

Characteristics of Paleotsunami Sediments, A Case Study in Cilacap and Pangandaran Coastal Areas, Jawa, Indonesia

Ciri-ciri Sedimen Paleotsunami, Studi Kasus di Wilayah Pantai Cilacap dan Pangandaran, Jawa, Indonesia

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ABSTRACT

A paleotsunami study having been conducted in 2011 took two study cases in Cilacap and Pangandaran coastal areas. These two regions have been devastated by tsunami in the past and had the most severe damaged on 17 July 2006. Trenching, beach profiling, and sediment sampling had been carried out, and further analysis at the laboratory had been done, such as grain size and fossil analyses and dating. In Cilacap, an iron sand layer was found as a key bed suspected as a paleotsunami deposits due to the content of anthropogenic fragments. In Pangandaran, two layers of tsunami deposit candidates were found having thickness of 5 - 6 cm at the top as a 2006 tsunami deposit candidate, and 5 - 10 cm at the bottom as a paleotsunami deposit candidate. Both grain size and fossil analysis results could explain that Pangandaran's sediments are tsunami deposits while Cilacap's ones are assumed to be deposited by another process rather than a tsunami.

Keywords: beach sediments, tsunami deposits, paleotsunami, grain size, fossil analysis

ABSTRAK

Pada tahun 2011 telah dilakukan studi paleotsunami dengan studi kasus di dua tempat, yaitu di wilayah pantai Cilacap dan Pangandaran. Kedua tempat ini memiliki sejarah pernah mengalami tsunami dan mengalami kerusakan paling parah saat terlanda tsunami pada tanggal 17 Juli 2006. Pekerjaan lapangan seperti pembuatan paritan dan penampang pantai serta pengambilan percontoh sedimen telah dilakukan. Analisis lebih jauh di laboratorium seperti analisis besar butir dan identifikasi fosil telah dilaksanakan. Dari Cilacap, ditemukan lapisan pasir besi sebagai lapisan kunci yang dicurigai sebagai endapan tsunami karena mengandung fragmen antropogenik. Sementara di Pangandaran, ditemukan dua lapisan sedimen yang dianggap sebagai endapan tsunami dengan ketebalan 5 - 6 cm di bagian atas sebagai endapan tsunami 2006, dan endapan paleotsunami di bagian bawah dengan ketebalan 5 - 10 cm. Hasil analisis besar butir dan fosil menunjukkan bahwa singkapan sedimen yang ditemukan di Pangandaran adalah endapan tsunami, sedangkan singkapan sedimen yang ditemukan di Cilacap bukan endapan tsunami melainkan endapan proses lainnya.

Kata kunci: sedimen pantai, endapan tsunami, paleotsunami, besar butir, analisis fosil

INTRODUCTION

The southern coast of Jawa has experienced tsunamis caused by earthquakes that were associated with subduction zone from the south of Jawa. A paleotsunami study has been conducted in order to understand the tsunami behaviour along this area by taking the case study at two places which are in Cilacap and Pangandaran. This study was conducted in a collaboration among Bandung Institute of Technology (ITB), Agency for Meteorological, Climate and Geophysics (BMKG), and Geological Agency.

Tectonically, Jawa Island is controlled by the main tectonics of Sunda subduction system of the collision between the Indian-Australian and the Eurasian Plates. The collision leads to the presence of many earthquakes occurring in the region due to this system and some of them were causing tsunamis.

According to Newcomb and McCann (1987), there were several tsunamis that had ever been

recorded in the southern coast of Jawa, such as 4 January 1840, 20 October 1859, and 11 September 1921 (Figure 1).

The last two tsunami events of 3rd June 1994 and 17th July 2006 had also attacked most of the southern coast of Jawa, including Cilacap and Pangandaran areas. Those two areas had the most suffered area in the 2006 tsunami event. Hence, this study took case studies in these two places (Figure 2). On the other hand, Cilacap is the site that has some environmental issues such as iron sand mining which still continues up to now.

METHODS

Some prospect outcrops of the tsunami deposit candidates were found both in Cilacap and Pangandaran areas. Trenching and sampling have been done at some locations along the studied area, using grab

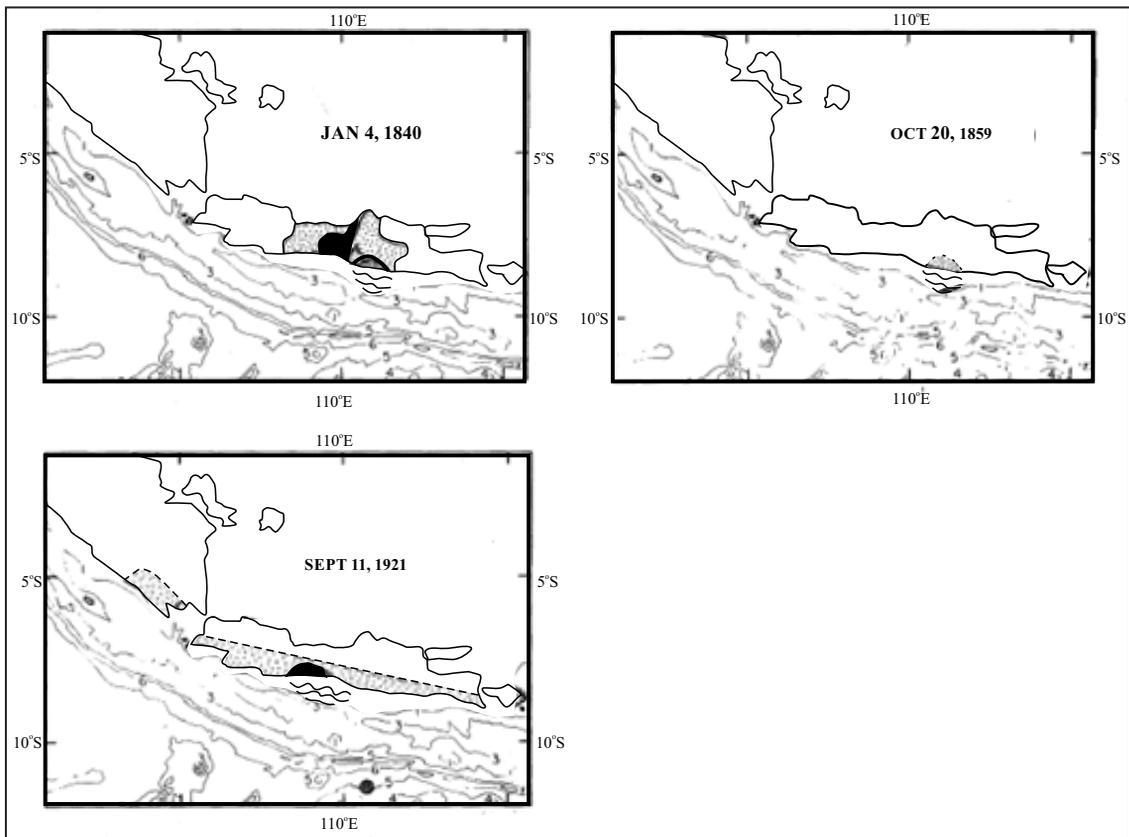


Figure 1. Historical tsunami events triggered by earthquakes. Shaded region were earthquake intensity, darker colour is higher than lighter colour, the tsunami impacted areas are shown by water mark (Newcomb and McCann, 1987).

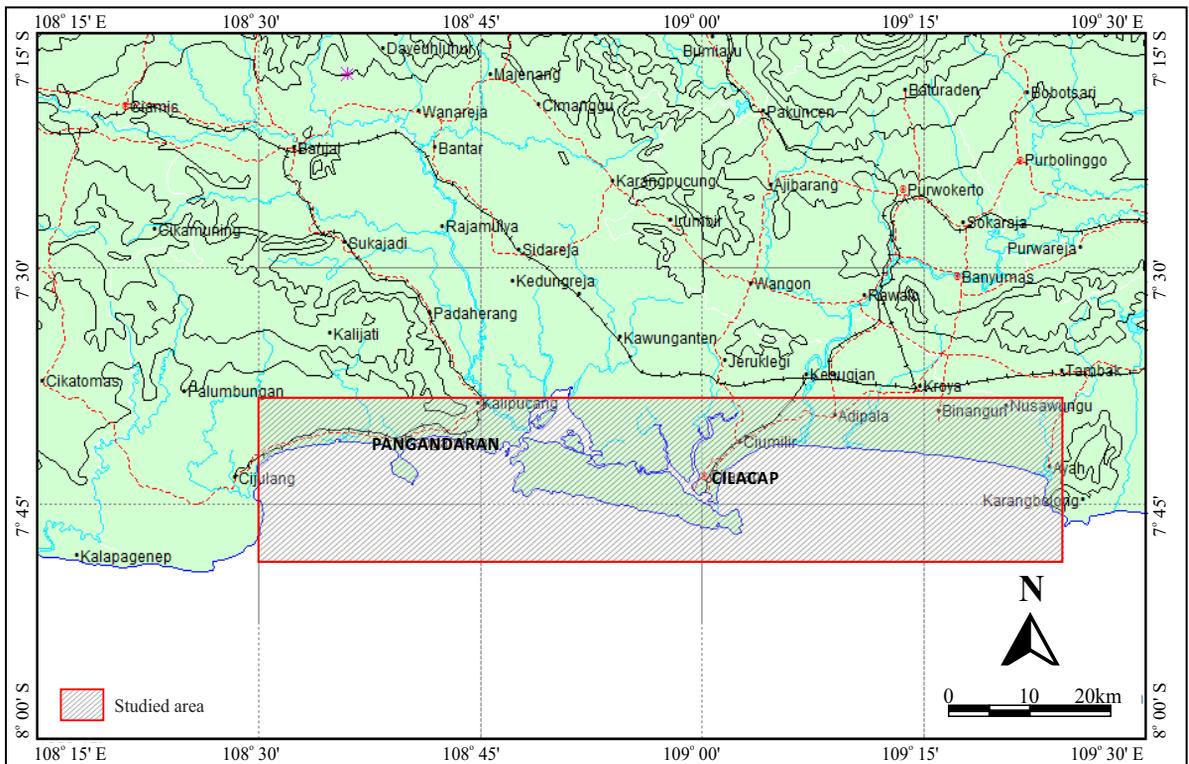


Figure 2. Locality map of studied area.

sampling. Shallow core beach profiling measurement was taken in order to see the existing morphology and how it affected the deposits (Figure 3).

A laboratory analysis has been conducted on selected samples, both grain size and fossil determinations. Dry sieving grain size analysis was applied and computation refers to Balsillie *et al.* (2002) programme. This is a plotting programme in excel which has intended primarily as a visualization tool for sediment grain-size distributions. Fossil analysis was carried out to identify whether there are mixing ages, mixing environment of land, transition, and marine fossils, and to see how deep those fossils rose from the sea bottom.

²¹⁰Pb method was applied in order to know the age of each layer in one outcrop by knowing how much ²¹⁰Pb content inside is (Boer *et al.*, 2006), using the formula ²¹⁰Pb decay (www.rl.ac.uk/UKDMC/Radioactivity, 1997):

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

Because of the dry soil, the core could be taken only for layers just under the key layer of Cilacap sample, and this core was dated using ²¹⁰Pb method.

FIELD FEATURES

Cilacap

Seven locations along the coast of Cilacap, such as Lengkong, Bunton, Selok, Widarapayang, Keta-pang, Jetis, and Ayah Beaches had been described. However, this study focuses only on one location which is at Bunton, because the outcrop condition in this site was more representative than in other locations (Figure 4).

At Bunton Village there is an outcrop at the road bank, as a continues layer with iron sand sheet used for a key bed lying under the recent soil. This iron sands have physical properties of solid and compact layer overlying sand layer containing rock fragments of gravel to pebble sizes trapped within the sediments. While sand having a parallel lamination structure is deposited at the bottom.

There are five layers which have gradual changing in colour and texture. A megascopic analysis on one outcrop from the bottom to the top respectively is as follows: (1) paleosoil containing fine grey sand sheet, has a sedimentary structure of parallel lamina-



Figure 3. Photograph of core sampling.

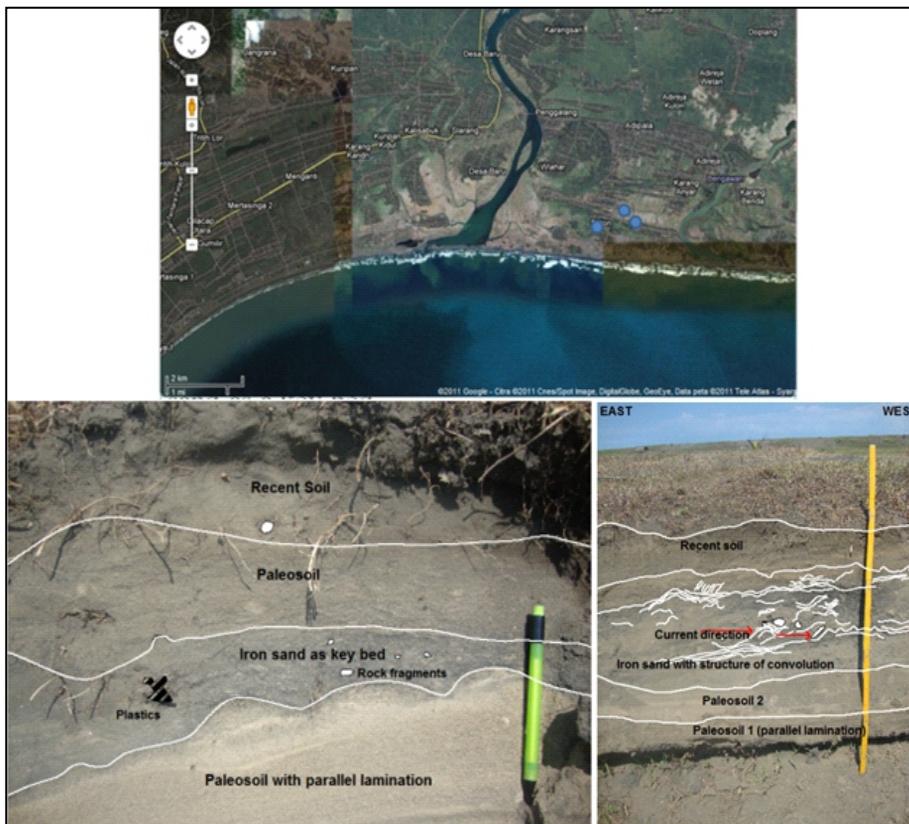


Figure 4. At least five layers of Bunton outcrops are anthropogenic within sediments of iron sand is claimed as a key bed layer. The direction shows the current involvement, and sediment structures show deposition energy. The White star is the location where samples are taken for dating.

tion; (2) fine sand layer of light grey containing rock fragments as inclusion with gravel to pebbles sizes underlying the (3) coarse black iron sand consisting of anthropogenic fragments, such as plastics, that show convolute sedimentary structure. This layer could be found in any exposure around the area. That is why this layer is claimed as a key bed.

At another location in the same area, this key bed shows cross bedding, dune, anti dune, and ripple structures (Figures 4 and 5). There are some rock fragments showing orientation to the certain direction (relatively from the east to the west), and anthropogenic fragments representing human activities remnant within the sediments, such as plastics, bottles, rubber wheels, and clothes. In general, the sediments have properties of fine- to coarse-grained sand, grey to blackish colour. Some of them contain rock fragments, and they are separated by gradual to sharp boundaries. There is a three centimeters of clay intercalation between sand layers.

At other locations in Cilacap area such as Ayah Beach, tsunami deposit was not found. It is assumed that tsunami sediments could not be carried due to decreasing tsunami wave energy when the wave reached Karang Bolong Hills.

At Widarapayung, it was difficult to distinguish the tsunami deposit even for the 2006 event. It is because the soil texture is very fine and loose, so when tsunami inundated the area in a very short time, the soil immediately absorbed it. It is difficult to distinguish between the recent tsunami sediment with the soil because of the grain mixing.

Pangandaran

In the Pangandaran area, the studied locations are Cikembulan and Karapyak regions. At the Cikembulan, the 2006 tsunami deposit candidate was obtained. In this location, based on the last tsunami in 2007, the 2006 tsunami deposits are a very thin at the top of the soil, and the paleotsunami candidate about 20 cm from the top has the thickness of 3 to 5 cm. Nearby the beach, there is the 2006 tsunami deposit occurring as very fine grey sand, and is covered by modern soil. The sample of modern sand beach was taken for a comparison between tsunami sand and modern beach sand.

Karapyak which is in the eastern part of the Pangandaran area has experienced a severe damage when the 2006 tsunami event hit this area. The tsunami run up height was about 8 m from the sea



Figure 5. Sand exposures at Bunton, Cilacap, showing different colours among layers, erosional boundaries, rock fragments, and current involvements.

level (Suantika *et al.*, 2006). There are two layers which are suspected as the recent tsunami deposit at the top (having thickness of 5 - 6 cm) and paleotsunami deposit at the bottom (having thickness of 5 - 10 cm) (Figures 6 and 10). Those two layers have similar properties, such as white to yellowish colour, poorly sorted, subrounded to rounded grain shape, and loose grain characteristics.

LABORATORY ANALYSIS

Grainsize Analysis

Cilacap area

Based on grain size analysis, each layer of Bunton samples in Cilacap area shows unimodal curve with the value ranging between 0.34 to 2.31 phi, that means the material is dominated by coarser sand rather than finer one. Paleosol was also composed of coarser grain but finer upward. Another layer has a coarsening upward feature, showing a stronger current involvement represented by its

sediment structure such as convolute. Based on the grain size cumulative percent curves, it shows that the saltation transport mechanism is more dominant as similar as a normal beach deposition, but the whole exposed sediments is created by the traction mechanism rather than suspension.

The megascopic description shows that grain texture of key bed at the Bunton outcrops is sub-angular, composed of mafic and felsic minerals in the same portion and poorly sorted reflected by its grain size distribution curve (Figure 7). The grain size analysis of this iron sand layer shows a unimodal curve, which is determined by a single source but varied in deposition energy. The grain size cumulative percent curve shows that this layer is dominated by traction and saltation process representing a strong current involved into the depositional time. However, it was suddenly fall off, reflecting that something extreme happened here. This mechanism of the sand layer is relatively different from the other layer, explaining that the mechanism of the deposition immediately changed at the time.

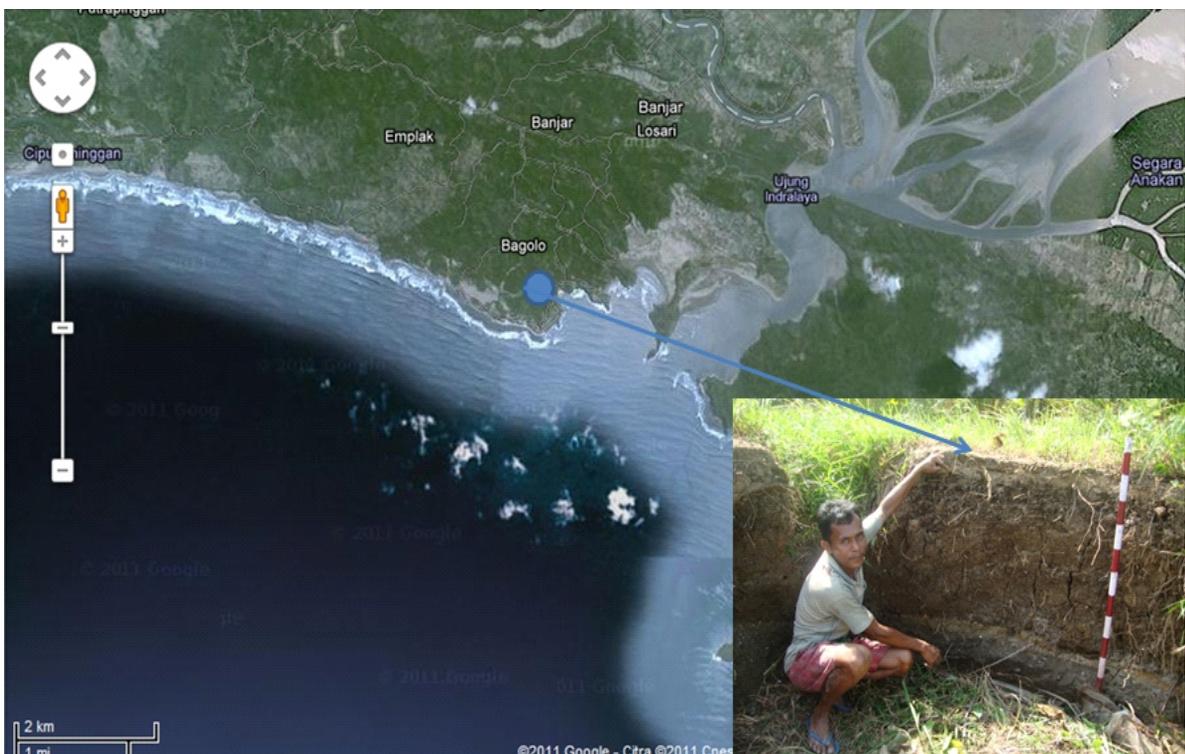


Figure 6. 2006 tsunami at the top and paleotsunami candidate at the bottom found at Karapyak, Pangandaran.

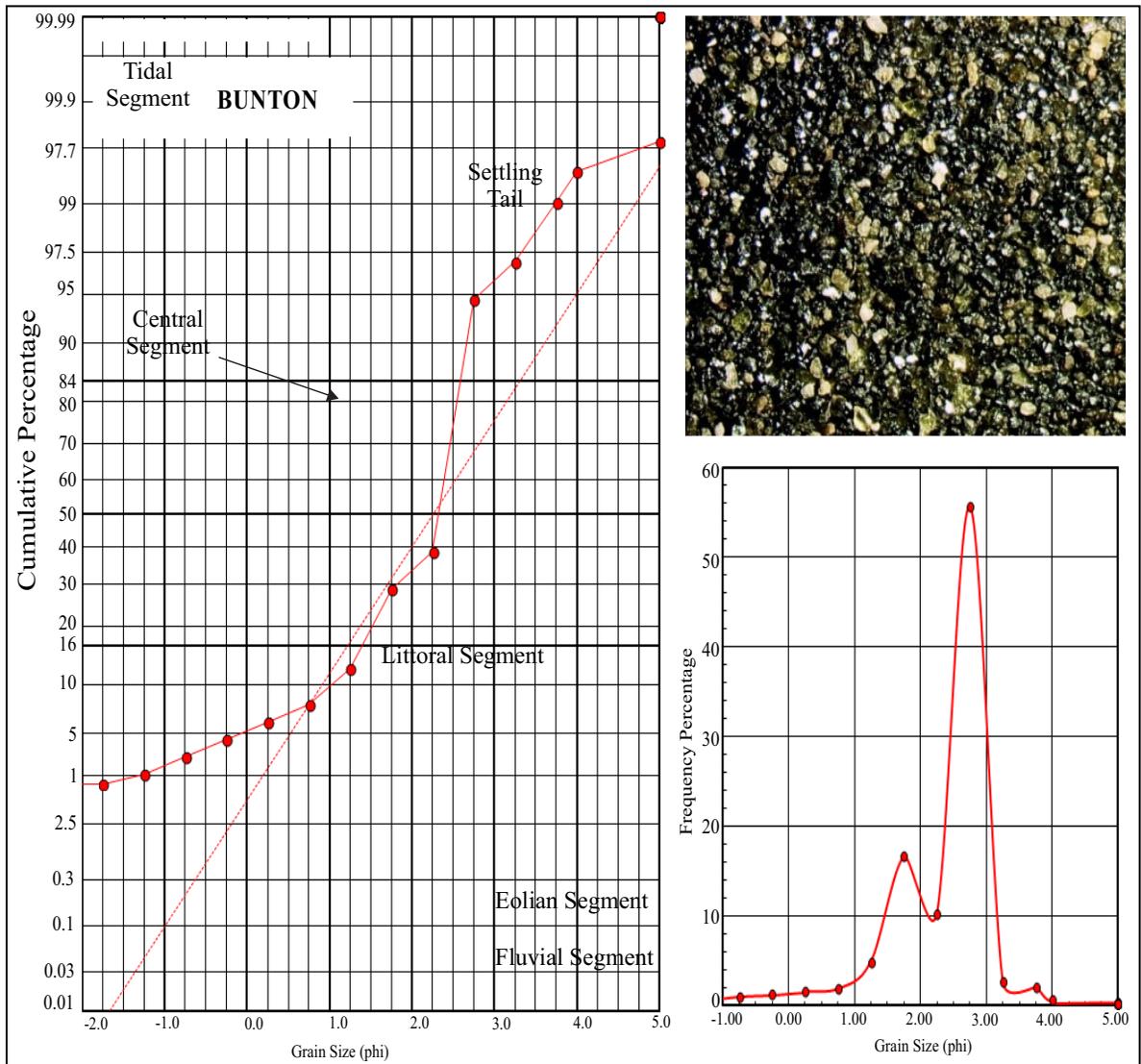


Figure 7. Grain size analysis of iron sand as a key bed layer from Bunton, Cilacap. Graph show dashed straight line as the precise Gaussian fit based on the sample mean and standard deviation (left); and grain size distribution curve (lower right).

Pangandaran area

At least two samples were taken from Cikembulan at Pangandaran area where the 2006 tsunami deposit was found 200 m away from the coastline. Three layers contain paleosol under the 2006 tsunami sands (having thickness of 5-10 cm) overlain by recent soil. The grain size analysis result shows that there is a bit difference between suspected 2006 tsunami sand layer and the recent beach sand. The grain size distribution curve of suspected 2006 tsunami has two modes (bimodal) reflecting two different material sources, while the recent soil shows

also two peaks but it tends to have a unimodal peak. Probably, there is a mixed tsunami deposit with the recent soil by the wind (Figure 8).

Grain size distribution from a recent Cikembulan beach sand shows two peaks of sand material of 1.75 ϕ and 2.75 ϕ which relatively form a unimodal curve, reflecting a difference in deposition mechanism, but it has only a single source. It can be described that this sample represents a normal beach deposit. Grain size cumulative percentage curve of recent beach sand shows deposition process of low energy at the beginning, then moving gradually with a relatively

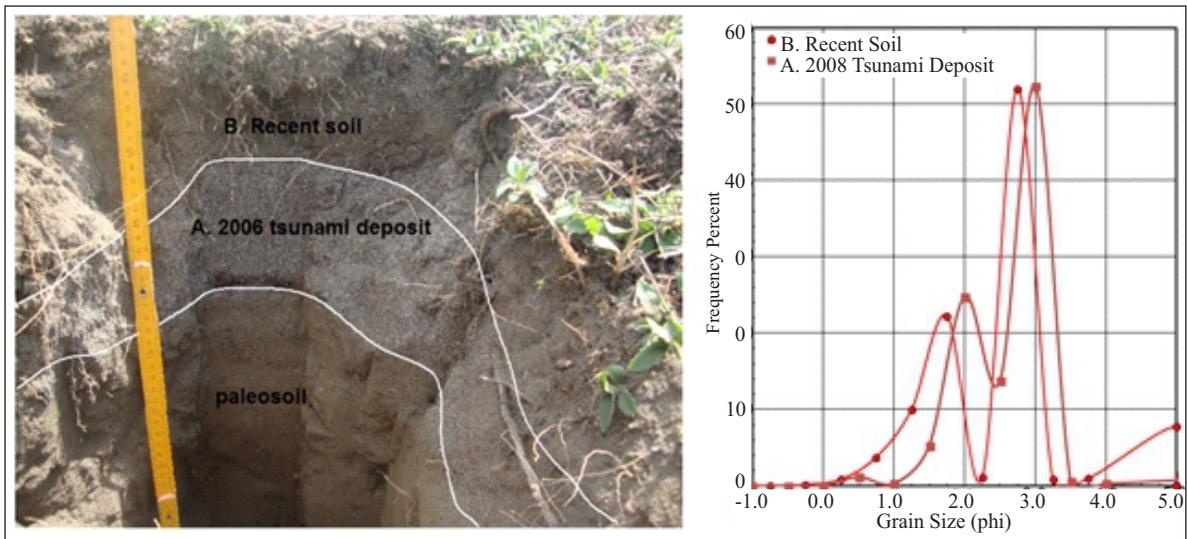


Figure 8. Grain size analysis of 2006 tsunami deposit (A) and recent soil (B) at Cikembulan. Graph show dashed straight line as the precise Gaussian fit based on the sample mean and standard deviation (left); and grain size distribution curve (right).

saltation mechanism. It is reasonable for beach sand which has behaviour of always being transported by the wind and sea water. Different from beach sand at Cikembulan, beach sand from Karapyak beach has only one mode (unimodal) of 2.75ϕ with domination of saltation process compared with another process (Figure 9).

The megascopic description of the Karapyak outcrops shows that the 2006 tsunami and paleotsunami candidate have subrounded to rounded grain shape, consisting of rocks, shells, and fossil fragments. Based on a stratigraphic section, the Karapyak outcrops consist of six layers, from the bottom to the top: (A) older paleosol has dark grey colour, coarse to very coarse sand, composed of white mineral and fossil (>30 cm thick); (B) paleotsunami candidate has yellow colour, coarse- to very coarse-grained (5 - 10 cm thick); (C) younger paleosol has brown to dark brown colour, containing rock fragments (60 cm thick); (D) paleosol of highly weathered clay (12 cm thick); (E) the 2006 tsunami deposit has yellow and very coarse-grain size (5 - 6 cm thick); and (F) recent soil (3 cm thick) (Figure 10).

These grain size distribution curves (Figure 11) show a very interesting charts of low energy of deposition. The paleotsunami candidate (B) has a unimodal curve with mean of 2.25ϕ (coarse sands), showing relatively low energy at the beginning then mixing mode of transportation at 10%. While the

2006 tsunami candidate (E) has a unimodal curve with mean of 2.75ϕ (coarse sand), with mixed transportation process, low energy at the beginning then changing abruptly at 1% and 30%.

Grain size of frequency cumulative curves (Figure 12) shows different tsunami types, paleotsunami candidate (E, F) and paleosol (C, D). A and B show mixing on saltation and suspension, small traction involved in the deposition process. Layers C and D exhibit mixing of traction and saltation is more dominant than suspension. While E and F reveal mixing of saltation and suspension is similar to A and B. Those layers are bounded by sharp, gradually, and erosional boundaries. Another character shown on those two layers is remains of vegetation root.

Fossil Identification

There is no planktonic nor benthic foraminifera found within the Bunton samples. While the Pangdaran samples have both planktonic and benthic foraminiferas within both 2006 tsunami candidate at the top and paleotsunami candidate at the bottom.

The 2006 tsunami candidate (E) contains planktonic foraminiferas such as: *Globoquadrina dehiscens* Chapman, Parr and Collin, *Gq. altispira altispira* Cushman and Jarvis, *Globigerinoides bulloides* Crescenti, *Gs. trilobus trilobus* Reuss, *Gs. ruber* d'Orbigny, *Gs. trilobus immaturus* Le Roy, *Gs. subquadratus* Bronnimann, *Globorotalia*

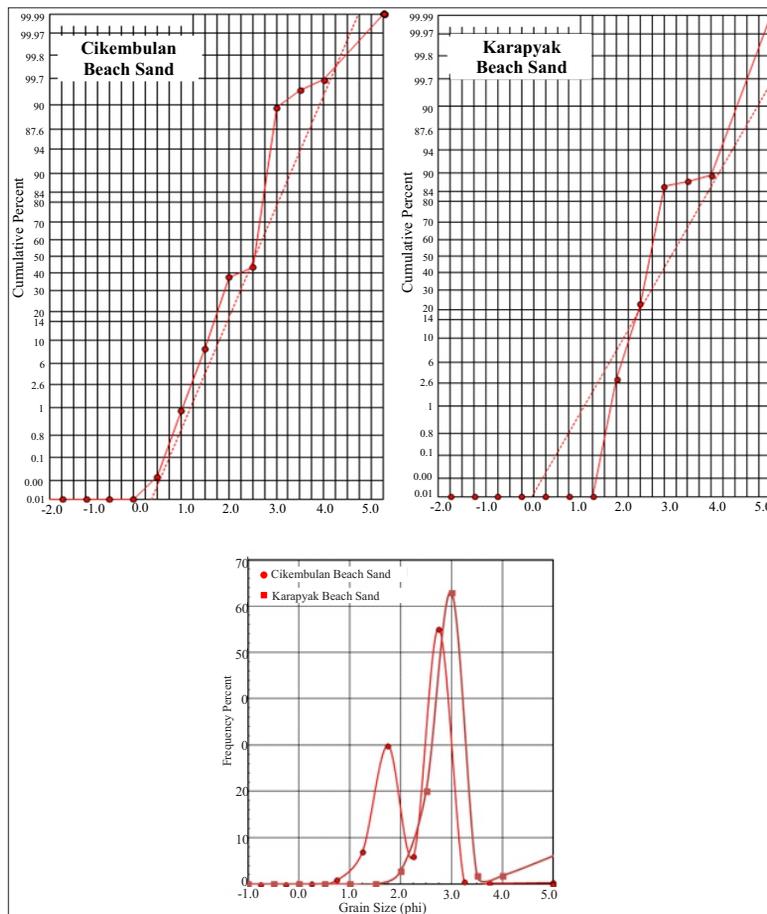


Figure 9. Grain size analysis of modern sand of Cikembulan (top) and Karapyak (bottom), Pangandaran.

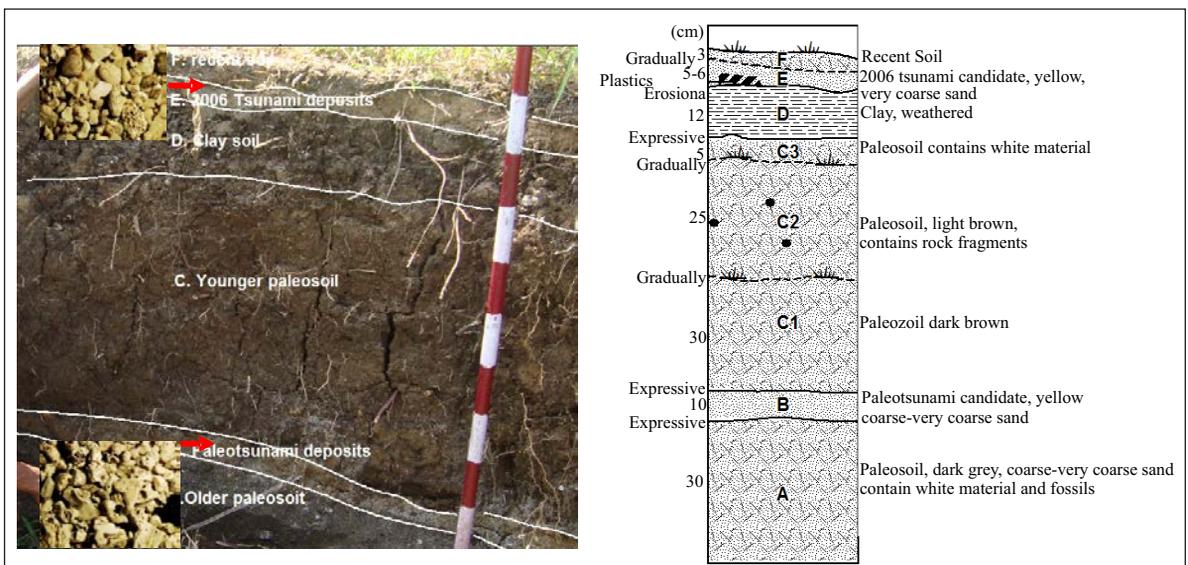


Figure 10. Detail columnar stratigraphic sections of two tsunami deposits at Karapyak, Pangandaran.

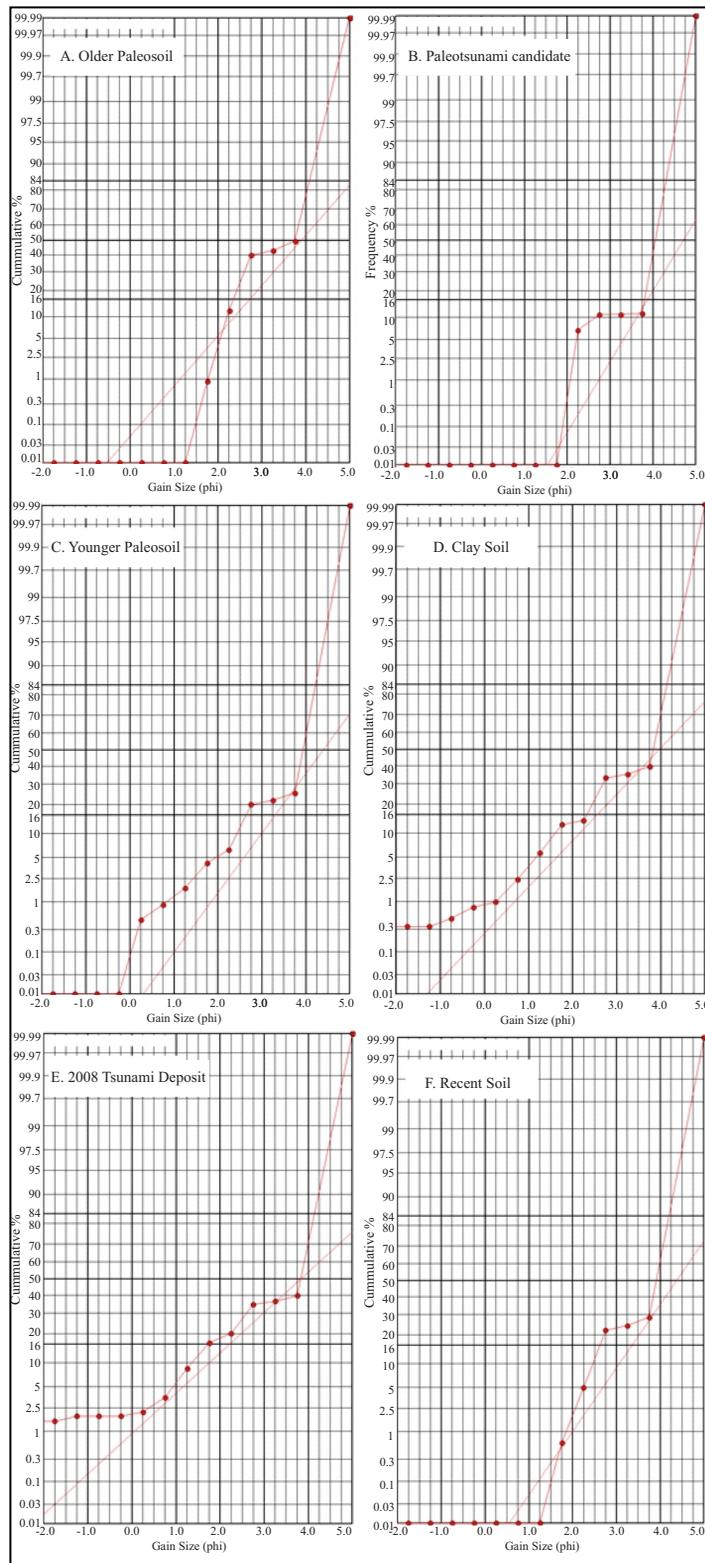


Figure 11. Grain size distribution graphs of Karapyak outcrop. Cumulative percentage as ordinate (y) and grain size (phi) in abscis (x). Dashed straight line as the precise Gaussian fit based on the sample mean and standard deviation

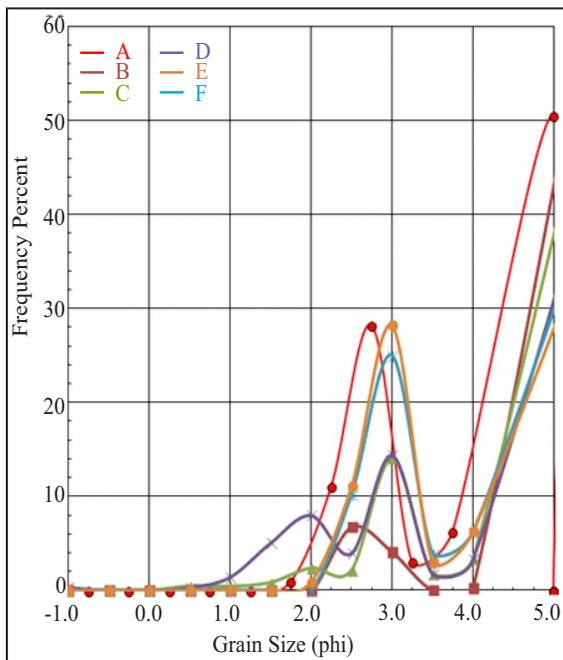


Figure 12. Grain size distribution curves of Karapyak outcrop. Frequency percentage as ordinate (y) and grain size (phi) as abscis (x).

mayeri Cushman and Ellisor, *Gl. continuosa*, Blow, *Catapsydrax dissimilis* Cushman and Bermudez, *Praeorbulina transitoria* Blow, and *Neogloboquadrina acostaensis acostaensis* Blow (Patriani, 2011). Based on those fossil assemblage, the relative age of this layer is about Early Miocene.

Benthic foraminifera content in this layer comprising *Amphistegina sp.*, *Quinqueloculina lamarckiana* d’Orbigny, *Rotalia beccarii* Linnaeus, *Haplophragmium sp.*, *Tuminella sp.*, and *Hyperammia sp.* indicates coastal to marsh environment, while *Cellantus craticulatus* Fichtel and Moll, indicates an inner neritic environment (low tide-20 m) (Patriani, 2011). Shells of gastropods and bivalvia, coral and *Coelenterata* were also found which indicate a coastal environment.

Paleotsunami candidate at the bottom (B) contains reworked planktonic foraminifera such as: *Globoquadrina dehiscens* Chapman, Parr, and Collin, *Globigerinoides sp.*, *Gs. trilobus trilobus* Reuss, *Gs. subquadratus*, *Gs. trilobus immaturus* Le Roy, *Gs. praebulloides praebulloides*, *Globorotalia sp.*, *Globigerina sp.*, and *Neogloboquadrina acostaensis acostaensis* Blow, indicating mixed ages of Early

Miocene (N5-N13) and Late Miocene (N16-N17) (Patriani, 2011).

Shells such as gastropod, bivalvia, coral, and *Coelenterata* show a coastal depositional environment. This environment could also be represented by the present of benthic foraminifera such as: *Quinqueloculina sp.*, *Rotalia beccarii* Linnaeus, and *Elphidium sp.*, while the presence of *Amphistegina lessonii* Parker, Jones, and Brady, *Cellantus craticulatus* Fichtel and Moll, and *Cibicides sp.* indicates an inner neritic environment (low tide-20 m). Fossil of *Haplophragmium sp.* indicates a marsh and mangrove swamp environment. These results show that the sediments contain fossil assemblage of coastal, marsh/swamp, until shallow water environments (inner neritic) as typical of tsunami deposits.

Dating

An age determination using ²¹⁰Pb method was applied, especially on one core sample taken from Bunton, Cilacap. The method gives the absolute age information of each layer, whether the sediments were deposited by tsunami or other processes such as storm surges, or others. This sample was taken just below the key bed layer of iron sand (Figure 13).

The dating results (Table 1) show that the iron sand key bed is younger than 2001. It means, the sediment is relatively recent, but occurred before the 2006 tsunami event. It could be indicated by its position under the soil. For this reason, this iron sand (which contains anthropogenic fragments) was deposited due to other natural phenomenon not by tsunami, because tsunami did not occurred in the South of Jawa between 2001 and 2006.

According to the storm surge report gained from BMKG (Wahono, 2012) at the Indian Ocean there is tropical cyclone occurring every five years, including year 2002 and 2007. Therefore, according to the report, the Cilacap key bed might coincidentally be deposited due to the storm surge occurrence, but could be deposited by another process such as mining disposal which has also occurred in Cilacap region since 2000 and the years after. One of disposals was into the Serayu River which is located in the east of Bunton, which can explain why the direction of the sediment movement is from the east to the west that was shown by the orientation of rock fragments within the iron sand layer.

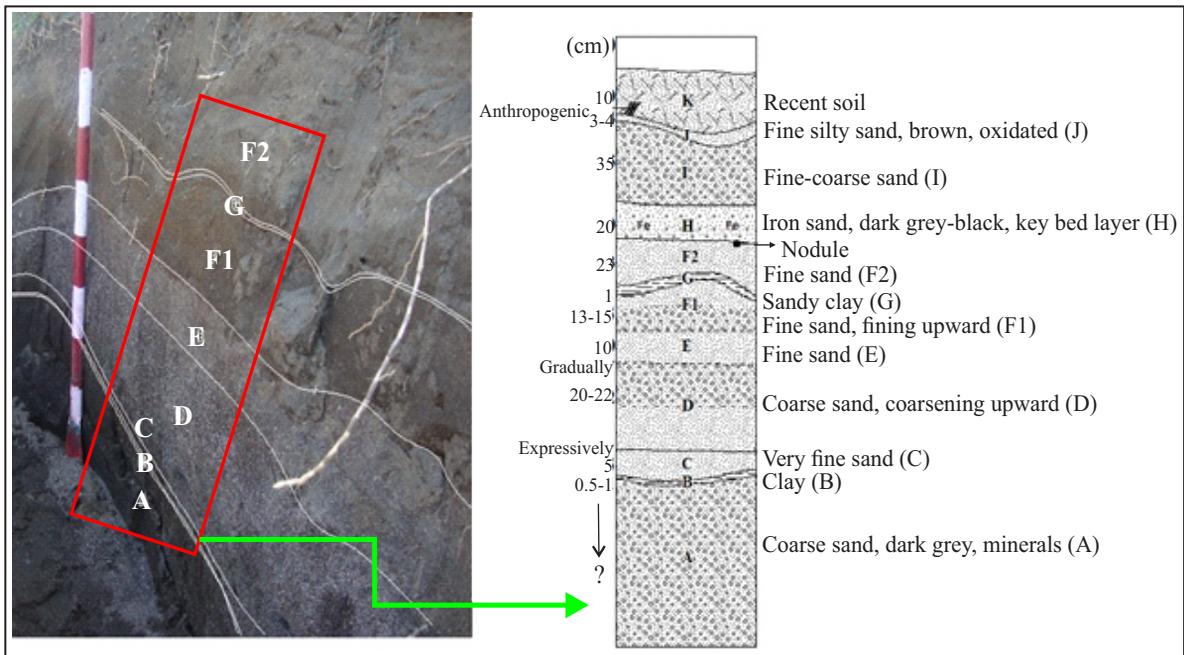


Figure 13. Bunton outcrops for ²¹⁰Pb dating analysis.

Table 1. ²¹⁰Pb Dating Result (from the top of core sample)

No.	Sample Label	Activity of ²¹⁰ Pb (Bq/kg)	Age (year)	Accumulation years
1.	0 - 5 cm	11.680	9.68	2001
2.	5 - 10 cm	9.363	18.64	1992
3.	10 - 15 cm	8.784	29.82	1981
4.	15 - 20 cm	7.722	41.01	1970
5.	20 - 25 cm	7.529	56.10	1955
6.	25 - 30 cm	6.660	69.50	1942
7.	30 - 35 cm	6.371	79.52	1931
8.	35 - 40 cm	6.178	89.84	1921
9.	40 - 45 cm	6.081	103.44	1908
10.	45 - 50 cm	5.985	119.89	1891
11.	50 - 55 cm	5.888	144.67	1866

DISCUSSION AND CONCLUSION

The iron sand layer in the Bunton area contains anthropogenic fragment (human activity remnants) remains within the sediments, and has a variation of sedimentary structures and strong current involvement indicating this layer was accumulated in a strong sediment transport mechanism. Supported by grain

size analysis, there is an abrupt changing on energy of sediment transport. No fossils found in this layer does not seem as the characteristics of tsunami deposits.

The Karapyak outcrop has a better explanation as 2006 tsunami and paleotsunami deposits, because of fossil findings both planktonic and benthic foraminifers, but grain size analysis of this outcrop tends to show a very weak energy of sediment transport. This indicates that paleomorphology at the time when paleotsunami was deposited is relatively flat, and sedimentation was in suspension mechanism rather than others. Based on the seafloor depth of fossil findings in the Karapyak, Pangandaran, it is assumed that tsunami started to scour at a very shallow water about 20 m sea deep, and there are mixed environments such as coastal, marsh/swamp, and shallow marine (inner neritic).

Although the southern coast of Jawa has experienced devastating tsunami, tsunami deposits could not easily be found along this area. Pangandaran is the site where tsunami deposit could be stored properly, while in Cilacap could not. By using dating information, the key bed found in Cilacap could be correlated with the storm surges in 2002 and 2007. But another process such as mining disposal could be the other possibility of this layer that could be deposited.

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