the surface and deeper buried sediments, respectively. Dating of these samples was carried out in 2014; therefore, the time unit refers to this year.

^{210}Pb analysis is preferred in this study because it is effective in determining the age of the sediments with a range of 30–150 years (Madsen et al. 2005; Boer et al. 2006). In addition to its age range, ^{210}Pb can detect abrupt sedimentation (Gelen et al. 2003) and the surface mixed layer (Boer et al. 2006) such as tsunami deposits. Natural ^{210}Pb is also more appropriate to be used in the study area

as it is considered to be far away from the nuclear activities, compared to the artificial ^{137}Cs method where ^{137}Cs origins from the nuclear explosion. Moreover, the ^{137}Cs method is not sensitive for abrupt sedimentation processes (Gelen et al. 2003) such as tsunami deposits.

By identifying the earthquake that deposited paleotsunami sediments, we will be able to know the magnitude of the earthquake and estimate the tsunamigenic cycle if two tsunami deposits are found in one particular location.

2 Methods

This study consists of three phases: field observation, laboratory test samples and data analysis. Shallow trenches in the area that potentially preserved paleotsunami deposits

were made during field observation stage. Trenches were made about 1.5 m × 1.5 m wide with a depth to groundwater about 1.5–2 m from the surface. The next step is sediment layers observation and to obtain sketch of the sediment layer sequence on the walls of each trench. Generally, paleotsunami sediments are relatively loose, light-coloured sandstone overlies on top of darker coloured of paleosoil layers (remnant former soil) such as surface soil (Yawsangratt et al. 2012; Rhodes et al. 2006). This is due to light-coloured sandy materials being brought from beach and shallow marine environments. Paleotsunami deposits are also characterized by massive fining-upwards and without sedimentary structure as they were deposited in a short interval. Rare parallel laminations are interpreted to occur only if there is a slower deposition during the backwash process. Tsunami deposit sedimentary structure characteristics are in contrast to storm or tidal deposit which generally consists of interbedded sandstones with foreset stratifications and planar stratifications with channel structures (Tuttle et al. 2004; Rhodes et al. 2006). Tsunami deposits also generally occur more towards landward than storm deposit (Tuttle et al. 2004).

Samples were obtained every 5-cm interval with the same volume. Each sample interval weight was 5 g. Sampling was performed starting from the surface level to the base of the trenches hole, including suspected paleotsunami sediments layers and paleosoil deposits. Each sample was separated for three laboratory analyses: faunal content analysis, grain size analysis and for ^{210}Pb age dating analysis. Faunal and grain size analysis was carried out to support the field observation to determine whether the analyzed sediment is paleotsunami sediment or not. The result of faunal analysis was used to determine depositional paleoenvironmental based on benthic foraminifers content according to Rauwenda et al. (1984). It was also used to determine whether there is mixing between shallow marine and deep marine faunal, while tsunami deposits usually contain a mixture between these two faunal kinds (Dahanayake and Kulasena 2008). Grain size analysis was carried out to understand the current system that deposited paleotsunami sediment in pursuance of Visher (1969) and to determine whether the sedimentation is influenced by one or more current systems while tsunami deposits are usually deposited by more than one current system (Yawsangratt et al. 2012). The ^{210}Pb analysis was conducted to identify the depositional age of the paleotsunami sediments. Several studies about sediment age determination based on ^{210}Pb analysis were successfully carried out by Sanches-Cabeza et al. (1999), Arman (2006), and Arman et al. (2007).

The natural ^{210}Pb in the sediment sample was measured with alpha spectrometer instrument. ^{210}Pb originated as decay product of ^{238}U present in soil and rocks. When Radon

gas is emitted into the air, unsupported ^{210}Pb is subsequently formed. ^{210}Pb binds with air particles, sinks to the earth surface and is deposited in the sediments. Conversion of ^{210}Pb to age and sedimentation is using simple models, namely Constant Flux and Constant Sedimentation (CF/CS), Constant Initial Concentration (CIC) or Constant Rate of Supply (CRS), depending on ^{210}Pb profile contained in the sediment (Sanches-Cabeza et al. 1999; Gelen et al. 2003; Madsen et al. 2005; Arman 2006; Boer et al. 2006; Arman et al. 2007). The ^{210}Pb CRS model with MARs factor was applied in this research to determine accurate ages of abruptly deposited sediments, such as tsunami deposits (Boer et al. 2006). To maintain data accuracy for ^{210}Pb measurement, samples were obtained systematically every 5-cm depth in the same volume. All samples were then wrapped in aluminium foil as soon as possible and stored in the plastic bag to avoid external contamination such as oxidation before directly sent to the laboratory.

Madsen et al. (2005) and Boer et al. (2006) proposed that representative maximum age for ^{210}Pb analysis is 150 years. The result from this study suggests that the oldest analyzed sample is not older than 150 years ago and thus the analyses results are representative for all the samples.

Using the absolute age of paleotsunami sediments obtained in the field, the tsunamigenic earthquake epicenter and its magnitude can be predicted. The epicenter and magnitude of the earthquake obtained from Indonesian earthquake catalogue were published by Masturyono et al. (2015) and Løvholt et al. (2012). The earthquake epicentral locations that interpreted to generate tsunami deposits on the Lombok Island are shown in Fig. 2. Tsunami cycle period on the Lombok Island and its surroundings could also be predicted based on data of time when the tsunami happened and the earthquake event related to it.

2.1 Paleotsunami sediments from Gawah Puduk (South Lombok)

This location is located on the river cliffs that are about 200 m from the beach in the Gawah Puduk village, South Lombok. Trenching was carried out at the river edge cliff and signed some sediment layers which are suspected as paleotsunami sediments (Fig. 3); they are: layer 3 located above beach deposit (layer 2) and layer 5 which overlies on the top paleosoil layer (layer 4). During field observation, micromollusc fragments were found in the paleotsunami suspect layers (layer 3 and 5). Some hand specimens as well as PVC tube core samples were also taken.

2.2 Paleotsunami sediments from Gili Trawangan

From the trenches (1.2 m deep) that were dug in the Gili Trawangan Mosque courtyard, fifteen sediments layers

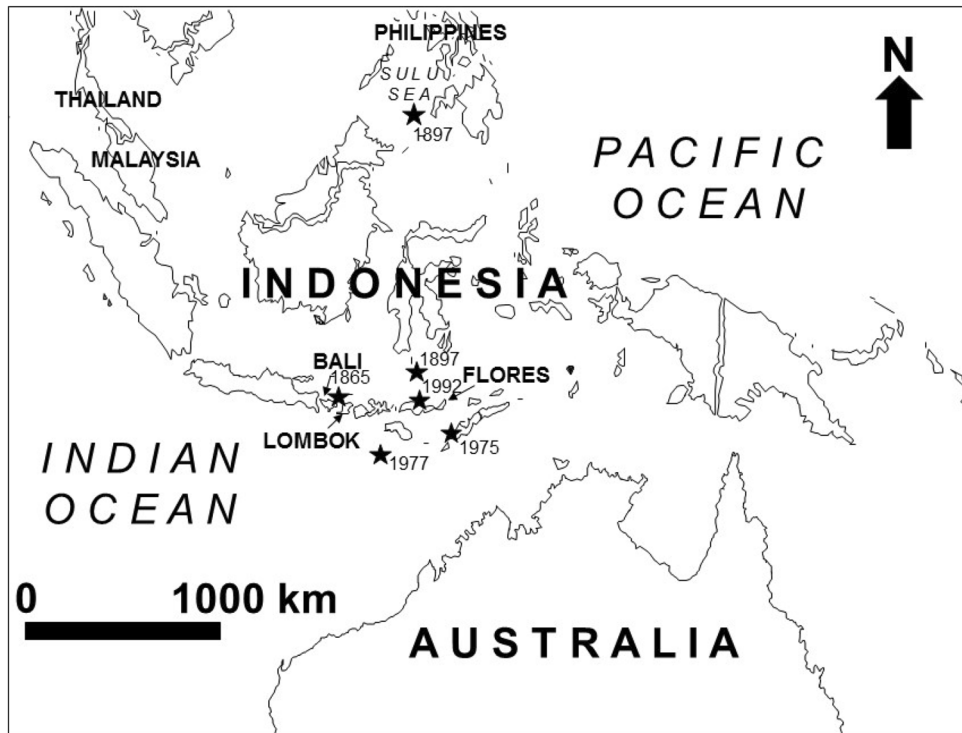


Fig. 2 Earthquake epicentral locations that generated tsunami deposits on the Lombok Island [star signs; data compiled from Løvholt et al. (2012), Masturyono et al. (2015)]

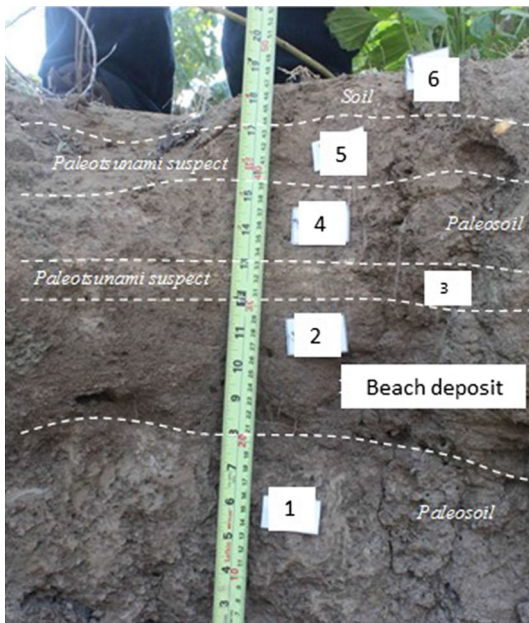


Fig. 3 Stratigraphy of the Gawah Pudak trench, South Lombok

with different thicknesses can be observed (Fig. 4). From fifteen layers which were observed, only three layers interpreted as paleotsunami sediments, i.e., layer 2, layer 5 and layer 10. These layers are light grey to brown fine sandstone, not calcareous, suspected paleotsunami



Fig. 4 Stratigraphy of the Gili Trawangan trench. Each red/white interval on the stick is 10 cm

Table 1 ^{210}Pb age analysis of Gawah Pudak sediments

Layer	Age	Explanation
6	2014	Soil (light brown clay)
5	1992	Tsunami Sediments (light grey loose sandstone) as product of 1992 earthquake, Flores, <i>M7.8</i> ; $S8^{\circ}28'52.11''$, $E121^{\circ}53'44.3''$
4	1984	Paleosoil (dark brown clay)
3	1977	Tsunami Sediments (light yellow loose sandstone with rip-up clast) as product of 1977 earthquake, Waingapu, <i>M8.0</i> ; $S11^{\circ}5'39.34''$, $E118^{\circ}27'50.86''$
2	1968	Beach Deposit/River (dark brown loose sandstone)
1	?	Paleosoil (light grey clay)

sediments, each overlies on top coarse sandstone layers (layers 1, 4 and 9).

3 Discussion

3.1 Gawah Pudak

Layer 3 which overlies on top beach deposit of layer 2 is loose, fine to medium light brown sandstone. Layer 5 is calcareous, loose, light brown fine to medium sandstone, overlying dark brown silty clay of paleosoil layer. Faunal analysis suggests that this layer contains *Acteocina* sp.

(micro molluscs shell) usually found at the depth of 3 m and *Alveolina* sp. usually found at 35–50-m depth and others broken shells of Pelecypods molluscs which are also the indicator of tsunami deposit (Tuttle et al. 2004). Grain size analysis result indicates a mixture of poor-sorting fine to coarse grains as turbulent high-energy currents sediment. Faunal and grain size analyses confirm layer 5 as paleo-tsunami sediments as it is shown by the current turbulence which brings mixed material from deep and shallow marine. Age dating analysis of ^{210}Pb reveals that layer 5 was deposited in 1992, most likely as a result of tsunami caused by *M7.8* earthquake on 12 December 1992 in the Flores Sea ($S8^{\circ}28'52.11''$, $E121^{\circ}53'44.3''$).

From samples in Gawah Pudak site, paleotsunami deposits in layer number 3 and 5 (Fig. 3) were deposited in 37 and 22 years ago, respectively. Each of these paleo-tsunami sediment ages when converted into years from old to young is 1977 and 1992, respectively. The 1977 paleo-tsunami deposit was triggered by the 19 August 1977 earthquake that occurred in Waingapu, Sumba (*M8.0*; $S11^{\circ}5'39.34''$, $E118^{\circ}27'50.86''$; Fig. 2; Table 1).

3.2 Gili Trawangan

In this location, faunal and grain size analyses were carried out on hand specimen from two paleotsunami sediment suspect layers (layer 5 and layer 10; Fig. 4). The faunal

Table 2 ^{210}Pb age analysis of Gili Trawangan sediments

Layer	Age	Explanation
15	2014	Thin weathered sediments
14	2014	Light brown clayey soil
13	2007	Volcanic Tuff
12	1988	Fine sand beach deposit
11	1979	Volcanic coarse sand
10	1972	Tsunami sediment (light brown coarse sand with pumice fragment) as product of 1975 earthquake, Nusa Tenggara ($S10^{\circ}6'16.61''$, $E123^{\circ}48'09.39''$) or as product of 1977 earthquake, Waingapu, <i>M8.0</i> ($S11^{\circ}5'39.34''$, $E118^{\circ}27'50.86''$)
9	1970	Tuff and pumice
8	1967	Beach deposit fine sand
7	1965	Calcareous beach deposit fine sand
6	1918	Calcareous sandstone
5	1897	Tsunami Sediment (calcareous coarse sand with pumice fragments) as product of 1897 earthquake, Flores Sea earthquake, <i>M5.5</i> $S6^{\circ}47'59.62''$, $E120^{\circ}48'03.5''$) or Sulu Sea earthquake (<i>M8.5</i> ; 70 km NW of Basilan Island)
4	1889	Paleosoil, dark brown silt
3	1882	Carbonaceous medium to coarse sandstone
2	1865	Tsunami Sediment (white loose sandstone with coral fragment) as product of 1857 earthquake in Bali Sea <i>M7.0</i> ; $S8^{\circ}00'09.45''$, $E115^{\circ}29'56.41''$
1	Older than 1865 (?)	White coarse sand beach deposit, calcareous, contains coral and shell fragments

analysis shows that sample from layer 5 contains some macrofaunal, such as *Alveolina quoyii* (which usually find at 40–60 m depth), *Pseudorotalia* sp. (5–10 m), *Ammonia* sp. (0–5 m), *Alvania arubensis* (micromollusc), and coral fragments. Based on microfaunal content, layer 5 is concluded as paleotsunami sediment that brought material from different depths up to 60 m mixed with shallow marine fauna. Layer 10 contains no microfaunal fossil (barren). Grain size analysis of layer 3, 5 and 10 sediment samples suggests a combination of poor-sorting, medium to very coarse grains. This grain size mixture is interpreted as a result of initial current which deposited fine to medium grain which was then mixed with coarse material brought by backwash current. This current reverse is likely to occur by the current caused by tsunami.

^{210}Pb analysis (Table 2). Age determination based on ^{210}Pb analysis for three paleotsunami deposit layers from Gili Trawangan is 149 years ago for layer no. 2, 117 years ago for layer no. 5, and 42 years ago for layer no. 10. Each of these paleotsunami sediment ages when converted into years from old to young is 1865, 1897 and 1972, respectively.

Layer 2 was deposited 149 years ago, related to the Bali Sea earthquake ($M7.0$; $S8^{\circ}00'09.45''$, $E115^{\circ}29'56.41''$). Layer 5 was deposited in 1897 and interpreted as a result of Flores Sea earthquake ($M5.5$; $S6^{\circ}47'59.62''$, $E120^{\circ}48'03.5''$) or Sulu Sea earthquake ($M8.5$; 70 km NW of Basilan Island) in 1897, while layer 10 was deposited 42 years ago and probably associated with 1977 Waingapu–Sumba earthquake in 1977 ($M8.0$; $S11^{\circ}5'39.34''$, $E118^{\circ}27'50.86''$; Fig. 2).

4 Conclusions

The results of age determination by ^{210}Pb method indicate that paleotsunami sediments from Gawah Pudak were deposited in c. 1977 and c. 1992. The three paleotsunami sediments from Gili Trawangan were deposited in c. 1865, c. 1897 and c. 1972. This age determination reveals that paleotsunami sediments from the Lombok Island and its surroundings, from older to younger, were caused by the 1857 earthquake (epicenter in Bali Sea; $M7$), 1897 earthquake (epicenter in Flores Sea; $M5.5$ Richter Scale or Sulu Sea earthquake; $M8.5$ where the epicenter was 70 km NW of Basilan Island), the 1975 earthquake (Nusa Tenggara), 1977 earthquake (in Waingapu, Sumba; $M8.0$) and the 1992 earthquake (Flores; $M7.8$).

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