

Tsunami Evidence in South Coast Java, Case Study: Tsunami Deposit along South Coast of Cilacap

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Abstract. Cilacap Area is situated in coastal area of Southern Java and directly affected by tsunami hazard in 2006. This event was triggered by active subduction in Java Trench which active since long time ago. To detect tsunami and active tectonic in Southern Java, paleo-tsunami study is performed which is targeted paleo-tsunami deposit older than fifty years ago. During 2011 - 2016, 16 locations which suspected as paleo-tsunami location were visited and the test-pits were performed to obtain characteristic and stratigraphy of paleo-tsunami layers. Paleo-tsunami layer was identified by the presence of light-sand in the upper part of paleo-soil, liquefaction fine grain sandstone, and many rip-up clast of mudstone. The systematic samples were taken and analysis (micro-fauna, grainsize and dating analysis). Micro-fauna result shows that paleo-tsunami layer consist of benthonic foraminifera assemblages from different bathymetry and mixing in one layer. Moreover, grainsize shows random grain distribution which characterized as turbulence and strong wave deposit. Paleo-tsunami layers in Cilacap area are correlated using paleo-soil as marker. There are three paleo-tsunami layers and the distribution can be identified as PS-A, PS-B and PS-C. The samples which were taken in Glempong Pasir layer are being dated using Pb – Zn (Lead-Zinc) method. The result of Pb - Zn (Lead-Zinc) dating shows that PS-A was deposited in 139 years ago, PS-B in 21 years ago, and PS C in 10 years ago. This result indicates that PS -1 occurred in 1883 earthquake activity while PS B formed in 1982 earthquake and PS-C was formed by 2006 earthquake. For ongoing research, the older paleo-tsunami layers were determined in the Gua Nagaraja, close to Selok location and 6 layers of Paleo-tsunami suspect found which shown a similar characteristic with the layers from another location. The three layers deeper approximately have an older age than another location in Cilacap.

Keywords: Cilacap; Dating; Earthquake; Paleotsunami layers; Tsunami.

1. Introduction

Tsunami hazard is the most dangerous in coastal hazard and give the dramatic human and infrastructure losses [1,2]. Therefore, geologic research has focused on modern tsunami and paleo-tsunami, including characteristic, causes, and evidence, in recent years. 75% of the Indonesian coastline is tsunami warning area [3]. NOAA (National Oceanic and Atmospheric Administration)



data shows that tsunami killed more than 470.000 lives worldwide during the last 450 years tsunamis. One of the locations which affected by tsunami and had the good record of tsunami sediment is Cilacap Area, Central Java.

Cilacap Area is situated in coastal area of Southern Java and directly affected by tsunami hazard in 2006. This event was triggered by active subduction in Java Trench which active not only in 2006 but also much older than it. Several record of tsunami and earthquake hazard has been recorded and reported by previous study, such as [4-6].

Newcomb and Mc Can [4] successfully reported that many paleo - tsunami had been detected in Southern Java on 4 January 4th, 1840, October 20th, 1859, and September 11th, 1921. Yudhicara et al described and dated two key beds which were suspected as paleo-tsunami deposit [5]. However, two key beds give the age in 2002 and 2007 and the beds are not correlated with paleo-tsunami deposit.

Catalogue which was developed by BMKG [6] reported many earthquake and tsunami related with Java trench activity in Central Java Area. Sixteen times tsunami and earthquake data have been collected, with the oldest earthquake were performed in 1416 (from NOAA reference) and the youngest was happened in 2006. The 2006 tsunami injured 600 people death and 15 people lost [7].

This study was focused for characterized and determine the age of paleo-tsunami deposit by observe, collect, and describe all of tsunami and paleo-tsunami deposit in Cilacap area. Moreover, regional correlation of paleo-tsunami deposit in Cilacap area is revealed, attempt to correlate paleo-tsunami deposit time by time, and help to prove and reconstruct previous paleo-tsunami reported before [6].

2. Material and Method

The study site is located in Cilacap areas, which have ± 105 km coastlines [8]. The research was conducted as joint research program between Institut Teknologi Bandung (ITB) with Meteorology, Climatology, and Geophysics Agency (BMKG in Indonesia) in 2015. Fifteen locations suspected as paleo-tsunami location were visited and examined based on image and topographic map analysis (Figure 1). All of the locations were confirmed as paleo-swale and back of ridge which give the good preservation of paleo-tsunami deposit. To get the precision location, a GPS system collaborated with topography measurement using total station was executed and corrected with sea level.

The identification of paleo-tsunami deposit was performed with made trenching area in the suspect location. After that, the samples were taken by systematically using grab and coring method. Laboratory analysis was examined in this study including micro-fauna, grainsize, and dating analysis.

Micro fauna analysis was examined to identify the mixing and transporting of marine fauna from different environment. Besides that, micro fauna analysis can be used to know how deep the fossils were transported to the land caused by tsunami. Paleo-tsunami samples were washed and soaked in the H_2O_2 . After that, the samples were dried using oven, and ready to determine. The samples were observed in Paleontology Laboratory, Institut Teknologi Bandung, using reflected-light microscope Nikon SMZ 1500 with 16X multiplies.

Grainsize analysis was applied using - 4.5 multiplies using oven, and ready to determine. The samples show grain size distribution of paleo-tsunami deposit. The 100 gram samples of paleo-tsunami were dried and the grains coarse were sieved out of each sample. The samples must be weighed before and after sieving to get the precision calculation of the weight percentage of the coarse fraction. The standard of the samples was that the different of weight before and after sieving must be less than one gram. For the analysis, grain size computation and plotting were performed using Program of [9]. This analysis was executed in Sedimentology Laboratory, Institut Teknologi Bandung.

Dating analysis for the paleo-tsunami deposit was conducted using ^{210}Pb method. The age can be known by counting ^{210}Pb content inside the samples [10]. The samples of ^{210}Pb dating were taken by systematically with 5 cm interval from top to bottom. This analysis performed in the Dating

Laboratory, Indonesian Atomic Agency. For the age measurement, the formula ^{210}Pb decay followed Olfield and Appleby method [11];

$$t_{1/2} = 22.3 \text{ y (t = 32.2 y)}$$

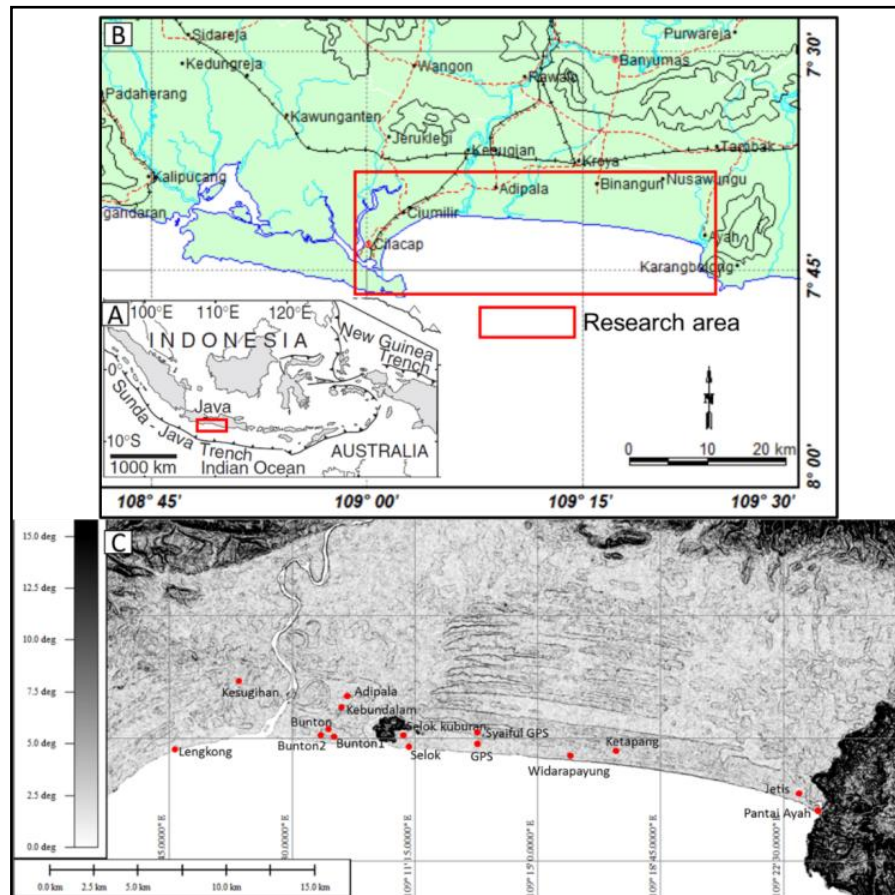


Figure 1 Location of research area. (A). Plate tectonic framework of Java [12]. Cilacap area (marked with red box) faces with Java Trench as earthquake trigger. (B). Administrative and road access map of research area (map from [5]). (C). Location of paleo-tsunami suspect (marked with red dot) overlay with satellite image (Image from USGS [13]).

3. Result and Discussion

3.1. Paleo-tsunami Deposit Characteristic

Many of sedimentary signatures were used to examine and separate paleo-tsunami deposit from another sand beach deposit. Paleo-tsunami deposit has special characteristic. Physical signatures of paleo-tsunami deposit can be distinguished by its colors, bedding contact, sedimentary structure, grain size, and the compositions. The signatures of paleo-tsunami deposit refer to previous study in several areas. Horton et al. [14] described the erosional contact as signatures in US Golf Coast. Another study from [15] in Florida Coast gives the similar result with [14]. Another characteristic of tsunami deposit is rip-up clast, which consist of intra-clast or reworked material. This characteristic was observed by [16] in Thailand and [15] in Florida Coast. The light sand in the upper part of paleo-soil is another signature of paleo-tsunami deposit. Cochran et al. [17] dug the paleo-tsunami deposit in Takui River, New Zealand, and found this character as paleo-tsunami signatures.

In Cilacap area, fifteen locations were visited and the result showed that nine locations contain paleo-tsunami deposits and six locations other indicate without paleo-tsunami deposit. Paleo-tsunami deposit can be found in paleo-swale and back of paleo-ridge area, with elevation from 5 meters to 18 meters mean sea level. Topography measurement shows that the location of paleo-tsunami deposit has 250 meters from the beach as the nearest location (Selok location) and 3 kilometers from the beach as the farthest location (Kesugihan location). The summary of paleo-tsunami layers in Cilacap area can be seen in Table 1.

Table 1 Summary of paleo-tsunami layers in Cilacap Area

Location	Coordinate	The amount of Paleo-tsunami layer	Paleo-tsunami signatures
Lengkong	07° 41' 36.96" E 109° 03' 54.396" N	2	Erosional contact, on-lap topography, liquefaction structure.
Kesugihan	07° 39' 37.20" E 109° 05' 52.332" N	2	Light brown sand, fine to medium grain size.
Bunton	07° 41' 2.724" E 109° 08' 43.908" N	2	Light gray sand, erosional contact.
Bunton 1	07° 41' 15.288" E 109° 08' 47.796" N	None	
Bunton 2	07° 41' 10.2012" E 109° 08' 38.904" N	None	
Adipala	07° 39' 56.736" E 109° 09' 7.344" N	None	
Kebundalam	07° 40' 18.012" E 109° 08' 55.068" N	3	Light gray sand, fine to medium grain size.
Selok Kuburan	07° 41' 9.816" E 109° 10' 51.384" N	3	Light gray sand, erosional contact.
Selok	07° 41' 24.54" E 109° 10' 57.252" N	2	Light gray sand, medium grain size, erosional contact.
Syaiful GPS	07° 41' 4.848" E 109° 12' 58.568" N	None	
Glempang Pasir (GPS)	07° 41' 18.024" E 109° 12' 56.376" N	3	Rip up clast, light gray sand, paleosoil, erosional contact.
Widara payung	07° 41' 49.092" E 109° 16' 3.144" N	1	Light gray sand, paleosoil, erosional contact.
Ketapang	07° 41' 48.984" E 109° 17' 30.984" N	None	
Jetis	07° 43' 4.834" E 109° 22' 53.148" N	None	
Pantai Ayah	07° 43' 31.656" E 109° 23' 40.704" N	3	Light gray sand, medium to coarse grain size, fragmented.

The ideal profile of paleo-tsunami deposit in Cilacap area can be observed in Glemgang Pasir (GPS) location (see Figure 1) by trenching method. Compared with beach sand, tsunami material has lighter color than beach sand, more enriched in fine grained sand and mix with silt and shale material, and rip-up clast is found in several place. Beach sediment in Cilacap Area is characterized by black sand sediments. The beach sediment is consisted of iron sand layer, medium grain size, well sorted, and without clay material as a product of traction flow during deposition.

Three layers could be examined as paleo-tsunami candidates, namely PS A, PS B, and PS C (Figure 2). PS- A description shows light gray sand, very fine – fine grain, with carbon fragment in the bottom with 5 cm thickness. PS-B, the younger paleo-tsunami candidate than PS-A, consist of sandy clay, light gray, and paleo-soil in the bottom part. The thickness of PS B has about 20 cm, with paleo-soil around 3 cm. At the upper part of trenching, the thickest paleo-tsunami candidate, namely PS-C, was deposited with 50 cm thickness. PS C has light sand, medium – coarse sand, rip-up clay, and erosional contact in bottom part.

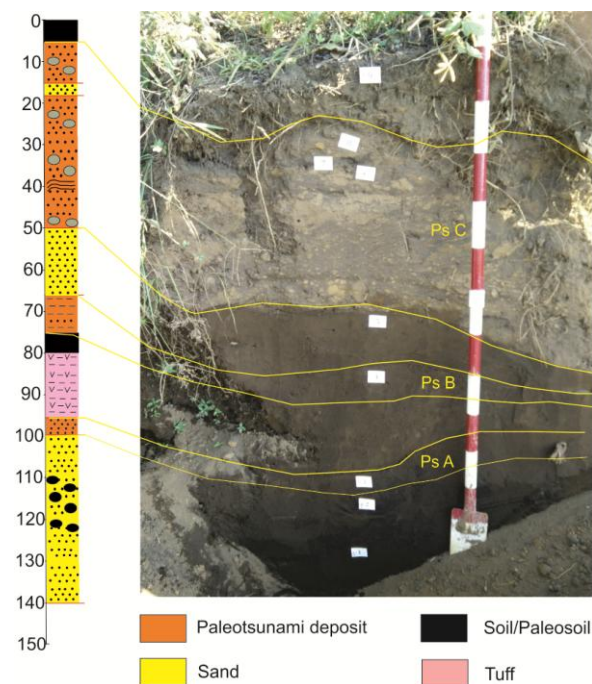


Figure 2 Profile of Paleo-tsunami suspect in Glemgang Pasir (GPS) location.

Tsunami energy erodes the sediment from deeper marine and deposits it in the shallower environment. To detect how far the material was transported, micro-fauna analysis was performed as indicator. Previous research by [18] in Thailand indicated that the transportation of the large volumes of coastal material and seaward material during the tsunami was followed by relocation of mangrove foraminifera. Another research by [19] observed in 2004 tsunami deposit in Thailand and Malaysia, tsunami layers consist of a mixing layer of fauna from of freshwater, brackish, and marine species. Therefore, paleo-tsunami layers can be concluded by sediments which contain from rework and transported fossils (Figure 3).

Observation of paleo-tsunami layer in Cilacap area indicates the similar result. The faunas which live in the neritic environment, *Oolina* sp., *Bolivina* sp., *Lagena* sp., and *Amphistegina* sp., mix with *Elphidium* sp. and *Ammonia* sp. which adapt in the litoral environment (Figure 3). Moreover, many foraminifer shells are broken and abraded which can be formed due to high energy condition.

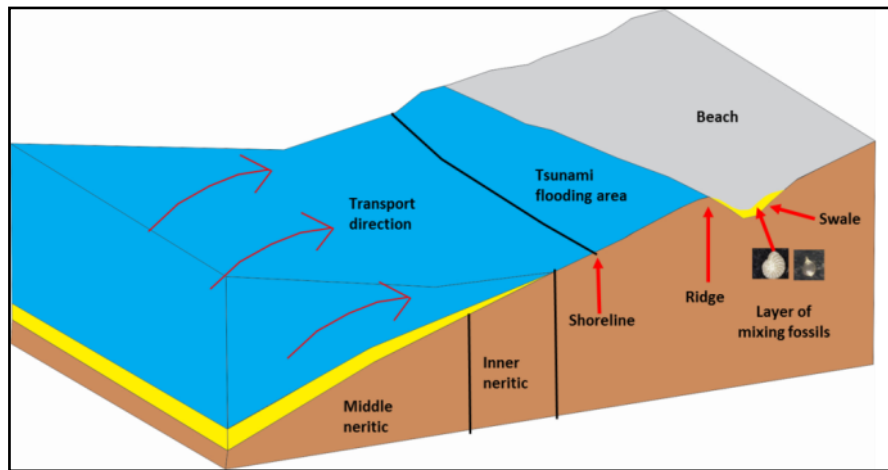


Figure 3 Illustration of transport fossil mechanism during tsunami activity. Paleo-tsunami was characterized by layer of mixing faunas and deposited in swale area.

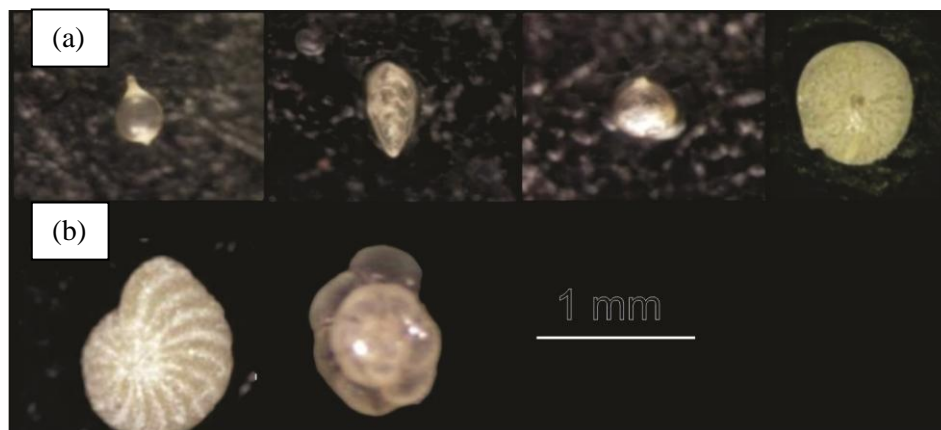


Figure 4 Micro-fauna from paleo-tsunami layers in Cilacap Area. (a) Microfossil from middle neritic environment (left to right); *Lagena* sp., *Bolivina* sp., *Oolina* sp., *Amphistegina* sp. (b) Micro-fauna from littoral environment (left to right); *Elphidium* sp. and *Ammonia* sp.

Grain size analysis of paleo-tsunami deposits performs fine – medium sandy sediment with rip-up clast as paleo-tsunami characteristic in Cilacap Area. Mean grain size of paleo-tsunami deposit is vary and shows fining-up succession and decreasing grain size from 2.63ϕ to 2.44ϕ . Relative dispersion has 0.474 and indicates excellent homogeneity and well-sorted sand. The distribution shows very finely skewed (around 0.1 – 0.3). All distribution reveal meso-kurtosis (kurtosis from 2.5 – 3.7). The distribution curves show the unimodal curve with another small peak at the end (Figure 5).

The unimodal grain-size distribution curves are interpreted as a re-deposition of the material from one source. The primary source of the mud fractions as the rip-up material is the re-deposited marine mud. The fact that the sediment source came from the marine deposit is revealed by the presence of neritic benthic foraminifera fossils (Figure 4) among which littoral benthic fossil. This indication is concluded as bottom erosion was developed during tsunami which carried out neritic foraminifera and settled out in the tsunami deposits [20].

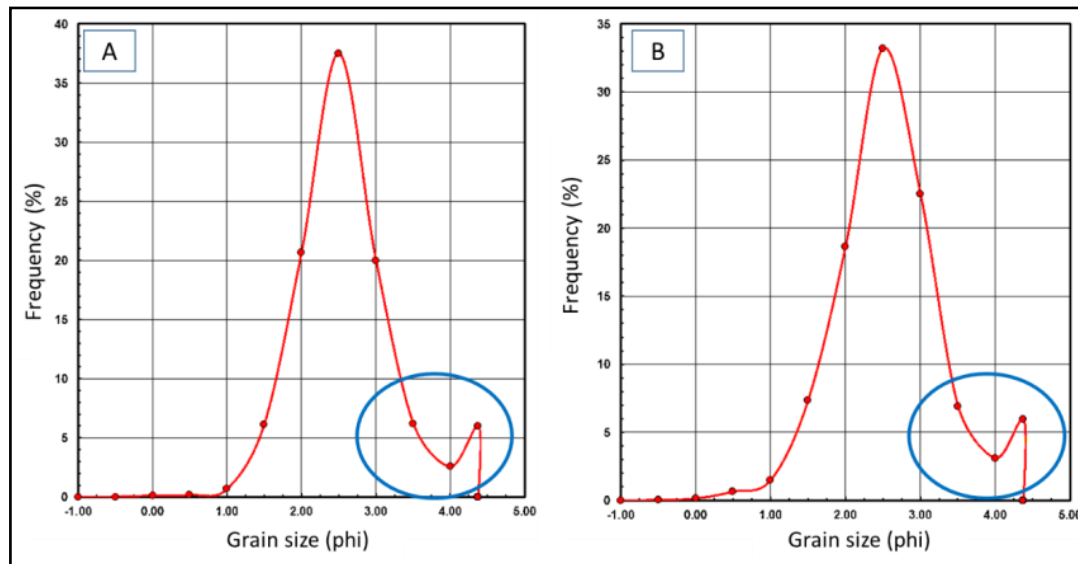


Figure 5 Distribution curves of paleotsunami deposit from Cilacap Area; (A) Glempang Pasir (GPS) location and (B) Selok. Small peak is observed at the end of curve (blue circle).

Yudhicara et al. [5] was analyzed the 2002 and 2007 storm deposit from Bunton location, Cilacap (Figure 6) and it became the good comparison between storm and paleo-tsunami deposit in Cilacap Area. Yudichara et al. [5] reported that storm deposits showed the coarse sand material, with coarsening upward features, poorly sorted material, without rip-up clast. This layers were not found fossil contain. The distribution curve showed unimodal peak with small peak at the start of distribution (Figure 7). Compared to storm deposit, the tsunami deposits in Cilacap Area exhibit the different characteristic which mentioned before. Tsunami deposit show fine sand – clay, rich fossils contain, and rip – up material.



Figure 6 The storm deposit from Bunton location, Cilacap [5].

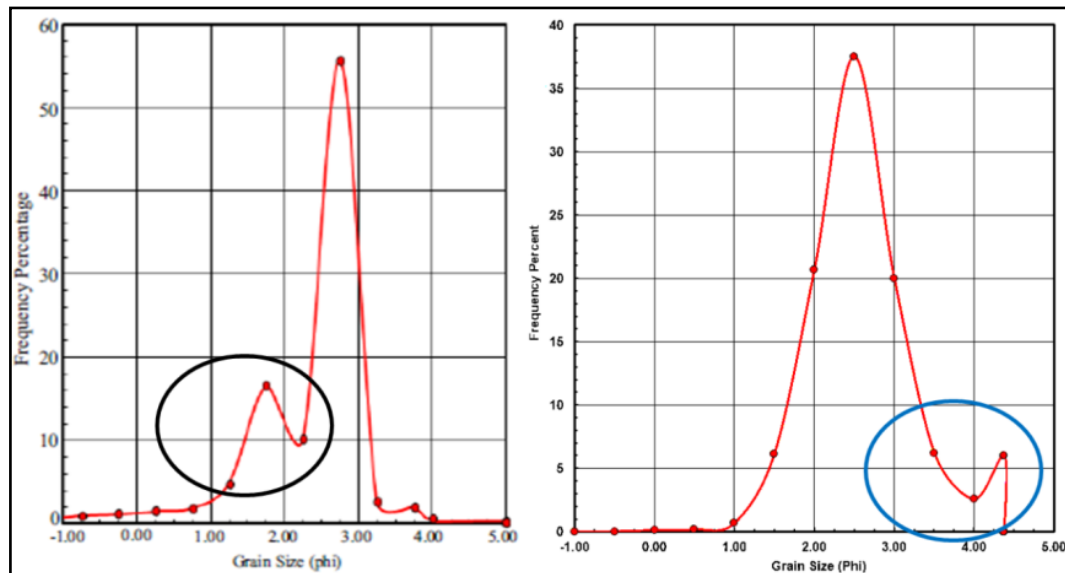


Figure 7 Distribution curve comparison between storm deposit (left) and tsunami deposit (right). The storm deposit has coarser material than tsunami deposit and small peak at the start (black circle). However, tsunami deposit has finer material and small peak at the end (blue circle). The picture of storm deposited was cited from [5].

3.2. Dating and the age of Paleo-tsunami deposits

Accurate and precision dating analysis is very important to reconstruct history and frequency of paleo-tsunami in Cilacap Area. The samples from Glemgang Pasir (GPS) location were chosen for ^{210}Pb dating because the outcrop in this location showed clearly paleo-tsunami signatures and easy to distinguish with another beach sand deposit which was deposited below paleo-tsunami sediments. The result of ^{210}Pb dating can be seen in Table 2.

Table 2 Result of ^{210}Pb dating from Glemgang Pasir (GPS) location.

Paleo-tsunami layer	Paleo-tsunami signatures	The age of sediment (years ago)
PS-C	Rip up clast, erosional contact.	10.6 ~ 2006
PS-B	light gray sandy clay, paleosoil,	29.6 ~ 1982
PS-A	Light gray sand	138.9 ~ 1883

^{210}Pb dating represents the conclusive result of paleo-tsunami history in the Cilacap Area. Three paleo-tsunami candidates give the strong correlation with earthquake event in Southern Java. The result of PS-A around 138.9 years ago correlates with 1883 earthquake which reported by BMKG catalogue [6]. Based on this report, 1883 earthquake triggered tsunami hazard which the source of earthquake and tsunami came from java trench movement in Southern Java (BMKG, 2010; source data from NOAA). Unfortunately, the catalogue was not written the magnitude of earthquake and the amount of fatalities which caused by tsunami and earthquake.

PS-B layer shows 29.6 years ago. This sediment was deposited as a product of earthquake activity in 1982, which near with ^{210}Pb calculation. BMKG [6] reported that 1982 earthquake was magnitude

5.4 Richter Scales and resulted 10 meters tsunami waves. Total of damage and injuries were not reported in BMKG [6] (source data from NOAA).

PS-C layer indicates 10.6 years ago as evidence of 2006 tsunami. The source of earthquake was Java Trench, with magnitude 7.7 Richter Scales. The damage was reported total 664 peoples death in Southern Java [6]. Rosyidie [7] counted the effect of tsunami resulted 600 people death and 15 people lost. Tsunami 2006 covered not only Cilacap Area, but also Ciamis, Pangandaran, Cipatujah, Tasikmalaya. Almost all of public facilities and recreational area were collapse [6]. The documentation of dangerous tsunami 2006 in the electricity power plant of Cilacap was recorded by Putra and can be seen in Figure 8.

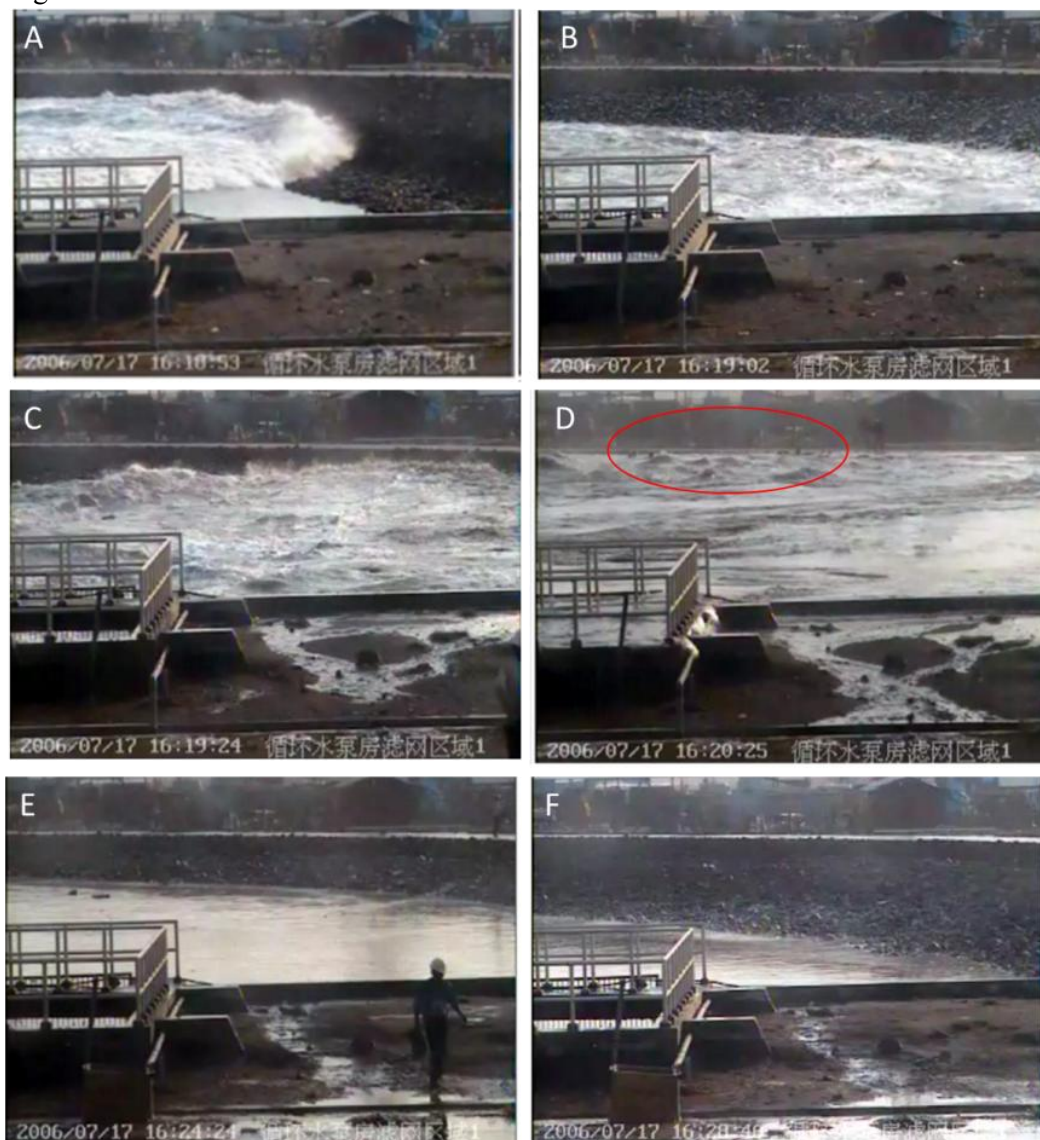


Figure 8 Effect of 2006 tsunami in the electricity power plant of Cilacap. (A). Tsunami started to flood at 16:18:53. (B). First wave of tsunami at 16:19:02 filled power plant area. (C) The second wave came at 16:19:24. (D). Highest waves at 16:20:25. Power plant workers were brought by tsunami waves (red circle). (E) The tsunami waves started down at 16:24:24. (F) Normal condition of sea level at 16:28:40 LT. All of photographs were taken by Putra and cited from [3].

3.3. Regional correlation

Paleo-tsunami correlation is developed to establish stratigraphic continuity of target paleo-tsunami layers in Cilacap Area. Paleo-tsunami event is correlated based on: a) clearly observation of the deposits in the field, b) number of paleo-tsunami layers, c) morphology of paleo-tsunami sites. Glemgang Pasir (GPS) location was chosen as the key profile because this section has complete laboratory analysis, including micro-fauna, grainsize, and dating, and clearly observed in the field.

Three paleo-tsunami layers which were recognized in Glemgang Pasir (GPS) location is correlated into paleo-tsunami deposits from another location in Cilacap Area (Figure 9). PS- A layer from GPS location continue into Kebundalam, Kesugihan, and Lengkong location. PS-A layer is missing in the Bunton, Selok, and Widarapayung because the sites were not dug deeper. PS-A has similar thickness in all of location, and it indicates that beach morphology when the tsunami happened has flat morphology. 1883 earthquake which triggered tsunami brought and uniformly distributed along Cilacap Coastline.

PS-B layer was deposited with the maximum thickness in Kesugihan Location, around 15 cm. This thickness represents that Kesugihan Location when tsunami destroyed in 1994 was a depression and the other location located in higher morphology than Kesugihan.

PS – C layer, a product of 2006 earthquake, deposited along Glemgang Pasir – Selok – Bunton for the maximum thickness. In higher location, Kesugihan, Kebundalam, Widarapayung, and Ketapang, tsunami deposits deposited with the thinner thickness. Erosion made tsunami deposits preserved in weather condition and reduce the thickness of deposits.

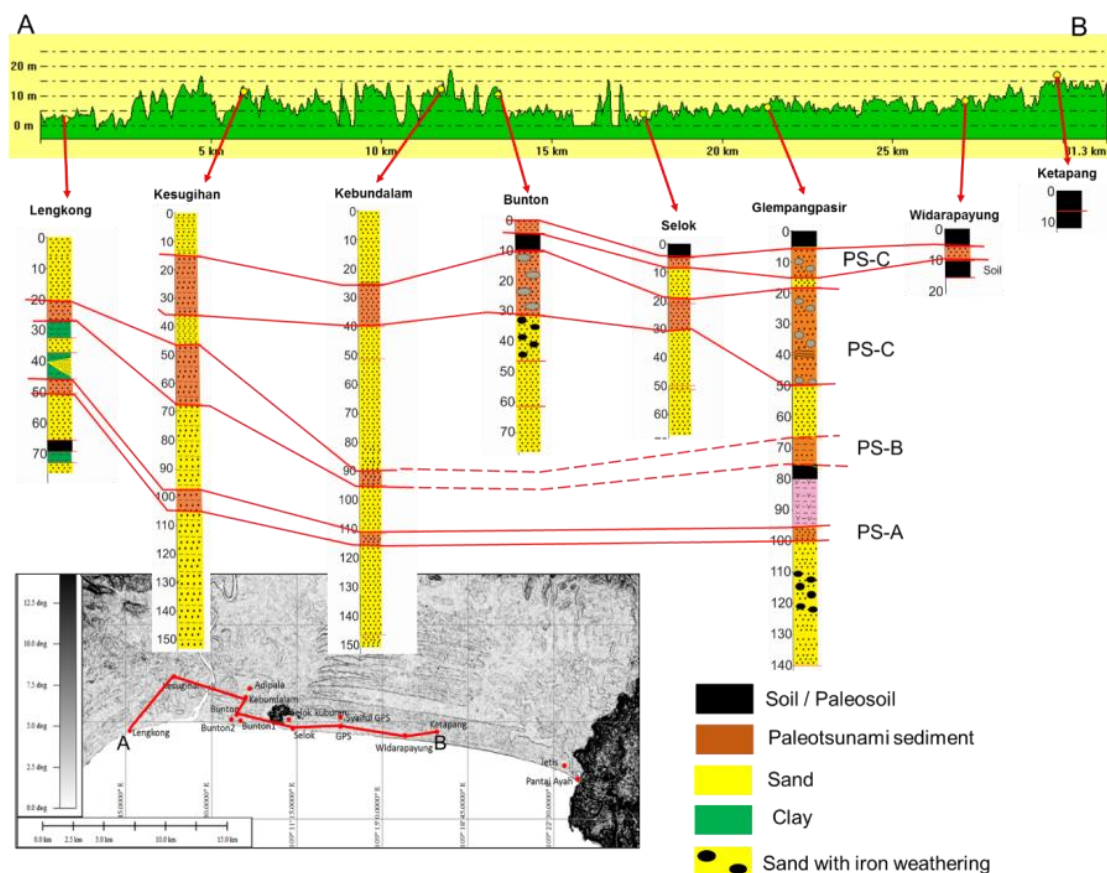


Figure 9 Correlation of Paleo-tsunami deposit in Cilacap Area

4. Conclusion

Three paleo-tsunami deposits in Cilacap Area were clearly identified, namely PS-A, PS-B, PS-C. PS-A has light gray sand, very fine – fine grain, with carbon fragment in the bottom with 5 cm thickness. PS-B observation shows sandy clay, light gray, and paleo-soil in the bottom part. PS - C can be distinguished by light sand, medium – coarse sand, rip-up clay, and erosional contact in bottom part.

The result of micropaleontology represents the mixing layer of faunas as paleo-tsunami indicator. The fossils which live in the neritic environment, *Oolina* sp., *Bolivina* sp., *Lagena* sp., and *Amphistegina* sp., mix with *Elphidium* sp. and *Ammonia* sp. which adapt in the litoral environment. Grain size analysis revealed fine – medium sandy sediment, rip-up clast, and the unimodal curve as paleo-tsunami characteristic in Cilacap Area. The unimodal grain-size distribution curves perform as a re-deposition of the material from one source.

The dating analysis shows the strong correlation between paleo-tsunami and earthquake event which the source was triggered by java trench activity. PS-A was deposited as a product of 1883 earthquake. PS – B was triggered by 1982 earthquake with magnitude 5.4 Richter Scales. PS – C, the youngest deposit in Cilacap Area, formed as evidence of 2006 tsunami with magnitude 7.7 Richter Scales.

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