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Late Miocene to Pliocene Tsunami Deposits in Tegal Buleud, South Sukabumi, West Java, Indonesia

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Abstract

Java is a volcanic island arc formed by the northwards subduction of the Eurasian and Australian Plates. Due to this active subduction, Java has been frequently shocked by earthquakes, which might induce tsunami events. However, there are hardly any ancient geological records of tsunami events in the area. This study aims to determine the presence and to identify sedimentary characters of tsunami deposit in Tegal Buleud, South Sukabumi, West Java. In the study area, there were 4 tsunami layers which were found as thin intercalation within the claystone layer of the Bentang Formation. Those paleotsunami deposits characterized by the occurrence of irregular/disturbed structure such as siltstone rip up, clay clasts, and flame structure occur in normal graded bedding sandstone layer. The grain-size distributions show bimodal and multimodal patterns, with mixing of marine microfossils from inner and middle neritic. The planktonic foraminiferal assemblage indicates that the age of the sediment comparable to N19 (equivalent to Late Miocene - Early Pliocene, at about 5.33 – 3.6 Ma), suggested that these paleotsunami layers were deposited due to the Mio-Pliocene tectonic activity. All the paleotsunami deposits found in Study area are the first and oldest tsunami deposit recorded in Java even in Indonesia. With the discovery of the previously unexplored Late Miocene to Pliocene tsunami deposits found in the study area, the result of this study can be used as a reference for the identification of the Tertiary tsunami deposits present in other parts of Indonesia.

Keywords: pleotsunami, late miocene to pliocene, Tegal Buleud, west Java, Indonesia

1. Introduction

The Indonesian Archipelago is located in a very active tectonic zone, at the boundary of three large plates of the world and nine other small plates that collide each other and form complex meeting paths of plates (Bird, 2003). The tectonic structure of the western part of Indonesia, or known as the Sunda Arc including Java Island, is formed by the collision between the moving northward Indo-Australian plate and the relatively idle Eurasian plate (Hamilton, 1979 and Hall, 1998). Active interactions between plates placed Indonesia as a region that is very vulnerable to earthquakes (Milsom et al., 1992). Sources of the earthquakes in Java that has been clearly identified are the active subduction zone at the south of the island (Figure 1). Epicenters of some major earthquakes were located under the ocean, therefore these earthquakes had a potential to induce tsunami.

West Java is one of the regions that exemplify high tectonic activity, including earthquakes. Java tectonics is dominated by subduction to the north of the Australian Plate under the Eurasian Plate with an approximate movement of 6 cm/year with near normal direction to the trough, 100-200 km below the island of Java. In the south of Java, the seismic is known as Java Megathrust (Figure 1). Tectonic, volcanic and sedimentary activities that have taken place since the Late Cretaceous produced a series of lithological formations in West Java. The sedimentary rocks found in West Java, particularly of the southern part are summarized in the comparison of stratigraphic column some previous researchers (Figure 2). The outcrop of the shallow marine Bentang Formation in particular, is well-exposed in Tegal Buleud (Figure 1).

Figure 1. (Above) Map showing the subduction and model of interplate megathrusts in Indonesia (modified after Irsyam et al., 2010), and as indicated by rectangle (below) is a map showing locations of the paleotsunami study in West Java.

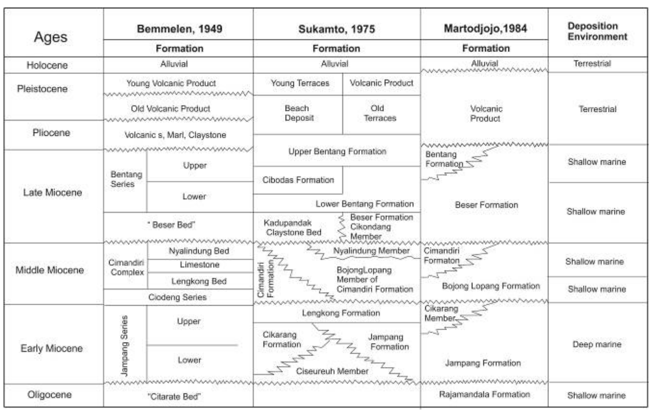

Figure 2. Regional Stratigraphy of Southern West Java, redrawn after van Bemmelen (1949), Sukamto (1975) and Martodjojo (1984)

The lithology of the lower sequence of the Bentang Formation consists of poorly consolidated tuff sandstone, crystal tuff, and pumiceous tuff with intercalation of globigerina claystone, siltstone, marly claystone, andesitic breccia, conglomerate, lapilli tuff and tuff breccia. The upper sequence consists of siltstone and claystone predominate, pumice breccia, and black sandstone occurs in thin layers especially at southern part of the study area. This formation is deposited in the transition to shallow marine environment during the Miocene - Pliocene. There are differences in interpretations of the position of the Bentang formation. Van Bemmelen (1949) referred the Bentang Formation as the Bentang Series, divided into the Upper and Lower Bentang Series, conformably deposited above the Beser Bed. The age of this series is estimated at the Lower Miocene. According to Sukamto (1975) the Bentang Formation deposited from the Late Miocene to Pliocene. On the other hand, Martodjojo (1984) suggested that the Bentang Formation is deposited during the Upper Late Miocene and interfingering with the Beser Formation. Unfortunately there is no absolute age has been determined for the sedimentary deposit of Bentang Formation in the study area.

Research of paleotsunami in Indonesia had only been a limelight since the tsunami events hit the West coast of Aceh in 2004 and South coast of Java in 2006. Tsunami deposits in Java are well documented from modern and historical times (e.g. Newcomb & McCann, 1987, Yudhicara, et al., 2013, Rizal, et al., 2017), but they have rarely been described from the longer, more ancient, in the geological record. The focuses of this study are to determine the presence and to identify sedimentary characters of Mio - Pliocene tsunami deposits by means of observation, collection, and description all of paleotsunami deposit in Tegal Buleud area.

The aim of this study is to identify and characterize any paleotsunami deposit found in the study area. Outcrop observation and sampling were carried along a former sand quarry, located next to Pelabuhan Ratu – Tegal Buleud main road (S 7^{o}24"35.9' and E 106^{o}42"02.2'). The shallow sediment exposed in this area was chosen as the focus of our study due to the indication that the depositions were affected by earthquake-driven tsunami activities. Favorable outcrop condition enabled us to analyze at various scales, from meter to cm, sedimentary structures and textures of tsunami deposits, and their lateral variations.

In South Sukabumi, especially in the research area, paleotsunami research has never been carried out. The research results are the first data on paleotsunami so that it can be used as a reference in further tsunami research.

1.1 Characteristics of Tsunami Deposits Based on Previous Studies

Some sedimentary signatures were used to examine and separate tsunami deposit from other coastal deposits, as deposits of tsunami-related processes exhibit a multitude of physical, biological and geochemical features. Physical signatures of tsunami deposit can be distinguished by its colors, bedding contact (Srinivasalu et al. 2009, Srisutam & Wagner, 2010), sedimentary structure (Gelfenbaum & Jaffe 2003, Szczuciński et al., 2006, Babu et al., 2007, Bahlburg & Weiss 2007, Paris et al., 2007, Matsumoto et al. 2008, Srisutam & Wagner 2010), grain size and compositions (Babu et al., 2007, Paris et al., 2007), as well as its fauna content (Dawson, 2007, Kortekaas & Dawson 2007, Donato et al., 2008, Sawai et al. 2009).

Tsunami deposit suspects, based on their depositional position, are distinguished into onshore tsunami deposits (Switzer & Jones, 2008 and Engel & Brückner, 2011) and offshore tsunami deposit (Shanmugam 2006, 2012). An onshore tsunami deposit is characterized by a distinct contact between tsunami layer and underlying sediment, which commonly appears as an erosional or unconformable contact (Srinivasalu et al., 2009, and Srisutam & Wagner, 2010). The tsunami deposits are usually, but not always, light colored. In most cases the sediments are fining upward and the sand is normally graded, with more coarse grained sand near the base and fine grained sand at the top, overlaid by clay or silt layer with gradational contact (Gelfenbaum & Jaffe 2003, and Srisutam & Wagner 2010).

In the offshore tsunami deposit, a disturbed or irregular layer caused by earthquake, known as liquefaction, formed in the lower part of the sequence (Bhattacharya & Bandyopadhyay, 1998, Engel & Brückner 2011, and Shanmugam, 2016). Basal tsunami units may contain loading structures termed truncated flame structures (Matsumoto et al., 2008). The disturbed layer is covered by a light colored fine to coarse-grained layer with reverse and normal graded bedding sedimentary structure, which also contains mud drape (Fujiwara & Kamataki, 2007, and Sarkar et al., 2013). Another characteristic of tsunami deposit is rip-up clasts, which consists of intra-clasts or reworked material (Szczuciński et al., 2006, and Srisutam & Wagner 2010).

As for modern example, tsunami deposit in Pangandaran from the 2006 event shows fining upward and landward of grain sizes within the deposit, in which overall upward fining occurred as two types, with an initial section of inverse grading followed by a section of normal graded bedding and density graded, with denser grains at the base. The two normally graded sections show no trends in density, while the inversely graded sections show high density sediment to the base, which represents traction carpet flows at the base of the tsunami. Sharp boundary occurred between the tsunami deposit and the underlying soil, however evidence of tsunami-induced erosion were not found (Moore et al., 2011).

Storm deposits, which often misinterpreted as tsunami deposit, or vice versa, typically are more than 30 cm thick, comprise multiple subhorizontal planar thin laminasets (hummocky cross stratification) that are normally or inversely graded. The storm deposit is characterized by hummocky cross stratification sedimentary structure and sometimes associated with herringbones sedimentary structure. The storm deposit has a highly variable grain-size distribution, coarser and better sorted beds with a marked coarsening at its landward extent, and has a sharp, non-erosional lower contact associated with buried vegetation and soil (Tuttle et al., 2004, Morton et al., 2007, Morton, 2009, Goff et al., 2004). Sediments structures such as stratified deposits corresponded with the transport of sediment by rolling and bouncing along the bottom (foresets, climbing ripples, backsets) and multiple and numerous thin (millimeters to a few centimeters) laminasets of alternating coarse and fine grain size indicative of high-frequency waves (Morton et al., 2007, Morton, 2009). Rip-up clasts and mud drapes rarely occur within storm deposits compared to tsunami deposits (Phantuwongraj & Choowong, 2012). Abundant shell fragments organized in laminae is also a characteristic of a storm origin (Morton et al., 2007, Kortekaas & Dawson, 2007). While tsunami deposits may have form onshore and offshore, storm deposits generally will only able to fill in the low places of antecedent topography, extend between 30 m and 300 m from the beach (Morton et al., 2007).

A rapid change energy regime occurred during a tsunami event, from a high turbulence of water during run up then followed by a tranquil water (pre-backwash phase) and succeeded again by turbulence flow during backwash. This mechanism resulted in mixed grain-size distribution and a grain population with varying size range. This kind of distribution is reflected by multimodal grain-size distributions, characterized by at least two dominant modes (bimodal) ranging between fine and coarse-grained sand (Shi et al., 1995, Babu et al., 2007, Paris et al., 2007). The distribution is different from normal sedimentation or storm deposits, which have unimodal particle size distributions. Additionally, Kortekaas and Dawson (2007) and Sugawara et al. (2009) proposed that faunal content in tsunami deposit reflects a mixture of different bathymetry/environment. Pelagic and/or benthic species appear in shallow water environments and their tests may be crushed and broken form.

2. Methods

Stratigraphic trenches were made on the quarry wall in the area that potentially preserved paleotsunami deposits by clearing outcrop planes. Coordinates and layers bearing are measured on cleared trenches, and then sedimentary structures and textures were observed and documented. Paleotsunami suspect layers were identified based on the sedimentary structure and textures. Samples were taken manually from each recognized layer. Each sample was separated for microfossil content analysis and grain size.

For grain-size analysis, a 100 gram samples for each paleotsunami suspect layer were dried and sieved by using a -4.5 ϕ to 4.5 ϕ diameter sieve in Sedimentology Laboratory, Institut Teknologi Bandung. The standard error for sieving must be less than 1%. The plotting of grain-size distribution curves is used to determine the modality of the grain-size distribution, which subsequently used to interpret the current system, occurred during the deposition of each layer.

For each paleotsunami suspect layer, a ± 100 g sample were washed and observed using reflected-light microscope Nikon SMZ 1500 with 16X multiplies, in the Paleontology Laboratory, Institut Teknologi Bandung. Microfossil analysis based on planktonic foraminifera was examined to determine the age of the sediments based on the classification by Blow (1969) and (BouDagher-Fadel, 2012). The benthic foraminifera was used to identify depositional paleoenvironment/ bathymetry based on classification by Rauwenda et al. (1984) as well as Holbourn et al. (2013). The depositional paleoenvironment identification thereinafter used to determine whether faunal mixing occurred in the sediment (Kortekaas & Dawson, 2007, Sugawara et al., 2009).

3. Result

3.1 Stratigraphic Section of the Outcrops

The marine sediment of Outcrop 1 and 2 (Figure 3 and 4) consists of compacted concoidal light grey to bluish carbonaceous claystones, and light to dark brown fine to coarse-grained tuffaceous sandstones. The grains of the sandstone are angular to sub-rounded, medium- sorted, matrix supported and less compacted than the claystones. The composition of fragment mainly is volcanic glass with a few quartz fragment, a few lithic and silica cement. Granule-sized lithic fragments supported by finer matrix are often found in the sandstone. Normal graded sandstones with irregular width of 3-10 cm are often intercalated between tuffaceous claystones and sandstones with sharp contact.

The correlation between Outcrop 1 and Outcrop 2 is displayed in Figure 5. The lower interval of both sections in Outcrop 1 and 2 comprises of tuffaceous sandy-clayey siltstone. A thin sandstone layer (Layer 1), suspected as a paleotsunami layer, intercalated between the siltstone at the lower part of the interval in the Outcrop 1. The Layer 1 does not appear in the Outcrop 2, instead an interfingering contact occurs between the light grey tuffaceous siltstone with underlying dark gray clayey siltstone (Figure 4). Another thin layer of sandstone, suspected as paleotsunami Layer 2, occurs on the upper part of this interval.

The middle interval of both outcrops consists of tuffaceous sandstone, fine-medium, light to reddish brown. At the top of sandstone in both section, found a thin layer of sandstone, which is suspected as paleotsunami Layer 3.

The upper interval comprises marly tuff, and tuffaceous sandstone. In the middle part of the Outcrop 2, a thin layer of sandstone was found and suspected as paleotsunami Layer 4.

Planktonic foraminifera were only found in the paleotsunami suspect Layer 2, from both outcrops, consists of: *Orbulina universa*, *Globigerinoides ruber*, *Globoquadrina dehiscens* and *Sphaerodinella deshiscens dehiscens* (Figure 6). The foraminiferal assemblage indicates that the age of the sediment comparable to N-19, according to both Blow (1969) and BouDagher-Fadel (2012) (Table 1). The foraminiferal-derived age is equivalent to Late Miocene - Early Pliocene (Blow 1969) or Zanclean (BouDagher-Fadel, 2012), or from 5.33 to at about 4 Ma. The age of this layer is corresponded to the Mio-Pliocene Upper Bentang Formation (Sukamto, 1975).

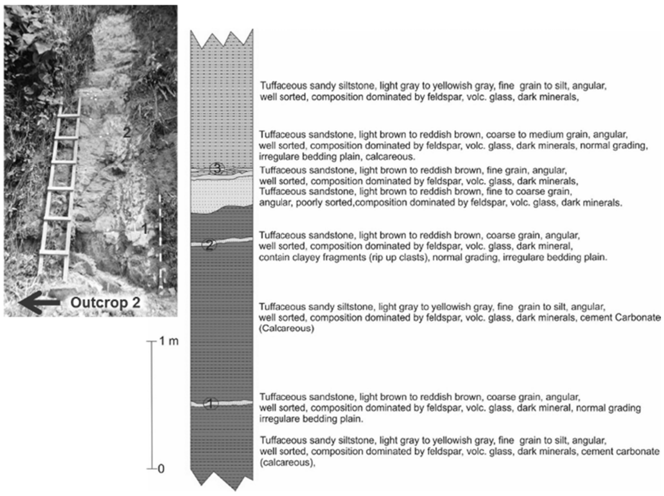

Figure 3. Left: Stratigraphy of Outcrop 1, each grey/white line on the stick represents a 10 cm interval. Right: Illustrated vertical succession of Outcrop 1, numbers represents paleotsunami suspect layers.

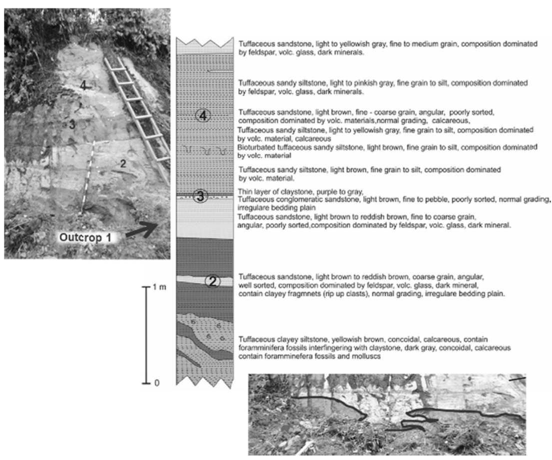

Figure 4. Left: Stratigraphy of Outcrop 2, each grey/white line on the stick represents a 10 cm interval. Right: Illustrated vertical succession of Outcrop 2, numbers represents paleotsunami suspect layers. Bottom right: profile of lower part of the section, showing an interfingering of tuffaceous clayey siltstone with dark gray claystones layers

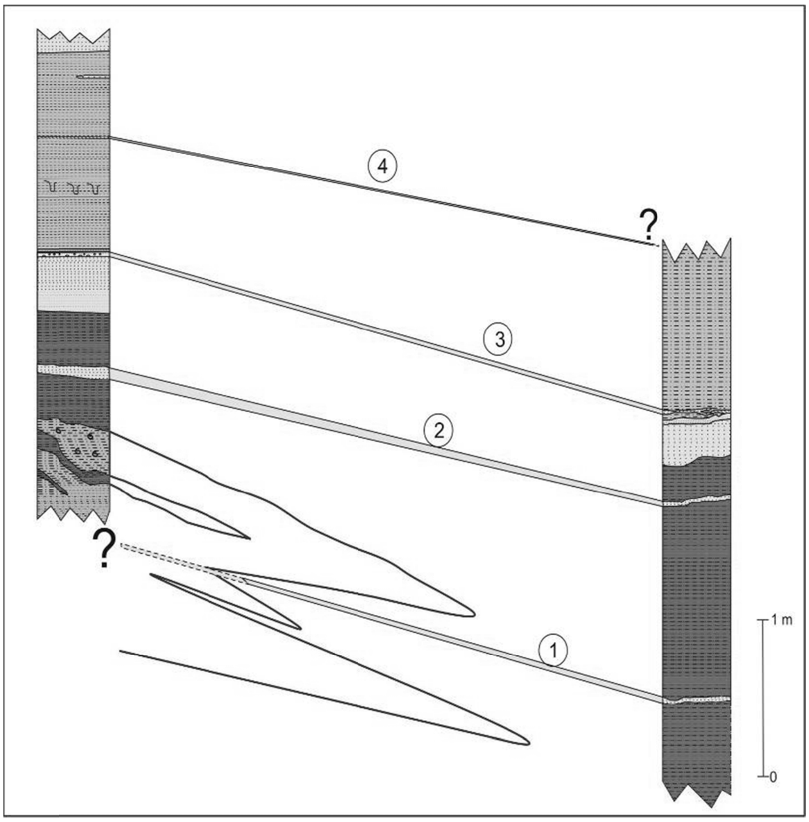

Figure 5. Correlation between Outcrop 1 and Outcrop 2

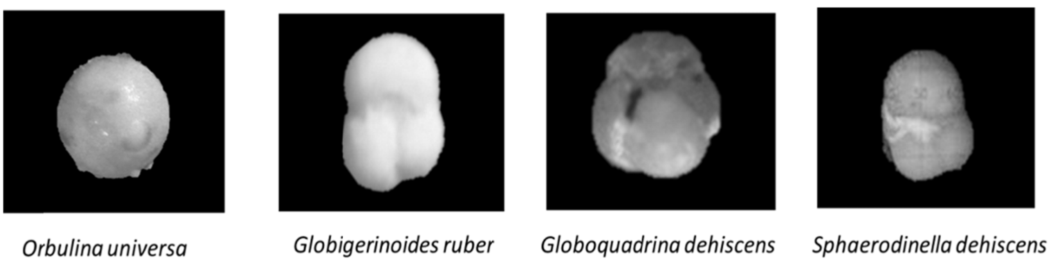

Figure 6. Planktonic foraminifera taxa identified from the paleotsunami suspect Layer 2.

Table 1. (a). Based On Blow (1969), (b). Based On Boudagher-Fadel (2012). Age determination of the paleotsunami suspect layer 2 based on planktonic foraminifera taxa Light grey blocks indicate ranges of taxa, dark grey blocks indicate the age of the sediment (N19)

a.

Fossil Taxa	***N9-N16***	***N17***	***N18***	***N19***	***N20***	***N21-N23***
Orbulina universa	-	-	-	-	-	-
Globigerinoides ruber			-	-	-	-
Sphaerodinella dehiscens dehiscens				-	-	-
Globoquadrina dehiscens	-	-	-	-		

b.

Fossil Taxa	***N9-N16***	***N17***		***N18***		***N19***		***N20***		***N21-N23***
		a	**b**	**a**	**b**	**a**	**b**	**a**	**b**	
Orbulina universa	-	-	-	-	-	-	-	-	-	-
Globigerinoides ruber	-	-	-	-	-	-	-	-	-	-
Sphaeroidinella dehiscens dehiscens						-	-	-	-	-
Globoquadrina dehiscens	-	-	-	-	-	-	-	-	-	-

3.2 Paleotsunami Suspect Layers

3.2.1 Layer 1

The paleotsunami suspect Layer 1 occurs as a thin sandstone intercalation within the carbonaceous clayey siltstone layer. Irregular/disturbed structure such as siltstone rip up, clay clasts and flame structure occur in the normal graded bedding sandstone layer (Figure 7a). A coarsening shift from fine-grained clay at the base to the coarse-grained sandstone layer show a sharp contact occurs between the two layers.

Two grain-size populations are observed from the paleotsunami suspect Layer 1, shows a bimodal distribution (Figure 7b). The high frequency of coarsening grain (mode 1) is likely due to the high energy current due to run off, followed by the decreasing number of coarse grain, and re-increasing of coarser grain frequency (mode 2) as a result of backwash current that brought back coarser particle from the landward.

The fossil content identified from this layer (Figure 7c) are: *Elphidium* sp. from the lithoral-inner neritic environment (Rauwenda et al., 1984) and *Vulvulina* sp. from the middle neritic environment (Holbourn et al., 2013).

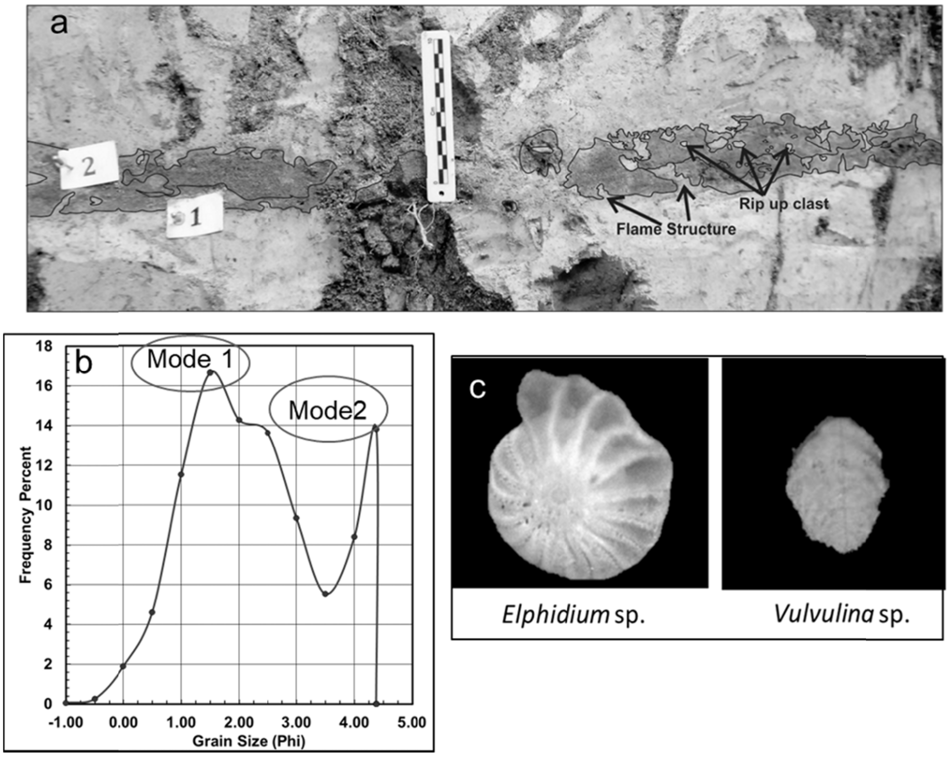

Figure 7. Type your title here. Obtain permission and include the acknowledgement required by the copyright holder if a figure is being reproduced from another source

3.2.2 Layer 2

Similar to paleotsunami suspect Layer 1, Layer 2 is also a thin sandstone intercalation in between carbonaceous clayey siltstone layers. Sedimentary structures such as irregular/disturbed rip up, clay clasts and flame structure (Figure 8a) occur in this layer and graded bedding sedimentary structure. An erosional contact is observed between the paleotsunami suspect Layer 2 and its underlying clayey siltstone layer.

A bimodal distribution representing two grain-size populations are also observed from the paleotsunami suspect Layer 2 (Figure 8b), suggesting two different current systems. However, the mode 2 in this layer has a lower frequency than in the paleotsunami suspect Layer 1, suggesting a low energy backwash current occurred during the depositional process.

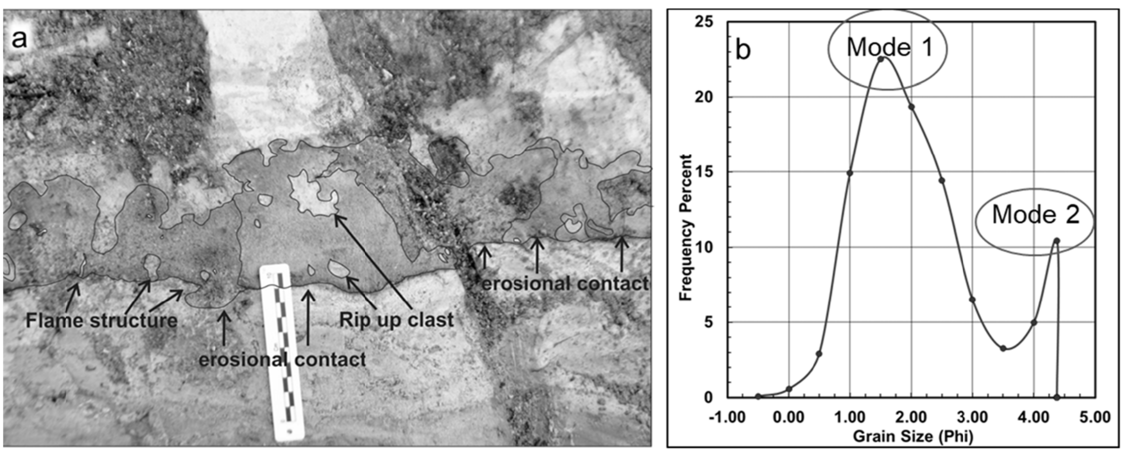

Figure 8. a. Paleotsunami suspect Layer 2, showing a disturbed/irregular normal graded layer with rip up clasts and flame structure; b. Grain-size distributions of paleotsunami suspect Layer 2, showing two populations/modes (bimodal) of grain-size distribution.

3.2.3 Layer 3

Tsunami suspect Layer 3 is a thin coarse-grained sandstone intercalation between the non-carbonaceous sandstone and carbonaceous clayey siltstone layers. It has sedimentary structures such as irregular/disturbed rip up, clay clasts, graded bedding and flame structure (Figure 9a) may indicate a liquefaction process. Similar to paleotsunami suspect Layer 1 and 2, the paleotsunami suspect Layer 3 also shows a bimodal distribution representing two grain-size (Figure 9b).

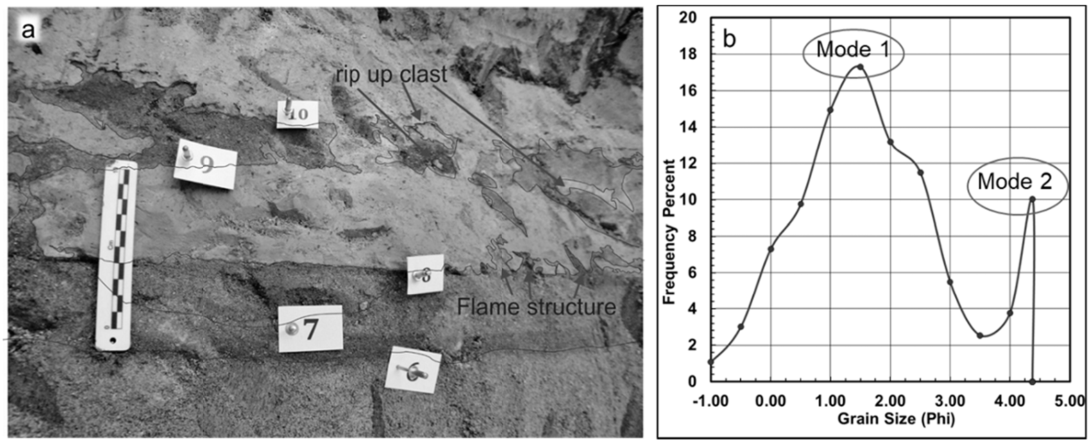

Figure 9. a. Paleotsunami suspect Layer 3, showing a disturbed/irregular normal graded layer with rip up clasts and flame structure; b. Grain-size distribution of paleotsunami suspect Layer 3, showing two population/modes (bimodal) of grain-size distribution.

3.2.4 Layer 4

Paleotsunami suspect Layer 4 occurs as a thin sandstone intercalation within the carbonaceous clayey siltstone layer. Irregular/disturbed rip up clasts structure (Figure 10a). The grain-size distribution of paleotsunami suspect Layer 4 (Figure 10b) generally shows a multimodal distribution pattern. The distribution of paleotsunami suspect Layer 4 appears to be different from other tsunami deposits. The difference presumably occurred due to the difference in the current system that works during the 4th tsunami

The fossil content identified from this layer (Figure 10c) are: *Bolivina* sp. *Nodosaria* sp., *Lagena* sp. from middle neritic environment (Holbourn et al., 2013) and *Rotalia* sp. from the inner neritic environment (Holbourn et al., 2013).

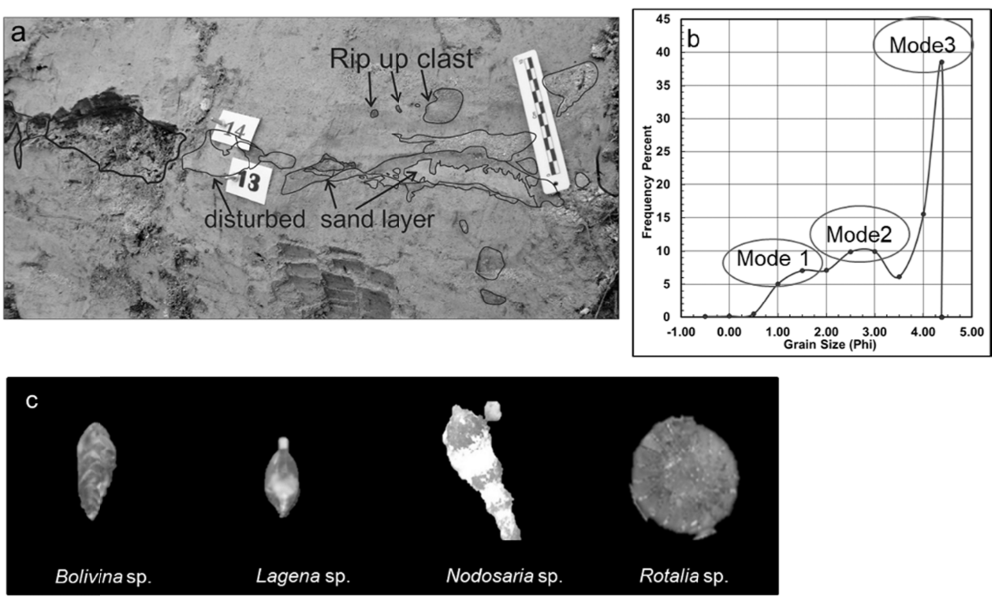

Figure 10. a. Paleotsunami suspect Layer 4, showing a disturbed/irregular normal graded layer with rip up clasts; b. grain-size distribution of tsunami suspect Layer 4, showing three populations/modes (multimodal) grain-size distribution; c. foraminifera fossils found in paleotsunami suspect Layer 4

4. Discussion

Four paleotsunami suspect layers were identified from the Outcrop 1 and Outcrop 2 observed in the study area, in which both outcrops generally have similar sedimentary features. The age of the marine sediment is derived from the microfossil content of the Layer 2, concluded as the Late Miocene to Pliocene (5.54 – 4.08 Ma) based on Blow (1969) or Zanclean (5.33 – 3.60 Ma) based on BouDagher-Fadel (2012).

The paleotsunami suspect Layers 1, 2 and 3 occur as thin sandstone intercalations within the carbonaceous clayey siltstone layers. These layers have irregular/disturbed structures such as siltstones rip up, clay clasts, and flame structure. Siltstone rip up and clay clasts indicate reworking in a high energy current occurred during the deposition of these layer. Flame structures suggest different densities/water contents between layers, which may indicate that earthquake happened while the sediments were not yet consolidated. However clastic dyke, which indicates liquefaction process during earthquakes was not observe in the outcrops. Sedimentary structures such as rip-up clast and flame structure are more indicative of tsunami deposits rather than storm deposit. The normal graded bedding occurred in these layers also opposed normally or inversely graded bedding associated in hummocky cross stratification or herringbones sedimentary structure occur in storm deposits.

The more convincing evidence of tsunami deposit came from bimodal grain-size distributions (Layer 1, 2 and 3). The bi-modal/multimodal grain-size distribution here indicates due to changes in depositional energy, which occurred during the tsunami run off and backwash. This kind distribution preceded by a small amount of coarse-grain fractions that may be caused by a weaker run off, followed by a coarser-grain fraction, formed due to a higher energy backwash. While multimodal grain-size distribution occurs in Layer 4, there is a possibility that the effect of backwash is quite large compared to the incoming currents, which can be seen from the coarser grain domination.

The microfossil content from paleotsunami Layers 1 and 4, which originated from two different bathymetry/environment: lithoral-inner neritic and middle neritic, indicates faunal mixing of different depositional environment. The faunal mixing from littoral-inner neritic and middle neritic environments amplifies the indication of tsunami rather than storm deposit. Storm wave-base typically affected maximum of 15-40 m-deep. Thus, the storm wave will only agitated ad brought the fauna from the littoral and inner neritic layer and would not likely transport the middle neritic faunas.

Different from tsunami deposits from Chile (Paskoff, 1991), Flores (Yeh et al., 1993) and NW Australia (Young & Bryant, 1992) that consists of coarser boulder fraction, the tsunami suspect layers that we found the study area consists only of finer grained fractions. Similar tsunami layers with fine-grained sediment character are also found in Thailand (Jean-Frank & Chanchai, 2011), Pacitan-Banyuwangi (Anugrah et al., 2015), Bali-Lombok (Aswan et al., 2017) and Cilacap (Rizal et al., 2017). Deposition of each fraction is very much determined by the condition of the beach morphology, distance and rocks that are passed by the water flow and the shape of the beach. The thin fine-grained sediment found in the study area may be due to the long distance from the beach or the shape of the ancient beach that caused a distal backwash process onshore that deposited by traction and suspension currents. Other characteristics such as coarser grained fractions, other fragments and bi-directional flow might be found in other area that located more proximal to the ancient beach.

Tsunami and earthquake events recorded on the Late Miocene to Pliocene sediments in the research area are presumably triggered by Mio-Pliocene tectonic activity that occurs regionally throughout the world including in Java. This tectonic event is referred as the Mio-Pliocene Orogeny (van Bemmelen, 1949, Simandjuntak & Barber, 1996, Hall & Wilson, 2000). The tectonic event is in accordance to the volcanic activities around the area during the Late Miocene-Pleistocene (Suriaatmadja et al., 1991), which may supply the volcaniclastics in the sediment. This discovery considered as the first and oldest paleotsunami layers in Java and even in Indonesia.

5. Conclusions

The lithological units studied in Tegal Buleud consist of claystones that belongs to Late Miocene to Pliocene of Upper Bentang Formation. In the outcrop exposed in the study area were found four layers identified as paleotsunami deposits, which are interpreted as formed by tectonic events.

Those paleotsunami deposits (Layers 1, 2, 3 and 4) characterized by the occurrence of irregular/disturbed structure such as siltstone rip up, clay clasts, and flame structure occur in normal graded bedding sandstone layer. The grain-size distributions show bimodal and multimodal patterns, with mixing of marine microfossils from inner and middle neritic (Layers 1 and 4).

All the paleotsunami deposits found in Tegal Buleud are the first and oldest tsunami deposit recorded in Java even in Indonesia. With the discovery of the previously unexplored Late Miocene to Pliocene tsunami deposits found in the research area, the result of this study can be used as a reference for the identification of the Tertiary tsunami deposits present in other parts of Indonesia.

The result of this study is expected to be used as a reference for paleotsunami deposits formed during the Mio - Pliocene, and this area were uplifted due to the Plio-Pleistocene tectonic activity. Furthermore, the result can be used as an evidence that Java, as one of the most populated islands, has not been a safe, tsunami-free area since Pliocene until present.

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References

Anugrah, S. D., Zaim, Y. Rizal, Y., Aswan & Istiyanati. (2015). A preliminary study of paleotsunami deposit along the south coast of East Java: Pacitan-Banyuwangi, *AIP Conference Proceedings*.

Aswan, Zaim, Y., Rizal, Y., Sukanta, I. N., Anugrah, S. D., Hascaryo, A. T & Nurochim. (2017). Age determination of paleotsunami sediments around Lombok Island, Indonesia &identification of their possible tsunamigenic earthquakes, *Earthquake Science*, 1-7. https://doi.org/10.1007/s11589-017-0179-2.

Babu, N., Babu, D. S. & Das, P. N. (2007). Impact of tsunami on texture and mineralogy of a major placer deposit in southwest coast of India, *Environmental Geology, 52*(1), 71. https://doi.org/10.1007/s00254-006-0450-7.

Bahlburg, H. & Weiss. R. (2007). Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya. *International Journal of Earth Sciences, 96*(6), 1195-1209. https://doi.org/10.1007/s00531-006-0148-9.

Bhattacharya, H. N. & Bandyopadhyay, S. (1998). Seismites in a Proterozoic tidal succession, Singhbhum, Bihar, India. *Sedimentary Geology, 119*(3), 239-252, https://doi.org/10.1016/S0037-0738(98)00051-7.

Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems, 4*(3).

Blow, W. H. (1969). Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy, *Proceedings of the first international conference on planktonic microfossils.*

Fadel, B. M. K. (2012). *Biostratigraphic and geological significance of planktonic foraminifera*. Vol. 22, Newnes.

Dawson, S. (2007). Diatom biostratigraphy of tsunami deposits: examples from the 1998 Papua New Guinea tsunami. *Sedimentary Geology, 200*(3), 328-335. https://doi.org/10.1016/j.sedgeo.2007.01.011.

Donato, S. V., Reinhardt, E. G., Boyce, J. I., Rothaus, R. & Vosmer, T. (2008). Identifying tsunami deposits using bivalve shell taphonomy. *Geology, 36*(3), 199-202. https://doi.org/10.1130/G24554A.1.

Engel, M. & H. Brückner. (2011). The identification of palaeo-tsunami deposits–a major challenge in coastal sedimentary research. *Coastline Reports, 17*, 65-80.

Fujiwara, O. & T. Kamataki. (2007). Identification of tsunami deposits considering the tsunami waveform: an example of subaqueous tsunami deposits in Holocene shallow bay on southern Boso Peninsula, Central Japan. *Sedimentary Geology, 200*(3), 295-313. https://doi.org/10.1016/j.sedgeo.2007.01.009.

Gelfenbaum, G. & B. Jaffe. (2003). Erosion and sedimentation from the 17 July, 1998 Papua New Guinea tsunami, *Pure and Applied Geophysics*, 1969-1999, https://doi.org/10.1007/s00024-003-2416-y.

Goff, J., McFadgen, B. & Chagué, C. (2004). Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine geology, 204*(1-2), 235-250. https://doi.org/10.1016/S0025-3227(03)00352-9.

Hall, R. (1998). The plate tectonics of Cenozoic SE Asia and the distribution of land and sea, *Biogeography and Geological Evolution of SE Asia*, 99-131.

Hall, R. & Wilson, M. (2000). Neogene sutures in eastern Indonesia. *Journal of Asian Earth Sciences, 18* (6), 781-808.

Hamilton, W. B. (1979). *Tectonics of the Indonesian region*. Washington: US Goverment Printing Office, 1078.

Holbourn, A., Henderson, A. S. & MacLeod, N. (2013). *Atlas of benthic foraminifera*: John Wiley & Sons.

Irsyam, M., Sengara, W., Aldiamar, F., Widiyantoro, S., Triyoso, W., Natawidjaja, D. & Ridwan, M. (2010). Development of Seismic Hazard Maps of Indonesia for Revision of Seimic Hazard Map in SNI 03-1726-2002. *Reseach report submitted to the Ministry of Public Works by the Team for Revision of Seismic Hazard Maps of Indonesia*.

Jean-Frank, W. & Chanchai, S. (2011). Grain-Size and Thin Section Characteristics of Tsunami Sediments from Thai-Andaman Coast, Thailand. In *The Tsunami Threat-Research and Technology*. IntechOpen.

Kortekaas, S. & Dawson, A. G. (2007). Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal. *Sedimentary Geology, 200*(3), 208-221, https://doi.org/10.1016/j.sedgeo.2007.01.004.

Martodjojo, S. (1984). *Evolusi Cekungan Bogo*r (Unpublished doctoral dissertation). Departemen Teknik Geologi, Institut Teknologi Bandung.

Matsumoto, D., Naruse, H., Fujino, S. A., Surphawajruksakul, T., Jarupongsakul, N., Sakakura & Murayama, M. (2008). Truncated flame structures within a deposit of the Indian Ocean Tsunami: evidence of syn‐sedimentary deformation. *Sedimentology, 55*(6), 1559-1570, https://doi.org/10.1111/j.1365-3091.2008.00957.x.

Milsom, J. D., Masson, G., Nichols, N., Sikumbang, B., Dwiyanto, L., Parson & Kallagher, H. (1992). The Manokwari trough and the western end of the New Guinea trench, *Tectonics, 11*(1), 145-153.

Moore, A., Goff, J., McAdoo, B. G., Fritz, H. M., Gusman, A. R., Kalligeris, N. & Synolakis, C. E. (2011). Sedimentary deposits from the 17 July 2006 western Java tsunami, Indonesia: use of grain size analyses to assess tsunami flow depth, speed &traction carpet characteristics. *Pure and Applied Geophysics, 168*(11), 1951-1961. https://doi.org/10.1007/s00024-011-0280-8.

Morton, R. A. (2009). Formation of storm deposits by wind-forced currents in the Gulf of Mexico and the North Sea. *Holocene Marine Sedimentation in the North Sea Basin, 5*, 385-396. https://doi.org/10.1002/9781444303759.ch27.

Morton, R. A., Gelfenbaum, G. & Jaffe, B. E. (2007). Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology, 200*(3-4), 184-207. https://doi.org/10.1016/j.sedgeo.2007.01.003.

Newcomb, K. R. & McCann, W. R. (1987). Seismic history and seismotectonics of the Sunda Arc. *Journal of Geophysical Research: Solid Earth (1978–2012), 92*(B1), 421-439. https://doi.org/10.1029/JB092iB01p00421.

Paris, R., Lavigne, F., Wassmer, P. & Sartohadi, J. (2007). Coastal sedimentation associated with the December 26, 2004 tsunami in Lhok Nga, West Banda Aceh (Sumatra, Indonesia). *Marine Geology, 238*(1), 93-106. https://doi.org/10.1016/j.margeo.2006.12.009.

Paskoff, R. (1991). Likely occurrence of a mega-tsunami in the Middle Pleistocene, near Coquimbo, Chile, *Andean Geology, 18*(1), 87-91.

Phantuwongraj, S. & Choowong, M. (2012). Tsunamis versus storm deposits from Thailand. *Natural Hazards, 63*(1), 31-50, https://doi.org/10.1007/s11069-011-9717-8.

Rauwenda, P. J., Morley, R. J. & S. R. Toelstra. (1984). *Assessment of depositional environment and stratigraphy on the basis of foraminifera paleoecology*, Robertson Research Private Limited, Singapore.

Rizal, Y., Zaim, Y., Santoso, W. D., Rochim, N., Anugrah, S. D., Gunawan, I. & H. Rahayu, R. (2017). Tsunami Evidence in South Coast Java, Case Study: Tsunami Deposit along South Coast of Cilacap, *IOP Conference Series: Earth and Environmental Science.*

Sarkar, D., Mukhopadhyay, A. & Hazra, S. (2013). Characteristics of Tsunami and paleo Tsunami deposits in South Andaman Island, India. *Indian Journal of Geo-marine Sciences, 42*(7), 839-848.

Sawai, Y., Jankaew, K., Martin, M. E., Prendergast, A., Choowong, M. & Charoentitirat, T. (2009). Diatom assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phra Thong Island, Thailand. *Marine Micropaleontology, 73*(1), 70-79. https://doi.org/10.1016/j.marmicro.2009.07.003.

Shanmugam, G. (2006). The tsunamite problem. *Journal of Sedimentary research, 76*(5), 718-730. https://doi.org/10.2110/jsr.2006.073.

Shanmugam, G. (2012). Process-sedimentological challenges in distinguishing paleo-tsunami deposits. *Natural Hazards, 63*(1), 5-30. https://doi.org/10.1007/s11069-011-9766-z.

Shanmugam, G. (2016). The seismite problem. *Journal of Palaeogeography, 5*(4), 318-362. https://doi.org/10.1016/j.jop.2016.06.002.

Shi, S., Dawson, A. G. & Smith, D. E. (1995). *Coastal sedimentation associated with the December 12th*, 1992 tsunami in Flores, Indonesia. In *Tsunamis: 1992–1994*, edited by Imamura F. and Satake K., 525-536. Springer.

Simandjuntak, T. O. & A. J. Barber. (1996). Contrasting tectonic styles in the Neogene orogenic belts of Indonesia. *Geological Society, London, Special Publications, 106*(1), 185-201.

Srinivasalu, S., Nadamuri, R. R., Thangadurai, N., Jonathan, M., Roy, P., Mohan, V. R. & Saravanan, P. (2009). Characteristics of 2004 tsunami deposits of the northern Tamil Nadu coast, southeastern India. *Boletín de la Sociedad Geológica Mexicana, 61*(1), 111-118.

Srisutam, C. & Wagner, J.F. (2010). Tsunami sediment characteristics at the Thai Andaman coast. *Pure and Applied Geophysics, 167*(3), 215-232, https://doi.org/10.1007/s00024-009-0015-2.

Sugawara, D., Minoura, K., Nemoto, N., Tsukawaki, S., Goto, K. & Imamura, F. (2009). Foraminiferal evidence of submarine sediment transport and deposition by backwash during the 2004 Indian Ocean tsunami, *Island Arc, 18*(3), 513-525. https://doi.org/10.1111/j.1440-1738.2009.00677.x.

Sukamto, R. (1975). *Peta Geologi Lembar Jampang dan Balekambang, Jawa.* Direktorat Geologi, Departemen Pertambangan Republik Indonesia.

Suriaatmadja, R., Maury, R.C, Bellon.H, Pringgoprawiro.H, Polve.M. & Priadi.B. (1991). *The Tertiary Magmatic Belt in Java: Proceeding of the Symposium on the Dynamics of Subduction and Its Product,* Yogyakarta.

Switzer, A. D. & B. G. Jones. (2008). Large-scale washover sedimentation in a freshwater lagoon from the southeast Australian coast: sea-level change, tsunami or exceptionally large storm? *The Holocene, 18*(5), 787-803. https://doi.org/10.1177/0959683608089214.

Szczuciński, W., Chaimanee, N., Niedzielski, P., Rachlewicz, G., Saisuttichai, D., Tepsuwan, T., Lorenc, S. & Siepak. J. (2006). Environmental and Geological Impacts of the 26 December 2004 Tsunami in Coastal Zone of Thailand--Overview of Short and Long-Term Effects. *Polish Journal of Environmental Studies, 15*(5).

Tuttle, M. P., Ruffman, A., Anderson, T. & Jeter, H., (2004). Distinguishing tsunami from storm deposits in eastern North America: the 1929 Grand Banks tsunami versus the 1991 Halloween storm. *Seismological Research Letters, 75*(1), 117-131. https://doi.org/10.1785/gssrl.75.1.117.

van Bemmelen, R. W. (1949). *The Geology of Indonesia*: Government Printing Office, The Hague.

Yeh, H., Imamura, F. Synolakis, C., Tsuji, Y. Liu, P. & Shi, S. (1993). The Flores island tsunamis. *Eos, Transactions American Geophysical Union, 74*(33), 369-373.

Young, R. & Bryant, E. A. (1992). Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunamis ca. 105 ka? *Geology, 20*(3), 199-202.

Yudhicara, Y., Zaim, Y., Rizal, Y., Aswan, Triyono, R. & Setiyono, U. (2013). Characteristics of Paleotsunami Sediments, A Case Study in Cilacap and Pangandaran Coastal Areas, Jawa, Indonesia. *Indonesian Journal on Geoscience, 8*(4), 163-175. https://doi.org/10.17014/ijog.v8i4.166.

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