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Discovery of Paleotsunami Deposits along Eastern Sunda Arc: Potential for Megathrust Earthquakes in Bali

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Master of Science

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ABSTRACT

Discovery of Paleotsunami Deposits Along the Eastern Sunda Arc: Potential for Megathrust Earthquakes in Bali

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Several laterally extensive candidate tsunami deposits are preserved along coastlines facing the eastern Java Trench, indicating it has experienced mega-thrust earthquakes in the past. We investigated 37 coastal sites in Bali, Lombok, Sumba and Timor islands, many of which preserve course sand and pebble layers that overlie sharp basal contacts with scour marks into mud, fine upward in grain size, and have bimodal grain size distributions. Other unique features are the common occurrence of marine fossils and concentrations of heavy minerals. The occurrence of these high-energy deposits interlayered with clay-rich units indicate the coarse clastics are anomalous because they were deposited in what is normally a very low-energy depositional environment. The lateral extent and paucity of thin, coarse clastic layers with marine organisms are inconsistent with local stream flood event, and the proximity to the equator of the sites diminishes the possibility of marine flood events from cyclones. The sparse, but consistent, occurrence of at least two candidate tsunami deposits at depths of 1 and 2 meters over 950 km along the strike of the Java Trench may reveal that mega-thrust earthquakes have occurred there and generated giant tsunamis in the recent past.

Five widely scattered imbricated boulder deposits are also found on Bali, Lombok and Sumba. The boulders consist of slabs of hardpan up to 2.5 m in length and 80 cm thick that were torn from a near-shore seabed and stacked on top of one another. Some of the boulders were carried over the erosional coastal bank and deposited up to 100 meters inland. Comparisons with imbricated boulder ridges formed during the 1994 tsunami in east Java indicate that these deposits are from one or multiple tsunamis sourced by the Java Trench.

Experiments in effective ways to communicate and implement tsunami disaster mitigation strategies have led us to train local communities about the 20-20-20 rule. If coastal communities experience more than *20 seconds* of shaking from an earthquake, even if it is not intense, they should evacuate the coast. The time delay between the earthquake and arrival of tsunami waves is around *20 minutes*, which is the time window for evacuation. Some tsunami waves may be as high as *20 meters*, which is the target elevation for evacuation. Adopting the 20-20-20 rule could save thousands of lives throughout the region, especially in Bali where nearly 1 million people inhabit likely tsunami inundation zones.

Keywords: tsunami deposits, Sunda Arc, Indonesia, subduction zone, earthquakes, imbricated boulders, tsunami disaster mitigation

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1. Introduction

The Sunda Arc of Indonesia is the site of intense deformation related to convergence between the Australia and SE Asian plates (Figure 1). Historical records (mostly compiled from Arthur Wichmann's Die Erdbeben Des Indischen Archipels (The Earthquakes of the Indian Archipelago, 1918 and 1922, Hamzah, 2000, and Harris and Major, 2016) document that more than 100 tsunamis have struck Indonesia in the past 400 years. The most common sites of historical mega-thrust earthquakes and giant tsunamis are the coastlines of Sumatra, which is in the western Sunda Arc. One of the largest and the deadliest earthquakes and tsunamis ever recorded struck the NW Sunda Arc in 2004. Fatalities and developmental setbacks from these events have increased drastically due to exponential population growth over the past 50 years in areas at risk (Table 1). Numerous coastal communities in Indonesia are built on deposits from past tsunamis (Harris and Major, 2016).

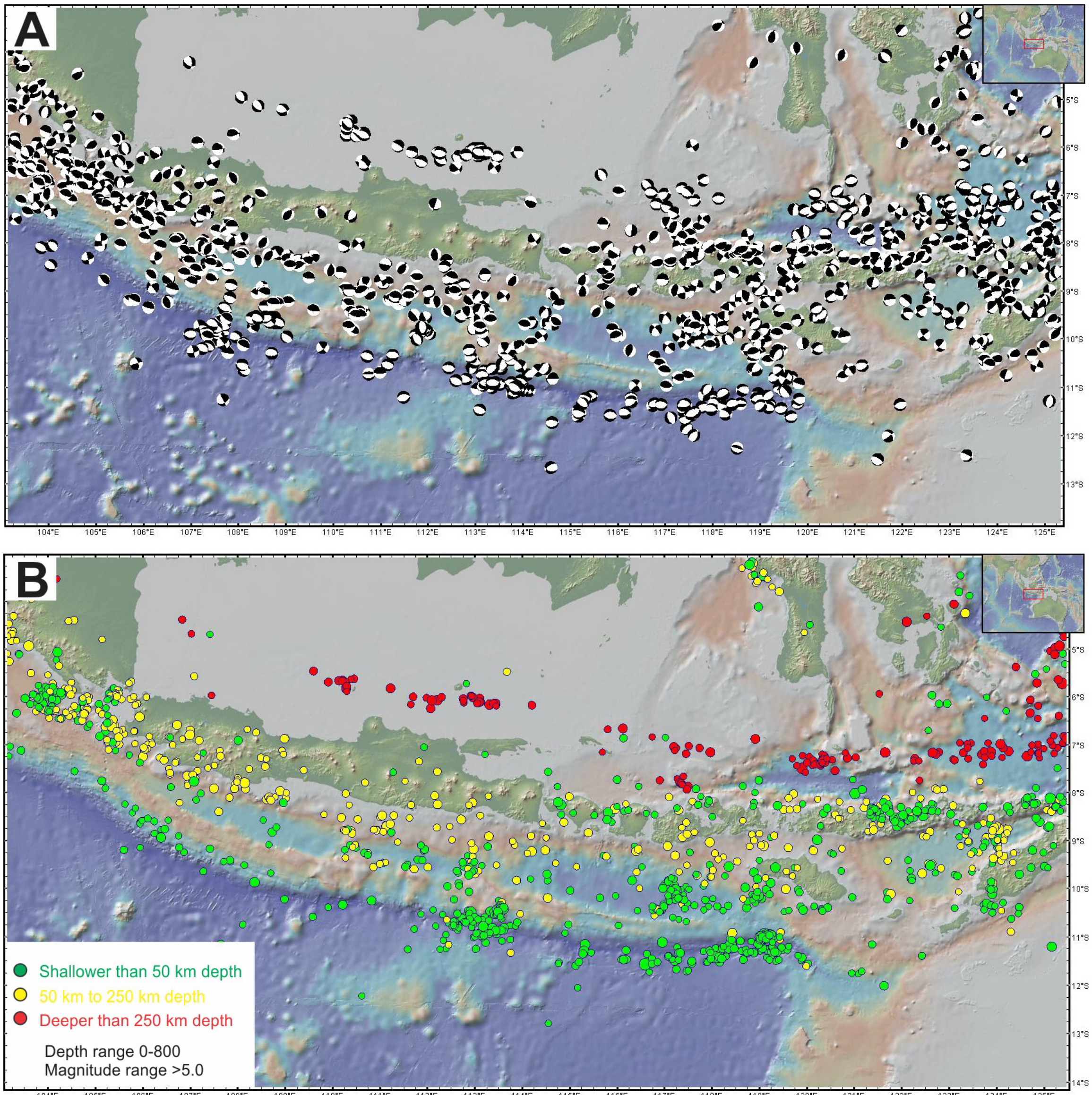

Figure 1.Earthquakes > Mw = 5 (1921-2017) for the Java Trench region. A) Fault plane solutions. B) Earthquake depth. Most shallow earthquakes south of the Sunda arc are thrust-related due to convergence between the Australian and Asian plates. However, most of these earthquakes are aftershocks surrounding much larger events and are clustered in time and space. From USGS archives.

Table 1. Data from 2010 for numbers of people living in the East Sunda Arc Islands, Indonesia. Data from Bps.go.id, (2017)

Island	Population (2010)
Jawa	136,610,590
Bali	3,890,757
Lombok	3,168,692
Sumba	693,673
Timor	1,359,494

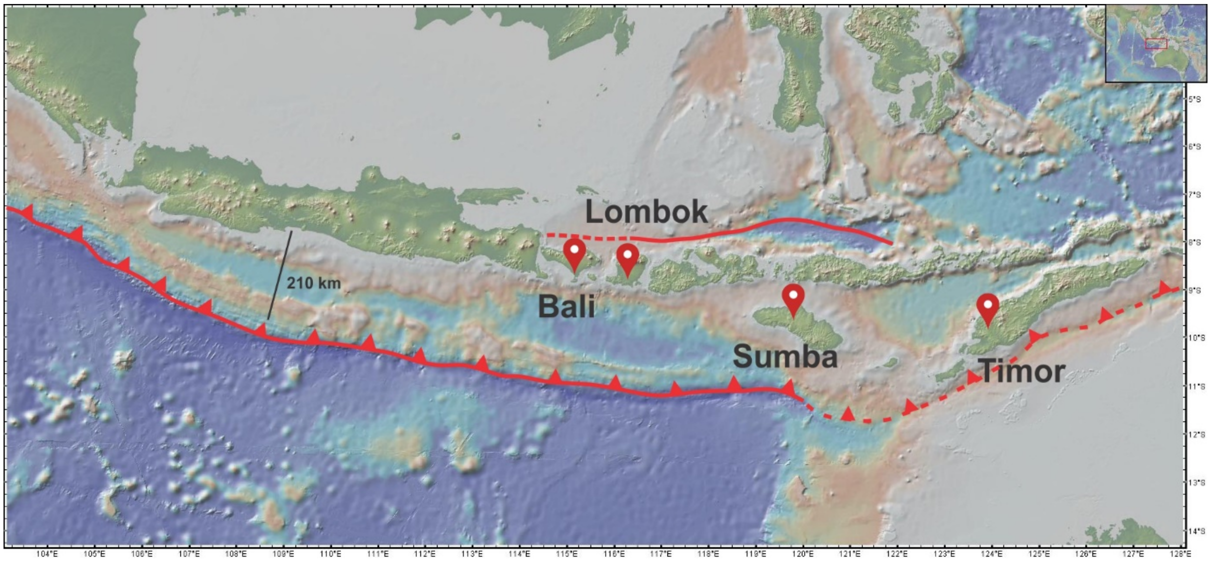

Figure 2. Eastern Sunda Arc islands investigated in this study. The distance of the Java Trench from the southern coasts of the islands is around 210 km, which means a tsunami can reach the coast in 20 minutes.

The most densely populated coastal area in Indonesia adjacent to a plate boundary is Bali, which faces the Java Trench (Figure 2). Although records of earthquakes in areas adjacent to the Java Trench data as far back as 1584, only a few local tsunamis are described (Harris and Major, 2016). The difference between the high activity in the western Sunda Arc versus the lack of mega-thrust events and giant tsunamis in the eastern Sunda Arc is commonly interpreted as a difference in coupling. If the Java Trench is deforming mostly by creep (low coupling) it will not accumulate enough elastic strain to produce a megathrust earthquake (>8.0) and associated giant tsunami (i.e. Newcomb and McCann, 1987).

This hypothesis assumes that the 430-year long observation period of available historical records samples a complete seismic cycle for the Java Trench. However, this may not be the case. For example, the two most recent intervals between mega-thrust earthquakes in the Sendai, Japan region span 585 and 557 years (Sawai et al., 2015). The last major megathrust earthquake was in 1454. A sand sheet deposited by this event that contains marine fossils is found only at scattered locations on the Sendai Plain. Such deposits may also be preserved along the coastal plains of islands of the eastern Sunda Arc that are adjacent to the Java Trench, such as Java, Bali, Lombok, Sumba and Timor (Figure 2).

Discoveries of candidate sands and imbricated boulder deposits likely deposited by tsunamis on the southern coast of Java were made by Meservy (2017), Deng (2018), Stuart (2018) and Eko Yulianto (personal communication). It is possible that these deposits record paleo-tsunamis generated by mega-thrust earthquakes before 1584, which is the earliest historical record known. If this is the case, then the Java Trench may have accumulated strain at near the convergence rate (7 cm/a) since at least 1584, which could be up to 30 meters of potential slip. This amount of slip released suddenly over a large area of the Java Trench could produce an earthquake of Mw = 9.0 or larger. If mega-thrust earthquakes are common along the Java Trench, but the seismic cycle is more like Japan than Sumatra, then recognizable tsunami deposits, such as marine sand sheets in low energy terrestrial depositional environments and imbricated boulders, may be found.

1.1 Objective and Focus

The primary purpose of this research is to search for paleo-tsunami deposits on coastal plains of islands of the eastern Sunda Arc to address this fundamental question: Does the Java Trench produce mega-thrust earthquakes and giant tsunamis?

The secondary focus of the project was to work with the Indonesian National Board for Disaster Management (BNPB) to address of the question of how best to communicate who's most at risk of tsunami hazards along the eastern Sunda Arc, and how best to assist with implementing disaster mitigation strategies. Up to this point the Indonesian government has focused its attention on areas where earthquakes are recorded by seismometers. Most of these earthquakes are aftershocks from previous major or giant earthquakes on fault zone where most of the elastic strain has been released and the seismic cycle is mostly reset. This approach overlooks areas where plate boundaries are mostly locked and have very little seismicity. The Java Trench is one of these areas due the fact that the recorded seismicity during the past 100 years is only a fraction of the potential slip that may have accumulated, if it is highly coupled (Cummins, 2017).

Most Subduction zone fault segments have an earthquake cycles greater than 100 years. Therefore, other methods besides instrumentation are required to assess earthquake and tsunami risks. Since most active faults in Indonesia are obscured by the sea, tsunamis deposits are the only indication of earthquakes caused by these faults.

1.2 Broader Impacts

Integrating information from instrumental, historical and geological data is key to obtaining representative long-term models of tsunami occurrence and hazards (e.g. Atwater and Moore, 1992; Shiki et al., 2008 and references therein). Moreover, geological data on actual inundation distances related to paleo-tsunamis are also extremely critical to constrain and validate inundation maps as well as to test various tsunami scenarios impacting hundreds of thousands of people and critical facilities in Indonesia.

1.3 Present Tsunami Hazard Risk

The Sunda subduction zone extends from north of Sumatra to the island of Sumba over about 6000 km. The eastern Sunda Trench parallels the southern coastlines of Java, Bali, Lombok, Sumba and Timor (Figure 2). The trench is between 150 and 220 km from the coastlines except in Timor where the plate boundary is < 50 km from the coast. The subduction process potentially produces devastating, shallow megathrust earthquakes. The seismic energy released from these events is extremely destructive; nevertheless, the earthquakes themselves rarely claim as many lives as the tsunamis they produce. The short distance between the plate boundary and shoreline allows a tsunami to reach coastal communities within 20-30 min after the shaking starts (Spahn et al., 2014).

Questionnaire surveys conducted in several coastal communities in Java indicate the people there depend on tsunami warnings from government officials and the new Early Warning System (EWS) versus natural signs (Hall et al., 2017). However, for the 5 tsunamis that have occurred since the EWS was deployed, it has failed to warn those in harm's way before the tsunami arrived (Lauterjung et al., 2010). The "system" consists of many parts, some of which might work and others not. Failure in any one of these parts can cause failure of the whole end-to-end system (IFRC, 2009). In addition, Srivichai et al. (2008) specified that the lack of a reliable predictive tsunami early warning system or tsunami education in the region has exacerbated the increases losses to tsunami hazards.

Tsunami inundation maps provide a way for coastal communities to assess who is most at risk, plan escape routes and conduct evacuation drills. However, local communities must use natural warning signs that a tsunami is approaching, such as sustained ground shaking (>20 seconds), to evacuate in time.

2. Significant Historical Earthquake and Tsunami Events in the eastern Sunda Arc

2.1 Java

Three notable earthquake and tsunami events are highlighted from Wichmann catalogue.

"1840, January 4, around 1:15 pm. Violent quake in Middle Java. In Patjitan (Pacitan) the first shocks were felt between 1 and 2 pm; the (shakings) lasted a good minute and were accompanied by a subterranean rumble. The walls of the houses received cracks. A flood wave followed the quake." (Wichmann, 1918)

“1859, October 20, around 5:30 pm. Patjitan, Patjitan Bureau, Madiun Province (East Java). Powerful shock accompanied by a flood wave. It occurred in the very moment that the ship “Ottolina” in the roadstead, Capt. J. J. PRANGE, was in the process on throwing out a TAU anchor. The rowboat performing this, loaded with anchor and chain, sank, and 11 of the 13 persons of the crew were able to be saved.” (Wichmann, 1922)

“1867 June 10, strong earthquake that stretched over all of Java and out in both east and west directions. In Middle-Java it was catastrophic.” (Wichmann, 1922)

The ground motion was felt all over Java Island; the longest shaking duration was estimated about 40 seconds by observer and by others as 3 minutes in Surakarta. Reconstruction from historical accounts showed that this earthquake was very similar to 2006 Yogyakarta earthquake, which was also an intraplate event.

2.2 Bali, Lombok and Sumba

In the islands of Bali, Lombok and Sumba the largest historical event is associated with the eruption of Mt. Tambora

“1815 -, about 10 p.m. Buleleng, north coast of Bali. Utmost violent quake that persisted almost an hour and was attended by strong, incessant rumbling, which seemed to come from a mountain that erupted, “with a tremendous explosion”. A part of the same crashed into the sea and caused a wave that flooded the land to a considerable”

“1815, October and December. Ternate. During said months three shocks were counted. 2) November. Bima on Sumbawa. Earthquake. 3) Apparently the shocks had occurred contemporaneously with those noticed on the 22nd on Bali and Lombok.”

“1815 shortly before the middle of August. Gempa on the Bay of Sumbawa. Violent earthquake of 5-minute duration. Similar is a report shared by H. G. J. G. VRIESMAN from domestic sources, which states that after the previous earthquake and rain, Pik of Buleleng [Selangdjana] split, to crash down and in its fall to bury Singaradja and Buleleng, as well and Kampong of Bugis. Also, the sea was agitated greatly as a result and there were 7 claps of thunder heard. By a stream of mud, 10,253 persons perished. 1) as ZOLLINGER indicates, the quake occurred powerfully on Lombok also.”

1977, the largest earthquake in the eastern Sunda Arc was Mw = 8.3. The earthquake was caused by a normal fault on the subducting plate, and therefore was not a mega-thrust event. It generated a tsunami that caused severe damage in Sumbawa and Sumba islands. Tsunami run-up of 5.5 m with the inundation distance of 1200 m was observed at Leterua on Sumba Island.

2.3 Timor

In Timor Island the first recorded earthquake and a tsunami event is in 1638. It does not mention a flood wave like in other records but does mention a huge lake after the event. The largest earthquake was in 1829 and was felt on 3 different islands.

"1638, (no date). Timor. "The fear of the mountain and the other on the Island, named Picus, elevation so great that it was visible, and fiery in this case, to the top from 300 miles in the sea; the year 1638 an earthquake shook the foundations together with the island was swallowed up by a horrible thing, that had left behind nothing but a huge lake. Thus, reference Annals Soc. Jesus"

"1829, (no date). In the first months of the year a strong shock was felt once in the territory of Amarasi, West Timor. 6) -October. Bima and other areas on Sumbawa. Violent earthquake."

All these events were observed before 20th century and there has not been any large earthquake afterward.

3. Paleotsunami Deposits

Thin subsurface sand beds interlayered with mud-rich units were discovered in Bali, Lombok, Sumba and Timor as part of this study. These layers display many of the physical characteristics mentioned in the methods section, such as distinct compositional and textural relations, types and organization of stratification, thickness, geometry, and landscape conformity.

Previous studies of tsunami deposit preservation in the tropics show that swales between sand ridges are the most likely sites to preserve tsunami sands because it is a site of ongoing low-energy deposition (Moenecke et al., 2008). However, along the Java coastline most deposits in swales are poorly preserved due to erosion or cultivation. The only paleo-tsunami deposits found in swales are those covered by lakes (Eko Yulianto, pers. com.), those found in river banks and scares deposits in swales that are currently cultivated (Stuart, 2018).

The physical attributes that strongly favor a tsunami origin are: a relatively thin (25 cm by average) bed composed of normally graded sand consisting of a single structureless bed or a bed with only a few thin layers. Additional attributes include the presence of internal mud laminae or intra-clasts near the base composed of the underlying cohesive sediments. Tsunami deposits generally conform to the landscape like a drape and they typically gain elevation landward.

Fields of imbricated boulders also may provide good markers of high-energy events (Nandasena et al. 2010). The eastern Sunda Arc islands adjacent to the Java Trench are particularly good environments for surveying for coastal boulder fields because major storms are less common at the equatorial location than tsunamis (Noormets et al., 2002; Goff et al., 2006). We used photos posted on google earth to identify many beaches with ridges of imbricated boulders that we later explored. We also explored every accessible beach along the south coasts of Bali, Lombok, Sumba and western–most Timor for other imbricated boulder sites and the best places for tsunami sand deposit preservation. These locations include several sites that were on coastal plains and in caves if the coast was cliffy. Some of the beaches are only accessible by boat.

4. Previous Work

This project builds upon earlier expeditions that prospected for paleo-tsunami deposits along the southern coastline of west and central Java. Eko Yulianto (LIPI) and his research team discovered some candidate tsunami sand deposits, but none of the data they have compiled is published. However, they have. These deposits yield consistent radiocarbon ages that form 3 groups: A) 400-362 YBP, B) 1893-1591 YBP, and C) 3663-2322 YBP (Eko Yulianto, personal communication). The WAVES expedition of 2016, which I assisted with, documented candidate tsunami deposits near Pelabuhan Ratu, Pangandaran and Pacitan (Figure 3).

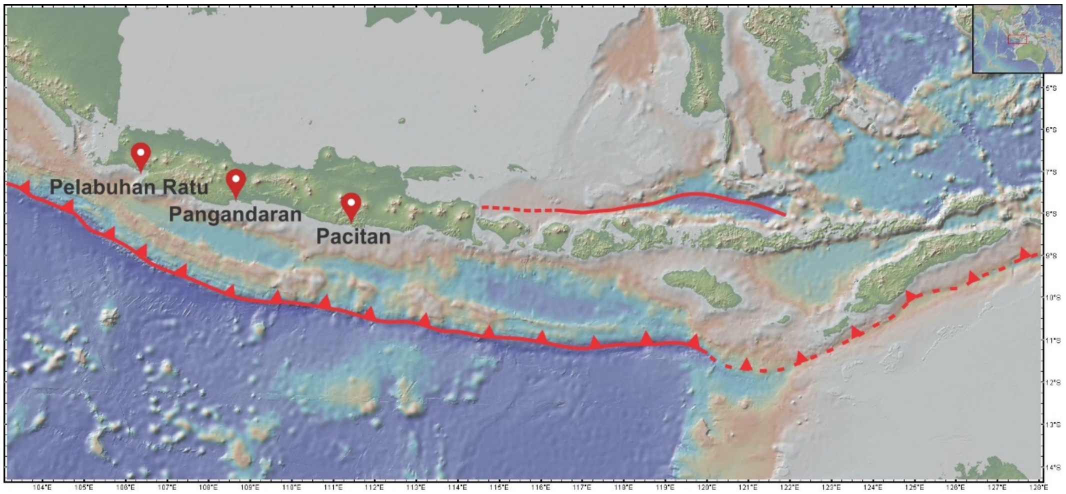

Figure 3 Map showing locations of 2016 expedition.

Deng (2017) found a tsunami deposit that yielded an age of 1053 +/- 22 AD preserved in an uplifted marine terrace exposed at Panto Cape, Banten Province. She estimated that the terrace has been uplifted about 4.6 m to its present height of 2 m above sea level, since the 1,053 AD event at an average rate of 4.8 mm/a. Uplifted coral marine terraces are found along this coast that document inter-seismic uplift (Deng, 2017). In addition, GPS measurements from the same area also document inter-seismic uplift at a rate of 5.7 mm/a. Inversions of the GPS data demonstrate that the west Java Trench is locked and can accumulating close to 100% of the 7 cm/a convergence.

Near Pangandaran in central Java candidate tsunami deposits consisting of sand with marine fossils were discovered at three different sites (Stuart, 2017). One is an archaeological site (Batu Kalde) where a layer of aragonitic sand with marine fossils stratigraphically overlies archaeological remains at an elevation of 3-4 m. A bivalve from that layer yields an age of 5584-

5456 +/- 22 cal YBP. Goa Panggung, a cave east of Batu Kalde, records candidate tsunami sands were jumbled by the 2006 tsunami there. Sands from the 2006 tsunami are well preserved there and in other parts of the central coast of Java. Some sand layers beneath the 2006 deposit fine upward from a coarse grain size and have heavy minerals concentrations emblematic of tsunami deposits. These deposits yield ages on organic material that date back to 5040-4864 cal YBP and overlie younger deposits. Thin sand sheets in swale mud deposits east of Pangandaran are also interpreted as tsunami deposits (Stuart, 2017).

In east central Java, near Pacitan, five imbricate coastal boulder fields were discovered (Meservy, 2017). Parts of these deposits yield ages of 1861 +/- 22 AD, which is likely from the 1859 tsunami generated by the Pacitan earthquake. Two similar imbricated boulder fields were also discovered at Pantai Papuma and Pantai Pasir Putih that were stacked there during the 1994 Mw = 7.9 event in East Java.

5. Methods

5.1 Satellite imagery and Historical records to identify potential sampling locations

The archipelago nature of Indonesia, and its dense population create challenges for tsunami deposit prospecting. It is difficult to access many coastal areas, and those that are readily accessible are heavily cultivated. We used Google Earth to locate identify possible low energy depositional environments within a few hundred meters of the coast such as lakes, swales, marshes, flood and coastal plains where tsunami deposits may be preserved. 54 locations were selected for a reconnaissance study, which was conducted before surveying, trenching and auguring on each island (Figure 4). The reconnaissance included visiting each location and determining if it was promising. 17 sites were eliminated during the reconnaissance based on accessibility and potential for prospecting activities.

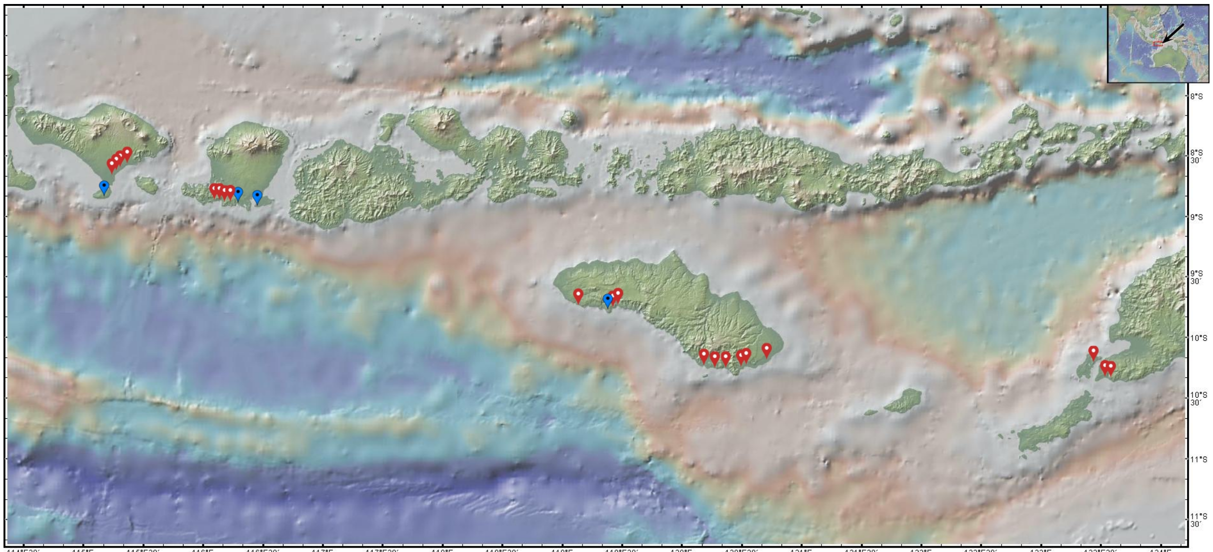

Figure 4. Identified possible low energy depositional environments.

5.2 Sampling methods and analyses

The objective of the sampling was to determine the stratigraphy, sedimentology and coastal settings of each location. Stratigraphic relations were exposed in river and wave cut banks, water wells and pits, trenching and auguring (see Appendix 1).

5.2.1 Grain size analysis LIPI (The Indonesian Institute of Sciences) lab

Grain size analysis is used to characterize the diameter of sand grains for parameters such as mean, standard deviation, skewness and kurtosis or the sand samples. The grain size analysis was conducted at the LIPI (Indonesian Institute of Science) laboratory using a Mastersizer 2000. A 2200 rpm pump speed was used for unit dispersion, 15:00 for ultra sound displacement, and a 2-minute ultrasound.

5.2.2 XRD

A small portion of each sample was powdered in acetone (to preserve the crystal lattice of any carbonates) using a mortar and pestle. Powdered samples were then dried in an oven at 60°C, after which a small amount of powdered corundum (~10% by volume) was added to act as an internal standard. X-ray diffraction (XRD) analysis was done using a Rigaku MiniFlex 600 instrument. Samples were loaded into standard sample discs. Data was collected from a 2-theta range of 6° to 65°, with a 1-second dwell time for each 0.02°. Washed samples were analyzed in zero-background sample discs with a 4-second dwell time. Analysis voltage was 40 kV with a current of 15 mA.

Pattern analysis was done using Rigaku PDXL2 version 2.6.1.2. Relative mineral proportions were determined by Rietveld whole powder pattern fitting analysis. The analysis searched for minerals that could be expected from erosion of andesite (including weathering products of those minerals) as well as minerals that were determined through pattern-matching experimentation and were suggested by the Auto search option in PDXL2 if those minerals were reasonable. Aragonite was also targeted due to its importance in identifying a possible marine origin. Minerals targeted include plagioclase, pyroxene, amphibole, magnetite, aragonite, calcite, gypsum, and quartz. Some minor peaks were not identified in the diffraction analysis. These unidentified peaks represent a small percentage of the sample and were mostly absent in the samples that were washed in hydrogen peroxide and nitric acid, suggesting that they are from organic material or clays.

5.3 OSL

Two optically-stimulated luminescence (OSL) samples were collected from Sukmawati area in eastern Bali. The collection was made according to instructions that can be found on the

Utah State University website (USU OSL Laboratory, 2016). A metal tube was used to collect the sample for age analysis and sand from around the sample was also collected for dose rate and water content calibration.

5.4 Aerial and Differential GPS surveys

The sample locations were surveyed by Dr. Michael Bunds of Utah Valley University and his students. Markers on the ground were surveyed at each location using differential GPS and surveyed from the air to for precise x, y and z positions. These data were referenced to the high tide mark on each Beach to relate the distance from coastline measurements for each site with elevation above sea level.

6. Results

6.1 Bali

The only place where potential tsunami deposits are preserved is in Sukawati, East Bali (Figure 5). Four locations in Sukawati that we investigated in detail are Pandawa Beach, Purnama Beach, Rangkan Beach, Manyar Beach, and Kebun bunga Beach.

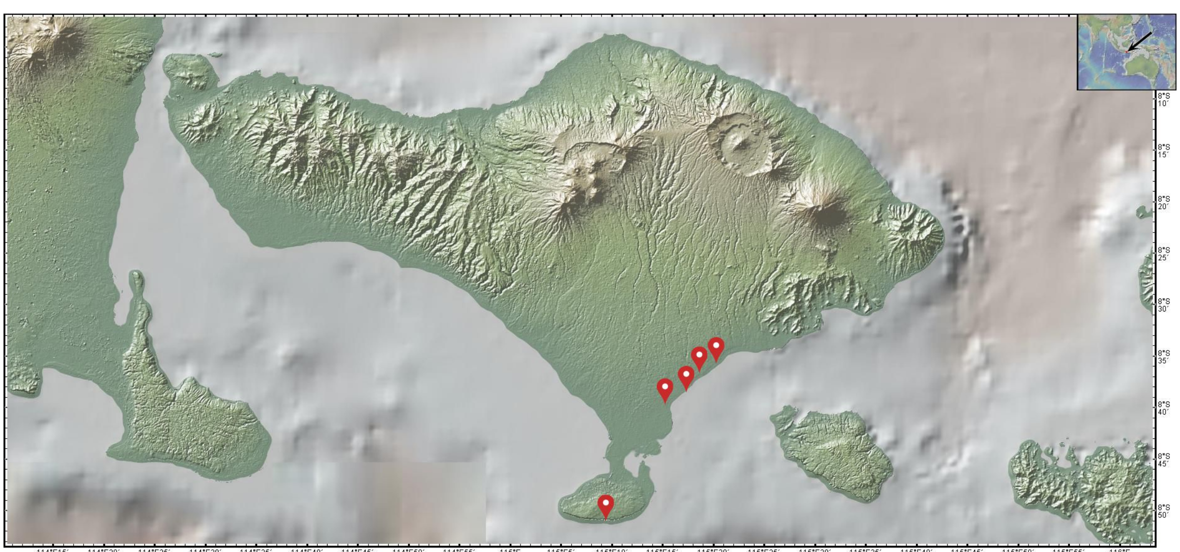

Figure 5. Map showing locations of tsunami deposits on Bali island.

6.1.1 Pandawa Beach

Imbricated boulders are exposed on the eastern part of Pandawa Beach (figure 6). The boulders consist of slabs of hardpan stacked on top of one another. The hardpan surface where the boulders were torn from is exposed seaward of the imbricated stack. Individual boulders range in length from 120 to 255 cm, in width from 89-180 cm and in thickness from 11-31 cm.

Figure 6. Coastal boulder imbrications at Pandawa Beach. The boulders are up to 255 cm in length, 180 cm in width and 31 in thickness.

6.1.2 Purnama Beach

We investigated 3 sites inland from Purnama Beach at an elevation of ~3 m above sea level. Site 1 is located on a cultivated coastal plain 180 m from the Beach. The coastal plain is cut by an irrigation trench 235 cm deep. In this trench we found mostly clay-rich deposits interlayered with 2 distinct sand layers found at 87-97 cm and 176-190 cm. The top sand layer is dark brown, sub-angular, poorly sorted, and no bioturbation. Grain size analysis of these sand layers show an average grain size from coarse to very coarse sand which fine upward and contain Pebble size pumice fragments. The basal contact of this layer has abrupt erosional contact and load structure. Grain size distribution shows a slightly bimodal curve (Figure 7)

One OSL sample was taken from this layer, which yield a preliminary age of ~0.5 ka BP.

The bottom layer is a light brown color and similar in every way to the upper layer except for medium to coarse average grain size and slightly bimodal grain size distribution. One OSL sample was taken from this layer, which yield a preliminary age of ~2.7 ka BP. Based on the depth of the sand layer the average rate of deposition from the upper sand to the lower sand is

Figure 7. Left: photo of the river bank in Purnama Beach showing sand layers. Middle: 2 sand layers identified on the field. Right: Grain size distribution of each sand layers.

Site 2 at Purnama Beach is 134 meters from the coast and 184 cm deep. Both trenches are essentially the same, it was 66 meters southeast from the first trench. Sand layers very similar to site 1 are found at 101-107 cm and 185-204 cm. These sand layers have the same physical properties as what we found in trench one.

Site 3 at Purnama Beach is an augur site in a rice field 38 m east from site 1 and 50 m north of site 2 (Figure 8). The purpose of the augur site was to test the lateral extent of the 2 sand layers found in site 1 and 2. We found the upper sand layer at 104 cm.

Figure 8. Coastal boulder imbrications at Pandawa Beach. The boulders are up to 255 cm in length, 180 cm in width and 31 in thickness.

6.1.3 Rangkan Beach

This location is 1 km southwest of Purnama Beach. It is cultivated coastal plain 169 meters from the shore and at an elevation of ~3 m above sea level. Using an augur, we found 2 potential tsunami deposits. The top layer is at 105-127 cm depth, is light brown with an average grain size from fine to medium muddy sand. The bottom sand layer is at 177-195 cm depth, is greenish color with average grain size was medium to coarse sand, angular and poorly sorted. Grain size distribution shows a slightly bimodal curve (Figure 9).

Figure 9. Left: photo of the coastal plain in Rangkan Beach. Middle: sand layers identified from augur. Right: Grain size distribution of the sand.

6.1.4 Manyar Beach

This location is 3.5 km southwest of Purnama Beach. It is cultivated coastal plain 43 meters from the shore and ~1 m above sea level. Using an augur, we found 2 potential tsunami deposits. The top layer is at 82-92 cm. It is light brown in color, sub-angular, poorly sorted, with an average grain size from medium to coarse muddy sand. The bottom layer is found at 160-176 cm. It is greenish in color, angular, and poorly sorted sand, with an average grain size from medium to coarse sand. Grainsize distribution shows a slightly bimodal curve (Figure 10).

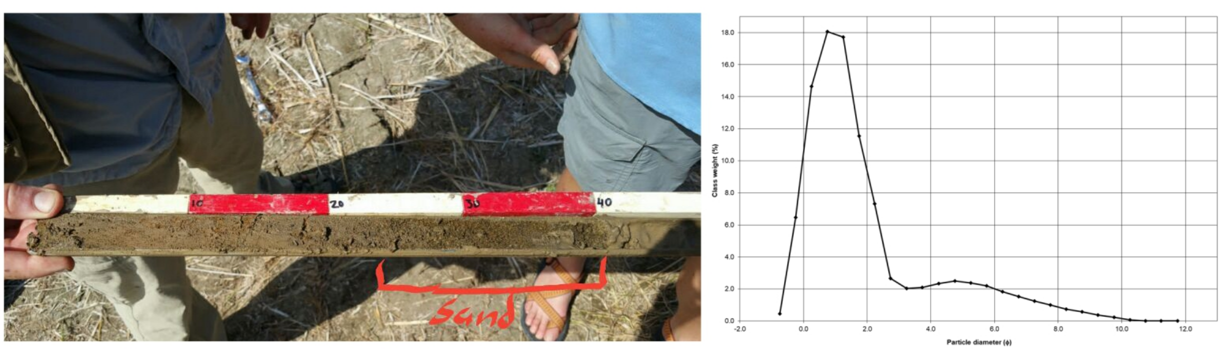

Figure 10. Left: Sand layers identified from augur. Right: Grain size distribution of the sand.

6.1.5 Kebun bunga Beach

This location is 5.4 km southwest from Purnama Beach. It is cultivated coastal plain 163 meters from the shore and ~2 m above sea level. We did 3 augur tests, but this location was the hardest to collect sample from due to the wetness of the rice field. One of the augur tests could not penetrate sand layers. The second augur collected sand and halted at 170 cm in a greenish sand, sub-rounded, with an average grain size from medium to coarse muddy sand. The third augur collected sand and halted at 175 cm in the same sand. Grainsize distribution shows a unimodal curve for the sand from the second augur and bimodal from the third augur (Figure 11).

Figure 11. Left: Rice field on coastal plain in Kebun Bunga Beach, Middle: Sand layers identified from augur. Right: Grain size distribution of the sand.

6.1.6 Summary of results from Bali

The only place in Bali where candidate paleo-tsunami deposits are found is in the Sukawati area along the Southeast coast. The coastal plain surface is at an elevation of approximately 1-3 m above sea level. We consistently found two sand layers in between mud layers at approximately 1 m and 2 m depth below the surface.

The composition of the sands from XRD analysis are nearly all uniform with plagioclase, +/-pyroxene and +/- magnetite (Table 2). The modern Beach sand has the same composition, including a lack of marine organisms.

The sand layers have the following characteristics of tsunami deposits: 1. variation in grain size from medium to very coarse sand, even found pebble size fragments, 2. poor sorting, 3. interlayered with mud, 4. thickness of around 10 cm, 5. sharp basal contact, 6. load structure, 7. fining upward, and 8. bimodal grainsize distribution.

Table 2. Mineral composition of Bali samples sand from XRD analysis

Location	Site	Depth	Plagioclase	Pyroxene	Magnetite	Quartz	Calcite	Aragonite	Other
Bali	Pantai Purnama 1	87-97 cm	x	x					
		176-190 cm	x						Ms?
	Pantai Purnama 2	101-107 cm	x		x	x			
		185-204 cm	x	x	x				Ms?
	Rangkan	105-127 cm	x		x				Ms?
		177-195 cm	x		x				
	Manyar	82-92 cm	x	x	x				Halite
		160-176 cm	x	x	x				
	Kebun bunga	170 cm	x	x	x				
		175 cm	x		x				

Ms = Muscovite

6.2 Lombok

Four locations along the southern coast of Lombok yielded candidate tsunami sand deposits interlayered with clay-rich deposits (Figure 12). Several Beaches also revealed partially exposed imbricated boulder deposits. The areas we focused for trenching studies are Tampah Beach, Mawun Beach, Aer Guling Beach, and Kura-Kura Beach.

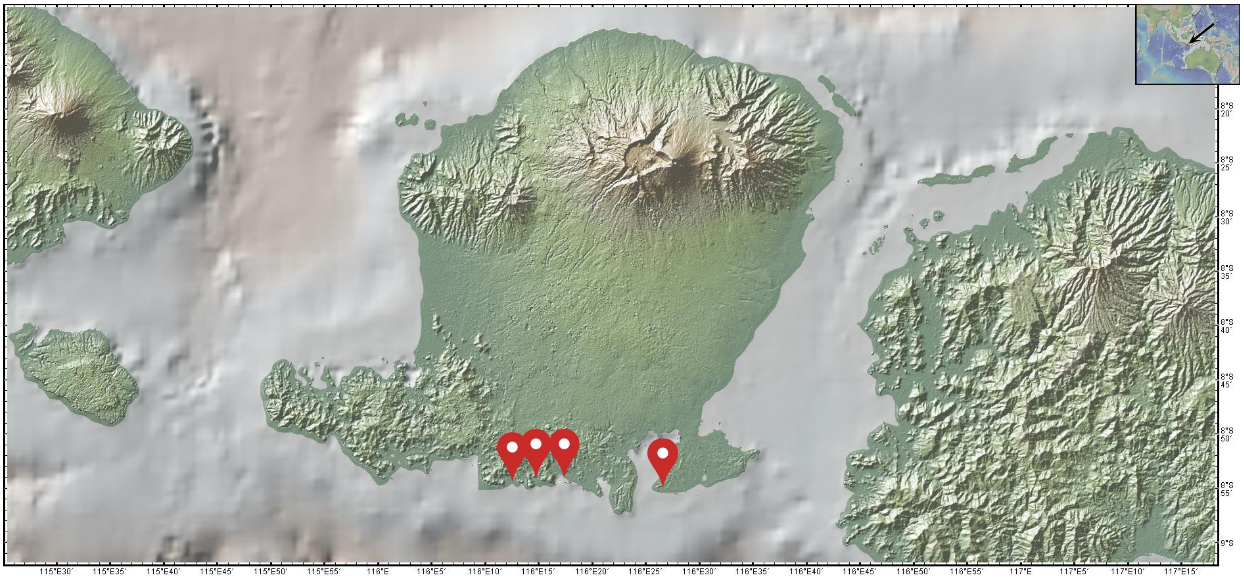

Figure 12. Map showing locations of tsunami deposits in Lombok Island

6.2.1 Tampah Beach

We investigated 3 sites inland from Tampah Beach at an elevation of ~7 m above sea level. Site 1 is located on a cultivated coastal plain 515 m from the Beach. The coastal plain stratigraphy is exposed in water wells up to 2.4 m deep. The top of the strata is covered by coarse sand with foraminifera and big shell fragments, which is likely from the 1977 tsunami. Below this layer, from 30 to 110 cm, we found mud with interlayered sand deposits. Samples we collected include shell and coral fragments at 100 cm depth. A third foraminifera and shell rich muddy sand was discovered at a depth of 230-240 cm. Grain size analysis of these sand layers show an average grain size from coarse to very coarse sand. The grain size analysis shows a slightly bimodal curve (Figure 13).

Figure 13. Left: Well on a coastal plain, Middle: Shell fossil, Right: Grain size distribution of the sand.

Site 2 is located on a cultivated coastal plain 447 m from the Beach (Figure 14). The stratigraphy of the coastal plain is exposed in an open pit 1.6 m deep. From that depth we used an augur to extract cores up to a depth of 260 cm depth. The augur penetrated mostly fine-grained sand and mud. At 260 cm a medium to coarse sand layer is found rich in foraminifera. The grain size analysis shows a unimodal curve.

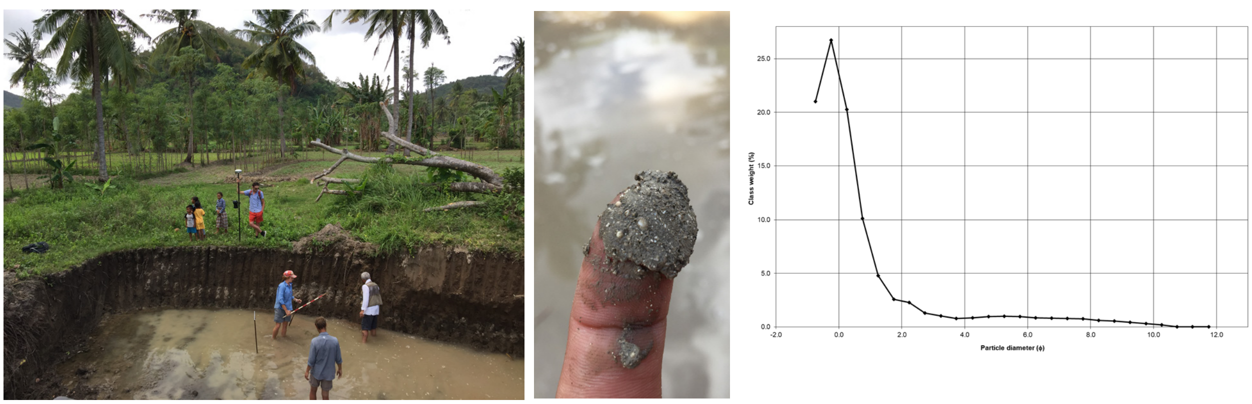

Figure 14. Left: Open pit on a coastal plain, Middle: Foraminifera in sand layer, Right: Grain size distribution of the sand.

Site 3 is located on a river bank 249 m from the Beach. The river bank is 65 cm deep. We found the foraminifera-rich sand discovered at the top of the other sites (probably 1977 tsunami deposits), but the rest of the bank were clay-rich units (Figure 15)

Figure 15. River bank showing upper candidate sand.

6.2.2 Mawun Beach

We investigated 4 sites inland from Mawun Beach at an elevation of ~5 m above sea level. Site 1 is a well 3 m deep located on a cultivated coastal plain 224 m from the Beach. In this trench we found 50 cm and a 10 cm thick foraminifera-rich muddy sand interlayered with clay-rich deposits. A distinct greenish sand layer is found at 280 cm. The upper sand layer is light brown, pumice rich, angular, poorly sorted, with average grain size coarse to very coarse and pebble size fragments. The grain size analysis shows a slightly bimodal curve (Figure 16).

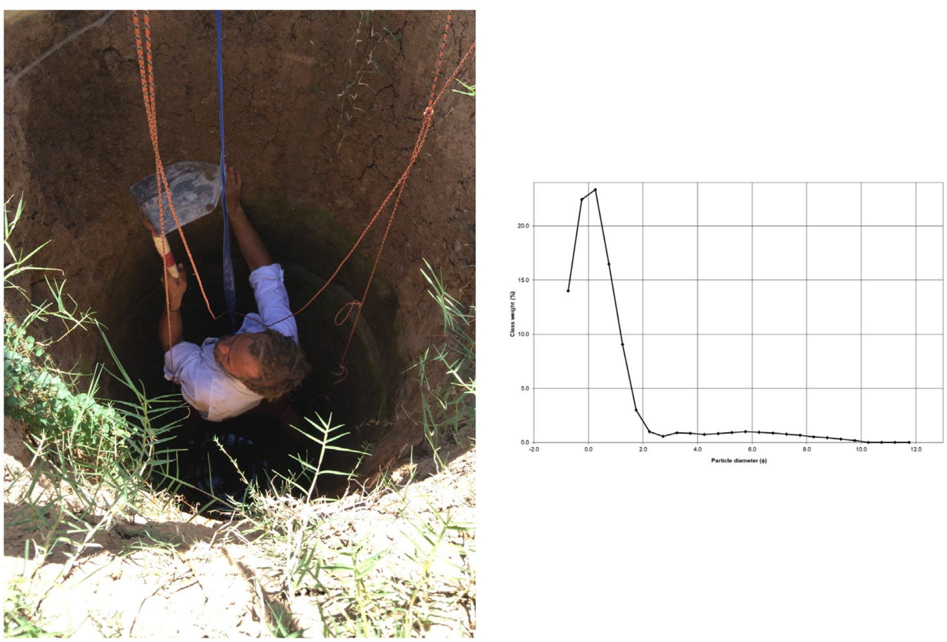

Figure 16. Left: Well on a coastal plain in Mawun beach, Right: Grain size distribution of the sand.

Site 2 is also a well in a cultivated coastal at ~5 m elevation and 172 m from the Beach. This well is 214 cm deep. In this trench we found 5 sand deposits in the interval from 40 – 180 cm. Each sand layers varies in grain size. The sand with the most characteristic features of tsunami deposits are found at 98-180 and 210-214 cm depth. The upper layer is light brown sand, sub-rounded, poorly sorted, erosional basal contact, load structures, with coral and shell fragments and fine mud layers. Average grain size is coarse to very coarse and pebble size fragments. The grain size distribution is bimodal (Figure 17). The lower layer is light brown, angular, poorly sorted, foraminifera and shell fragment rich, with an average grain size from coarse to very coarse. The grain size distribution is also bimodal.

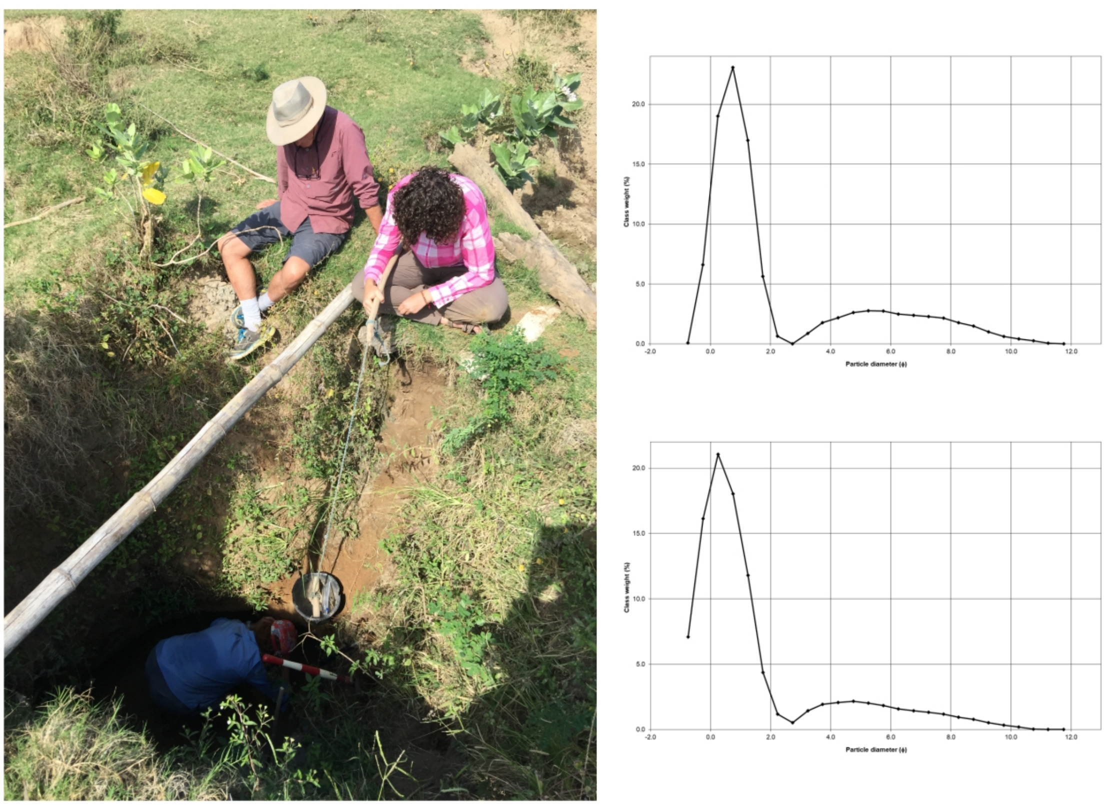

Figure 17. Left: Well on a coastal plain in Mawun beach, Right: Grain size distribution of both sands.

Site 3 is also a well in a cultivated coastal at ~5 m elevation and 129 m from the Beach. This well is 214 cm deep. In this trench we found one potential tsunami deposits at 170-185 cm depth. This sand layer is brown in color, angular, poorly sorted, and contains shell fragments. Average grain size coarse to very coarse and pebble size fragments. Grain size distribution shows bimodal curve (Figure 18).

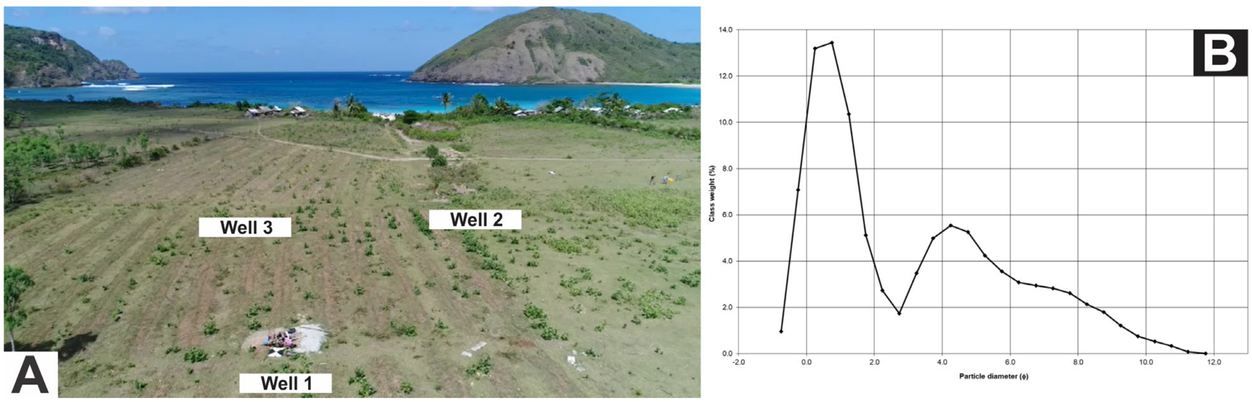

Figure 18. Locations of water wells on cultivated coastal plain near Mawun Beach. Grain size distribution of the sand layer.

6.2.3 Aer Guling Beach

We investigated 1 site 388 m inland from Aer Guling Beach on a cultivated coastal plain at an elevation of ~5 m above sea level. We found a 1 m deep pit that we used to augur to a depth of 294 cm. In this trench we found 4 foraminifera-rich muddy sands from 20-190 with different grain sizes interlayered with clay-rich deposits. A distinct greenish sand layer was found at 280 cm, similar to the one found at Mawun Beach (see above). Grain size analysis of these sand layers show an average grain size from coarse to very coarse sand. The grain size analysis shows a bimodal curve (Figure 19).

Figure 19. Left: Well on the coastal plain near Aer Guling Beach. Middle: Sand deposit from augur, Right: Grain size distribution of both sands.

The bottom layer is grey in color, muddy, sub-rounded, poorly sorted, and foraminifera and shell fragments rich with an average grain size course to very coarse. The grain size distribution is bimodal.

6.2.4 Putri Nyale and Kura-kura Beach

We investigated 2 locations of imbricated boulders. The boulders consist of slabs of hardpan stacked on top of one another. Putri Nyale beach has individual boulders that range in length from 37 to 169 cm, in width from 11 to 120 cm and in thickness from 15 to 33 cm (Figure 20).

Figure 20. Left: Imbricated boulders at Putri Nyale beach, Right: Coral fragments on boulders

Kura-kura beach has the best imbricated boulders site in this expedition, the individual boulders (slabs) range in length from 80 to 360 cm, in width 47 cm to 186 cm, and in thickness from 13 to 41 cm (Figure 21).

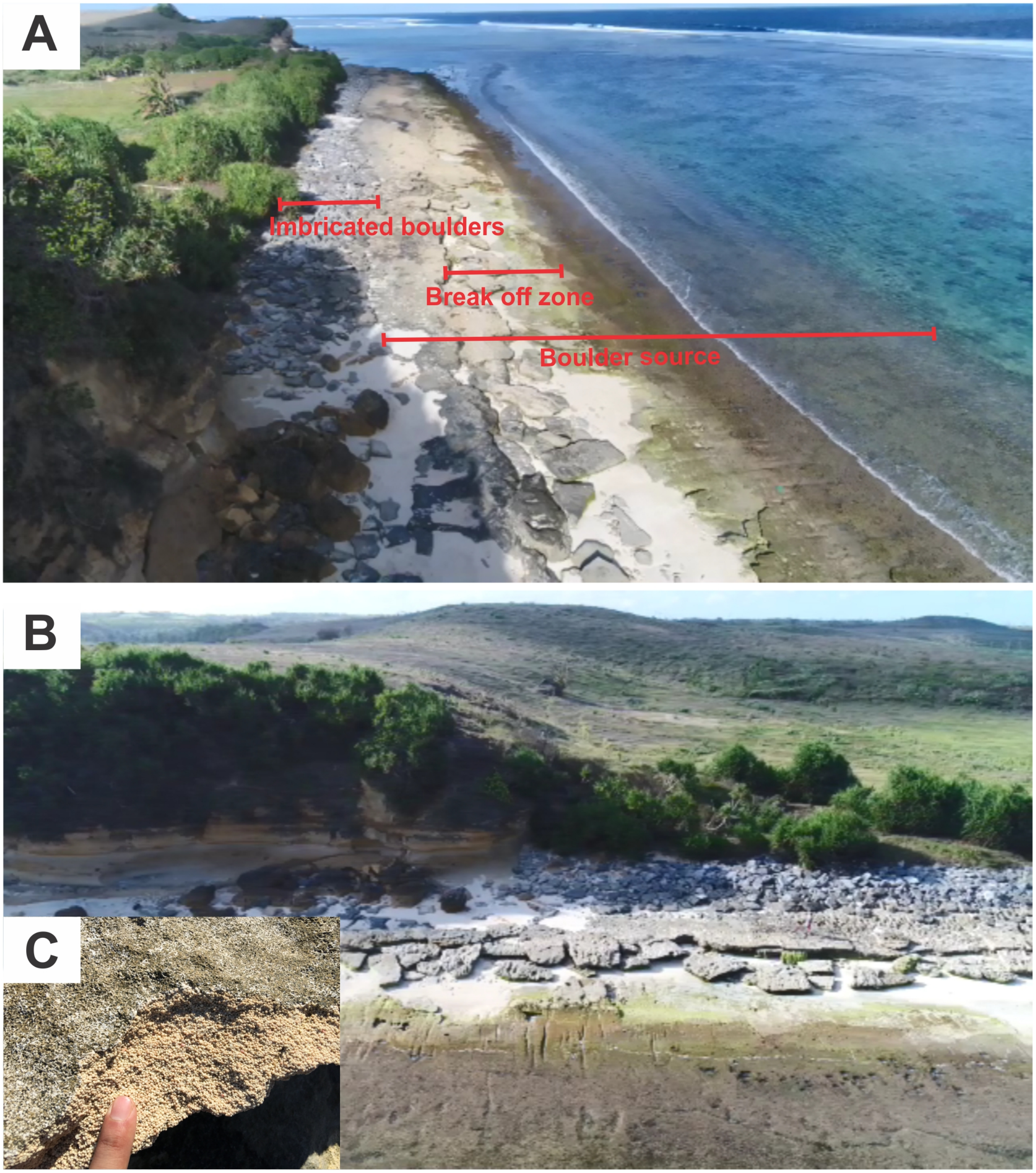

Figure 21. Imbricated boulders at Kura-kura beach. A) Aerial view looking east during low tide of the boulder source and stacking zones. B) Aerial view looking north of large sections of hard pan calving off source due to undercutting by wave action. The next tsunami will shove these slabs towards the pile made by other tsunamis. C) Detail of fossiliferous calcareous sandstone that makes up the hardpan surface.

6.2.5 Summary of results from Lombok

We found several beach coves in southwest Lombok that accumulated coarse and fossil-rich sand deposits interlayered with clay-rich units. Many of these deposits are near beaches with well-exposed imbricated boulder deposits. Deposits from the 1977 Sumba tsunami are found at some sites, but not at others indicating lack of deposition or preservation after deposition.

The coastal plain surface is at an elevation of approximately 5-7 m above sea level. XRD analysis of sand grain composition indicates mostly plagioclase, calcite, aragonite, pyroxene, magnetite and quartz (?) (table x). The modern Beach sand has the same composition, including the abundance of marine foraminifera and other marine fossils.

Table 3. Mineral composition of Lombok samples sand from XRD analysis

Location	Site	Depth	Plagioclase	Pyroxene	Magnetite	Quartz	Calcite	Aragonite	Other
Lombok	Tampah	100 cm					x	x	
		230-240 cm				x	x	x	
	Mawun well 1	157-168 cm	x	x	x				
	Mawun well 2	58-62 cm	x	x		x			
		83-98 cm				x		x	
		98-180 cm				x	x	x	
		210-214 cm	x	x	x				

The sand layers have the following characteristics of tsunami deposits: 1. variation in grain size from medium to very coarse sand, 2. poor sorting, 3. interlayered with mud, 4. thickness of around 20 cm, 5. sharp basal contact, 6. load structure, 7. fining upward, 8. marine organisms and 9. bimodal grainsize distribution.

6.3 Sumba

Sumba is an anomalous island since it is not volcanic like the other islands of the eastern Sunda Arc but, is where thin continental crust of the passive Australian continental margin has entered into the Java Trench and uplifted the forearc ridge to over 1000 meters above sea level. The arc-continent collision initiates south of Sumba and matures to the east through Timor.

Whether this part of the Java Trench can cause mega-thrust earthquakes and giant tsunamis is unknown.

The southern coast of Sumba is very remote and difficult to access. We found six locations on the southern coast with candidate tsunami deposits. These include: Kerewei Beach, Konda Maloba Beach, Karera, Wula waijelu, Pohungga Lodu, and Lamakera (Figure 22).

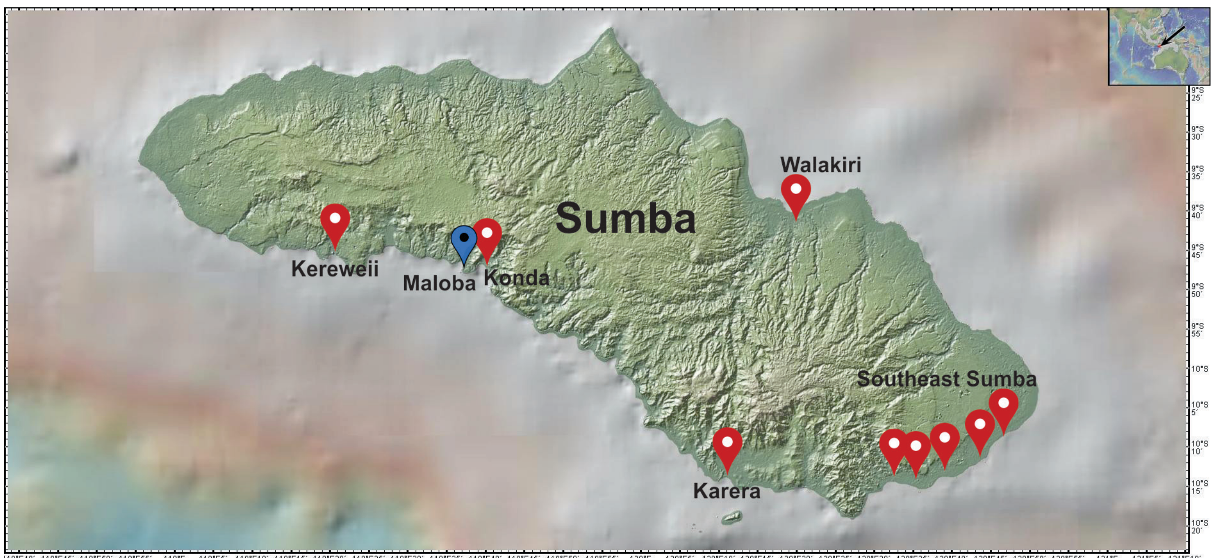

Figure 22. Map showing locations of tsunami deposits in Sumba Island

6.3.1 Kerewei Beach

This site is located on a coastal plain at ~3 m elevation and 240 m from the Beach. We dug a 1.2 m deep trench and found 2 candidate tsunami sands at 25-30 cm and 110-120 cm depth (Figure 23). The top sand layer is light grey in color, with sub-rounded and poorly sorted grains. The average grain size of the sands is very fine to fine and the grain size distribution is unimodal. Small shell fragments are also found.

The bottom sand layer is dark grey in color, sub-rounded, poorly sorted, contains organic and small shell fragments, and average grain size from very fine to fine. Grain size distribution shows a unimodal curve.

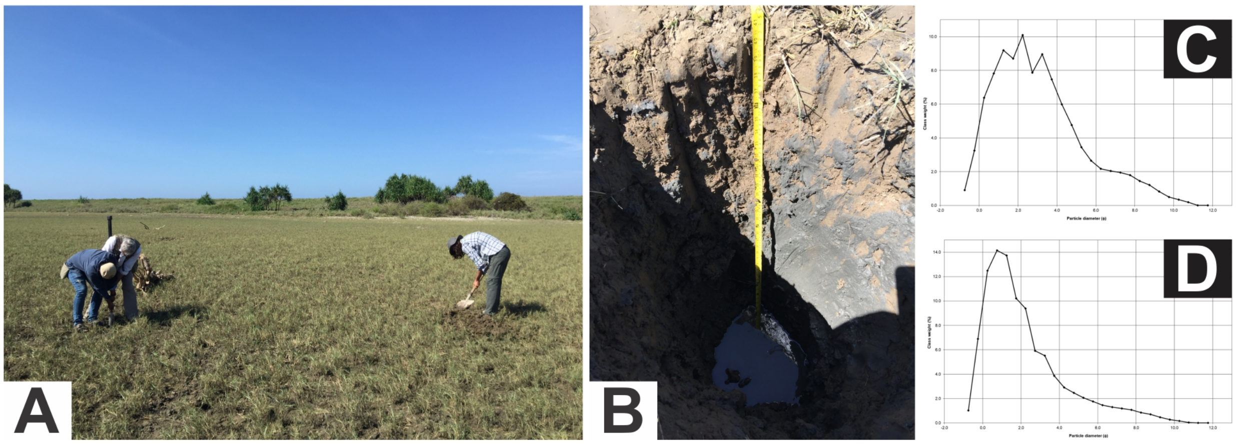

Figure 23. A) Trenching location on coastal flood plain near Kerewei Beach. B) Sand deposit with shells. C) Grain size distribution of sand layers.

6.3.2 Konda Maloba Beach

We investigated 3 sites inland from Konda Maloba Beach at an elevation of ~4 m above sea level. Site 1 is where we found imbricated boulders. Most boulders aretorn slabs of hardpan and altered grey in color. The hardpan surface, where the boulders were torn from, is exposed seaward of the imbricated stack. Individual boulders (slabs) range in length from 66 to 246 cm, in width from 54-159 cm and in thickness from 12-60 cm. These boulders were transported >25 m from the source. Some blocks as large 70 x 50 x 10 were deposited on a bench 50 m from the Beach berm (Figure 24). The wave cut bank of the coastal plain bench is further from the shore than the stack of imbricated boulders.

Figure 24. Imbricated boulders of Konda Maloba Beach. A) Panoramic view that shows the extent of the boulders to the east and west along the beach. B) Detail of imbricated boulder slabs of hardpan. C) Largest allochthonous slab of hard pan (246 cm in length).

Site 2 is a trench along the shore of a coastal lake 50 meters from the Maloba Beach imbricated boulder site (Figure 25). The lake is ~5 m above sea level and separated from the coast by a 25 m wide strip of land that is 3 meters high. The trench encountered lake mud 1 m deep. The lakeshore is all mud with a thin veneer of scattered coarse sand with shells and pebbles from the nearby Beach. Between the lake and Beach is a bedrock ridge 3 m above the high tide mark. The scattered sand and shells are likely the remains of the 1977 tsunami, which breached the ridge. The trench contains all mud except for a horizon of cobbles mixed with coral at 70 cm. The largest cobble we found is 25x10x5 cm. The cobbles are shale like those on the nearby Beach. A shell mixed with mud was also found at the base of the trench at 100 cm. There are streams into the lake just crocodiles.

Figure 25. Site 2 near Konda Maloba Beach. Left: Google Earth image showing the loaction of the site relative the imbricate boulders and the narrow neck of land between the bay and the lake shore, Right: Trench site in lake mud.

Site 3 is a trench on a coastal plain at ~3 m elevation and 0.8 km from Maloba Beach, but 4.8 km from site 2 (Figure 26). This trench was excavated to a depth of 1.2 m deep where we hit a pebble layer we could not penetrate with shovels. We encountered all mud except for two horizons of pebbles like those found on the beach. The top horizon of pebbles is at a depth of 67-100 cm. We found a small shell in the basal pebble layer at around 110 cm depth.

Figure 26. Site 3 near Maloba Beach.

6.3.3 Karera Village

We investigated 2 sites inland from Karera Beach at an elevation of ~9 m above sea level. Site 1 is a cultivated coastal plain 1.12 km from the shore. Using an augur, we found all organic-rich mud. Site 2 is in a cashew plantation on a coastal plain 0.41 km from the shore and ~11 m above sea level. Using an augur, we found all mud until it halted at 64 cm depth in a more indurated sand. This sand is light brown in color, sub-rounded, with an average grain size from very fine to fine. Grain size distributions shows a slightly bimodal curve (Figure 27).

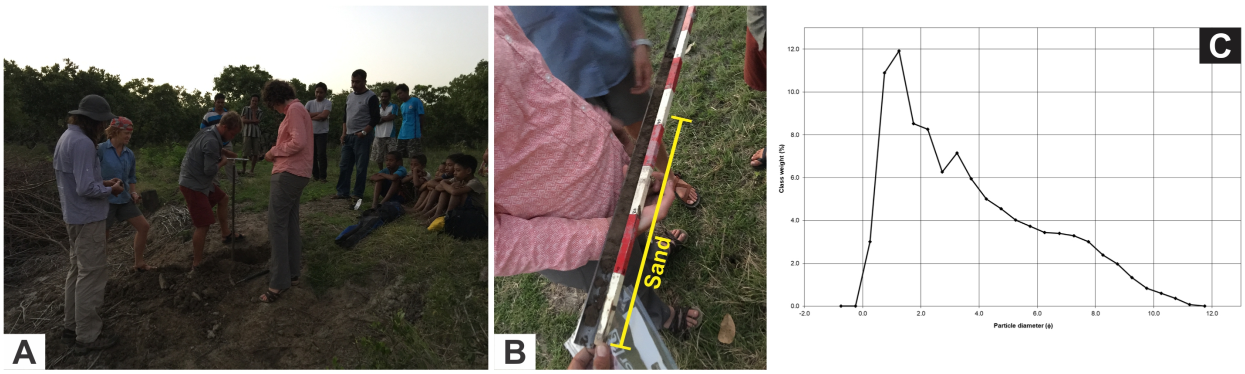

Figure 27. A) Photo of site 2 at cashew plantation. B) Sand layer identified on the field. C) Grain size distribution of sand layer

6.3.4 Wula waijelu Village

We investigated 6 sites inland from Wula waijelu Beach at an elevation of ~6 m above sea level. However, none of the sites contained candidate tsunami sand deposits except for those in Wula waijelu and Waiarara lakes.

6.3.5 Wula waijelu Lake

Two augur draws were taken at Wula waijelu lake. Site 1 is 0.68 km from the shore and at ~7 elevation on the southern part of the lake. We found all mud until to a depth of 72 cm where we penetrated a sand that continued to a depth of 95 cm. This sand is greenish in color, sub-rounded, poorly sorted, rich in foraminifera and shell fragments with an average grain size from very medium to coarse. The grain size distribution is unimodal (Figure 28).

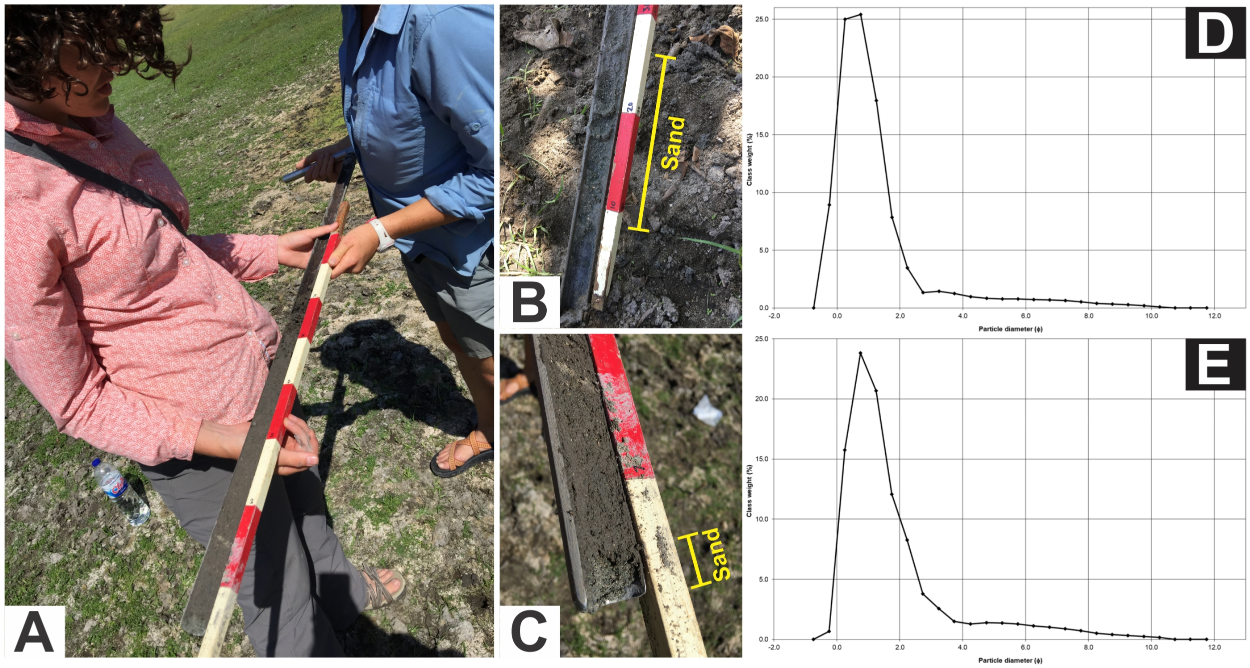

Figure 28. A) Photo of augur location on Wula waijelu lake. B) and C) 2 sand layers identified on the field. D) Grain size distribution of sand layers.

Site 1 is on 0.72 km from the shore and at ~6 elevation on the eastern part of the lake. Using an augur, we found all mud to depth of 80 cm where we encountered a sand until 94 cm. This sand has the same physical properties as in site 1.

6.3.6 Wairara Lake

This site is 2.9 km from the shore and at an elevation of ~5.5 m. The augur halted at 43 cm depth in sand. We found sand from 28-43 cm depth. This sand is light brown in color, poorly sorted, rich in foraminifera and shell fragments, has some pebbles, with an average grain size from very coarse to coarse. The grain size distribution is unimodal (Figure 29).

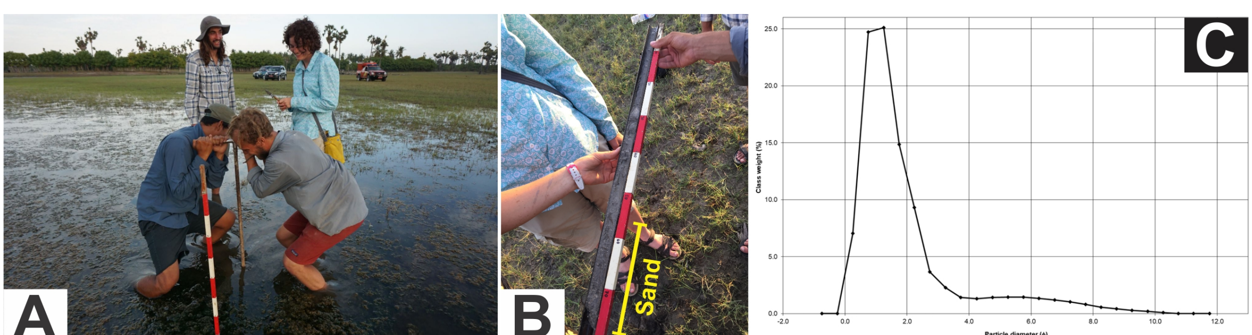

Figure 29. A) Photo of augur location on Wairara lake. B). Sand layer identified on the field. C) Grain size distribution of sand layer.

6.3.7 Pohungga Lodu Village

We investigated 3 sites inland from Pohungga Lodu Beach at an elevation of ~16 m above sea level. Site 1 is on a coastal plain 2 km from the shore. Using an augur, we encountered nothing but mud until finding sand at 100-105 cm depth. This sand is dark grey in color, muddy, poorly sorted, with an average grain size from very fine to medium, and a bimodal grain size distribution (Figure 30).

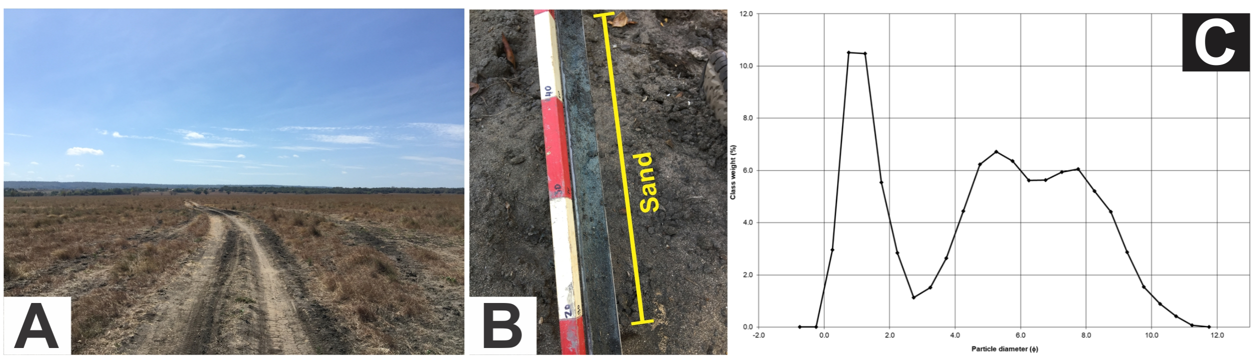

Figure 30. A) Photo of augur location in Pohungga Lodu village. B) Sand layer identified on the field. C) Bimodal grain size distribution of sand layer.

6.3.8 Lamakera

We investigated 2 sites inland from Lamakera Beach at an elevation of ~10 m above sea level. Site 1 is 327 m from the coast and only yielded sand. Site 2 is 700 m from the shore and at an elevation of ~11 m. Mud was encountered to a depth of 80 cm where we penetrated a sand layer until a depth of 150 cm. This sand is light grey in color, muddy, poorly sorted, angular, foraminifera and shell fragment rich with an average grain size from coarse to very coarse. The grain size distribution is unimodal (Figure 31).

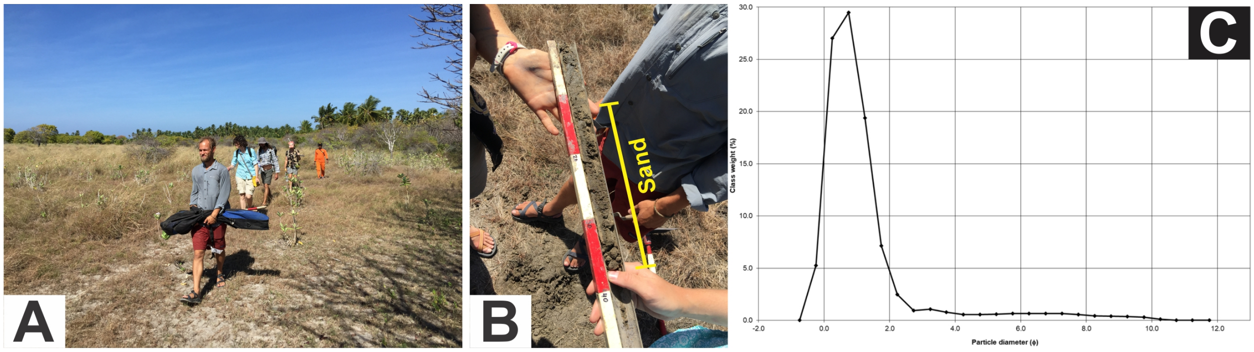

Figure 31. A) Photo of augur location in Lamakera. B) Sand layer identified on the field. C) Bimodal grain size distribution of sand layer.

6.3.9 Summary of results from Sumba

Some of the best-preserved candidate tsunami deposits along the eastern Sunda Arc are found in Sumba because of the abundance of lakes near to the coast. Few, if any, of the lakes are fed by streams, which limits the possible sources of sand layers, especially those with marine fossils. All the lakes also too high for storm wave intrusion. Unlike the other islands, the coastal plain surface of southern Sumba rises rapidly near the shore from elevations up to16 m. This morphology provided a way to test how high paleo-tsunamis might have reached.

XRD analysis of sand deposits show abundant quartz, plagioclase, calcite, some aragonite, pyroxene, and magnetite (table x). The modern Beach sand has abundant marine fossils, and many of the candidate sands are also rich in marine fossils even though they are in fresh water lakes and at elevations up to 16 m above sea level. The sand layers have the following characteristics of tsunami deposits: 1. variation in grain size from medium to very coarse sand, 2. poor sorting, 3. interlayered with mud, 4. thickness of around 25 cm, 5. marine organisms and 6. bimodal grainsize distributions.

Table 4. Mineral composition of Sumba samples sand from XRD analysis

Location	Site	Depth	Plagioclase	Pyroxene	Magnetite	Quartz	Calcite	Aragonite	Other
Sumba	Lamakera	100-150 cm					x	x	
	Wairara	28-43 cm				x	x	x	
	Walakiri	10 cm				x	x		
		50 cm				x	x		
	Kaliuda	70 cm				x	x	x	
	Karera	64 cm	x			x			
	Kereweii	25-30 cm	x		x	x	x		
		110-120 cm	x			x			Ms?
		110-120 cm	x	x	x	x			
	Pohungga lodu	100-105 cm			x	x			
	Wula waijelu	72-95 cm	x			x	x		
		80 cm	x			x	x		

6.4 Timor Island

Like Sumba, Timor is an anomalous island along the eastern Sunda Arc since it is not adjacent to Java Trench where oceanic lithosphere is being subducted, but the Timor Trough where continental lithosphere is subducting. The trough is 3 km shallower than the Java Trench due to isostatic uplift of the subducting Australian continental margin. Convergence across the Timor Trough (~20 mm/a) is much less than that along the Java Trench (Nugroho et al., 2009).

Figure 32. Map showing locations of tsunami deposits in Timor Island

We only investigated the western-most coast of West Timor (Figure 32). One location in is on the offshore island of Semau and the other is on SW point of Timor Island. On Semau Island we dug a 73 cm deep trench on a coastal plain at 0.38 km from the shore and at 1 m elevation. The trench contains all mud except for a few horizons of pebbles like we found on the Beach at 20-27 cm depth and one sand layer at 42-57 cm depth. This sand layer is light brown in color, muddy, poor sorted, with average grain size fine to medium (Figure 33).

Figure 33. Left:Trench location on Semau island, Right: All sand lithology from the trench

On Timor Island, we found a marshy lake 0.3 km from the shoreline with no streams feeding it (Figure 34). A 3-meter-high barrier separates the lake from the Beach. We dug 3 trenches on the southern part of the lake. Trenches 1 and 2 are 10 m apart and had identical stratigraphy. We found a thin sand layer from 7-10 cm depth, which may be from the 1977 tsunami, if it reached this area. From trench 2, we collected a macrofossil at a depth of 27 cm. In trench 3 we found a thicker sand layer at 17-34 cm depth with many gastropod fossils in the mud layer beneath it. This sand is dark brown in color, muddy, poorly sorted, rounded, foraminifera- and gastropod-rich with an average grain size from coarse to very coarse. The grain size distribution is bimodal (Figure 35).

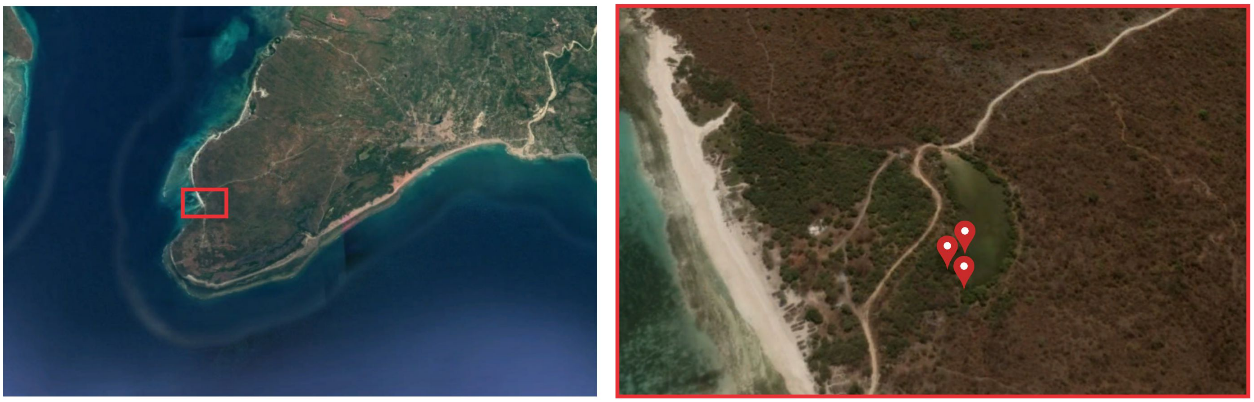

Figure 34. Google Earth image of site 1 on the lake shore near Oesina Beach on Timor Island.

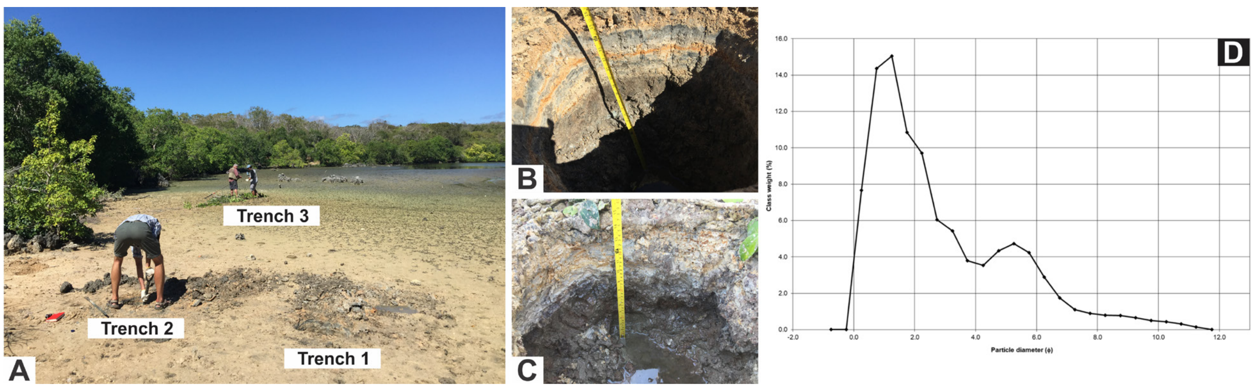

Figure 35. A) Trenching location on marshy lake near Oesina Beach. B) Sand layers from trenches. C) Bimodal grain size distribution of sand layers.

6.4.1 Summary of results from Timor

The near shore lake in Timor preserved two candidate tsunami sand deposits. The composition of the sands from XRD analysis have quartz, calcite, and aragonite (table x). The modern Beach sand has the abundance of marine organisms. Timor is closer to the cyclone belt than the other islands, so it possible that these deposits are from storms that inundated the lake, especially at the low elevations we sampled.

The sand layers have the following characteristics of tsunami deposits: 1. variation in grain size from fine to coarse sand, 2. poor sorting, 3. interlayered with mud, 4. thickness of around 5 cm, 5. marine organisms and 6. bimodal grainsize distribution.

Table 5. Mineral composition of Timor samples sand from XRD analysis

Location	Site	Depth	Plagioclase	Pyroxene	Magnetite	Quartz	Calcite	Aragonite	Other
Timor	Oesina	7-10 cm				x	x	x	
		17-34 cm				x	x	x	

7. Discussion

7.1 Stratigraphy and Sedimentology

Consistent candidate tsunami deposits were discovered on all the islands we investigated over a distant of 1000 km along the strike of the Java Trench and Timor Trough (see Appendix 2). Most of these sand, pebble and cobble layers are interlayered with mud, and were deposited in normally very low energy settings. Coral and shell fragments are found mixed in with most of the deposits. Imbricated boulders up to 3 m in diameter and 40 cm thick were also found on all the islands except for Timor. There are 3 different possible origins for the high energy deposits found in low energy environments: first, is that they are tsunami deposits; second, is that they are flood deposits from streams; third, is that they are from storm waves. It is possible that each one of these processes is responsible for some of these deposits.

7.1.1 Flood deposits

Flood deposits share some characteristic with tsunami deposits, such as sharp basal contact, fining upward grainsize, unimodal grain size distribution, heavy minerals, lack of marine fossils, cross stratification and rip up clasts.

These similarities permit samples from near Purnama Beach, Bali to be interpreted as possible flood deposits. However, the lateral extent of the 2 sand layers we found over large area argue against a flood origin. Sand layers in Lombok, Sumba and Timor all have marine fossils and abundant calcite and aragonite, which is not consistent with stream flood deposits.

7.1.2 Storm deposits

Flooding caused intense storms can leave coarse clastic deposits that are indistinguishable from tsunami deposits in many ways (Morton et al., 2007). However, the eastern Sunda Arc is not in the cyclone pathway. Local residents at the locations we sampled confirmed that storm waves do not encroach on the coastal plain or flood low-lying coastal areas where the tsunami deposits are found. Some of the highest waves ever recorded have hit the shorelines of these islands in the past year, but slow flooding only inundated tens of meters inland.

Nott (2004) documents that large cyclones impacting the northwest coast of Australia did not imbricate boulders like those observed throughout the study area or leave sand deposits as far inland as we observed. The 1994 East Java tsunami formed ridges of imbricated boulders (Meservy, 2017) like those we observed in Bali, Lombok and Sumba. All the imbricated boulder deposits, except for some at Batu Payung, consist of hardpan ripped from the bottom offshore and carried over the storm berm.

7.1.3 Tsunami deposits

The most likely interpretation of the consistent occurrence of high energy deposits in low energy environments across over a distant of 1000 km along the strike of the Java Trench and Timor Trough is that they were deposited by giant tsunamis. Tsunamis of this size would require megathrust earthquakes along the Java trench.

The preliminary age of the sand deposits in Bali indicate 2 tsunamis occurred one at ~0.5 ka BP and the other at ~2.7 ka BP. These ages are similar with those found from candidate tsunami deposits in Java (see above). We have also submitted 10 other samples for 14C age analysis. It is possible that some of these will produce ages between the two we have, which may document other possible events.

7.1.4 Tsunami disaster mitigation

We conducted some communication effectiveness experiments in each of the villages we visited. These experiments involved questionnaire surveys and presentations to help communities at risk of tsunami hazards identify the natural signs that a tsunami may be approaching (Hall et al., 2017). We also provided training in how to respond to these disaster signs. With the help of local Disaster Agency, we educated the communities most at-risk through a "20-20-20" campaign: if the ground shakes for > 20 seconds, then evacuation efforts may only have 20 minutes to reach a place at least 20 meters above sea level.

8. Conclusion

Based on evidence discovered in Eastern Sunda arc, a very large tsunami inundated over a distant of 1000 km along the strike of Bali, Lombok, Sumba and Timor Island, depositing two 10-24 cm thick paleo-tsunami deposits. Interpretation was based on grain size variation, stratigraphy, and OSL sample ages. Flood deposits will not be able to as laterally extensive as our finding, also large storms are rarely known to make landfall along eastern Sunda Arc.

The preliminary age of the sand deposits in Bali indicate 2 tsunamis occurred one at ~0.5 ka BP and the other at ~2.7 ka BP. These ages are similar with those found from tsunami deposits in Java. The imbricated boulders along beaches of eastern Sunda Arc were emplaced because of one or several tsunamis along the Java trench. Nevertheless, findings in Eastern Sunda arc support the previous findings from 2016 wave exploration. At risk communities should be prepared for potential tsunami with the "20/20/20 principle" (Hall et al. 2017).

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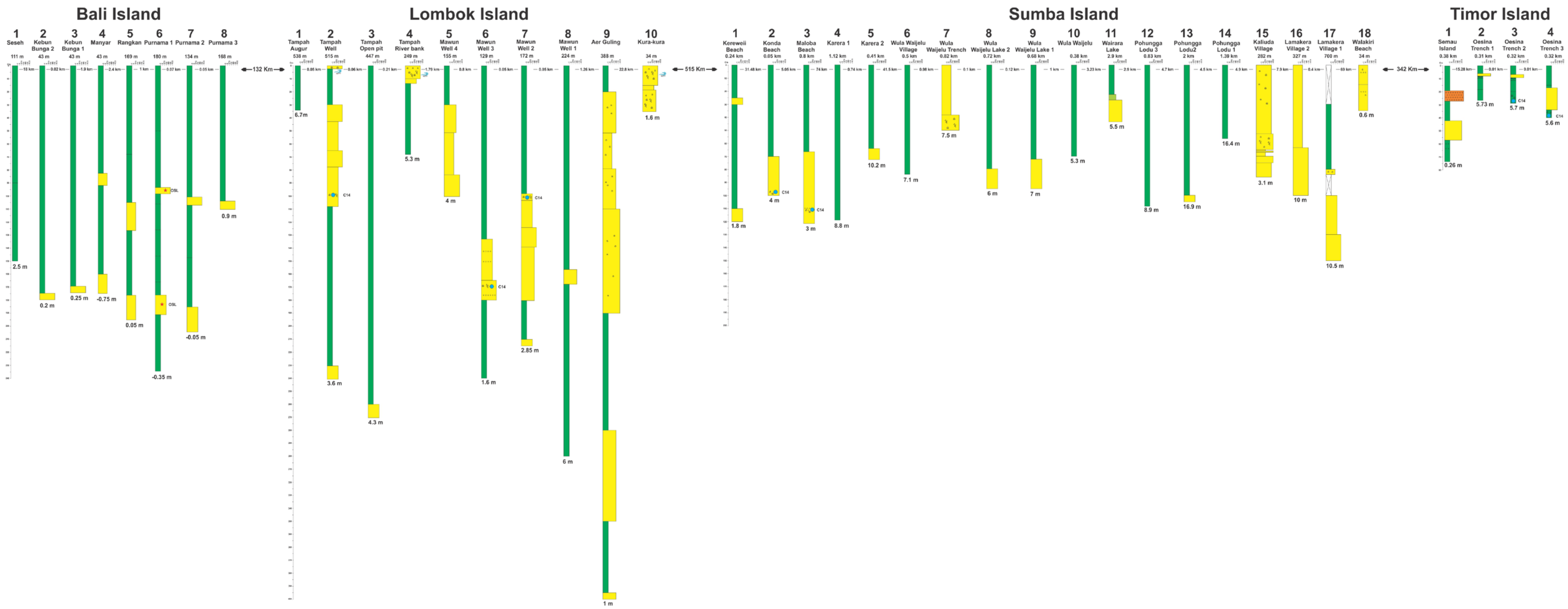
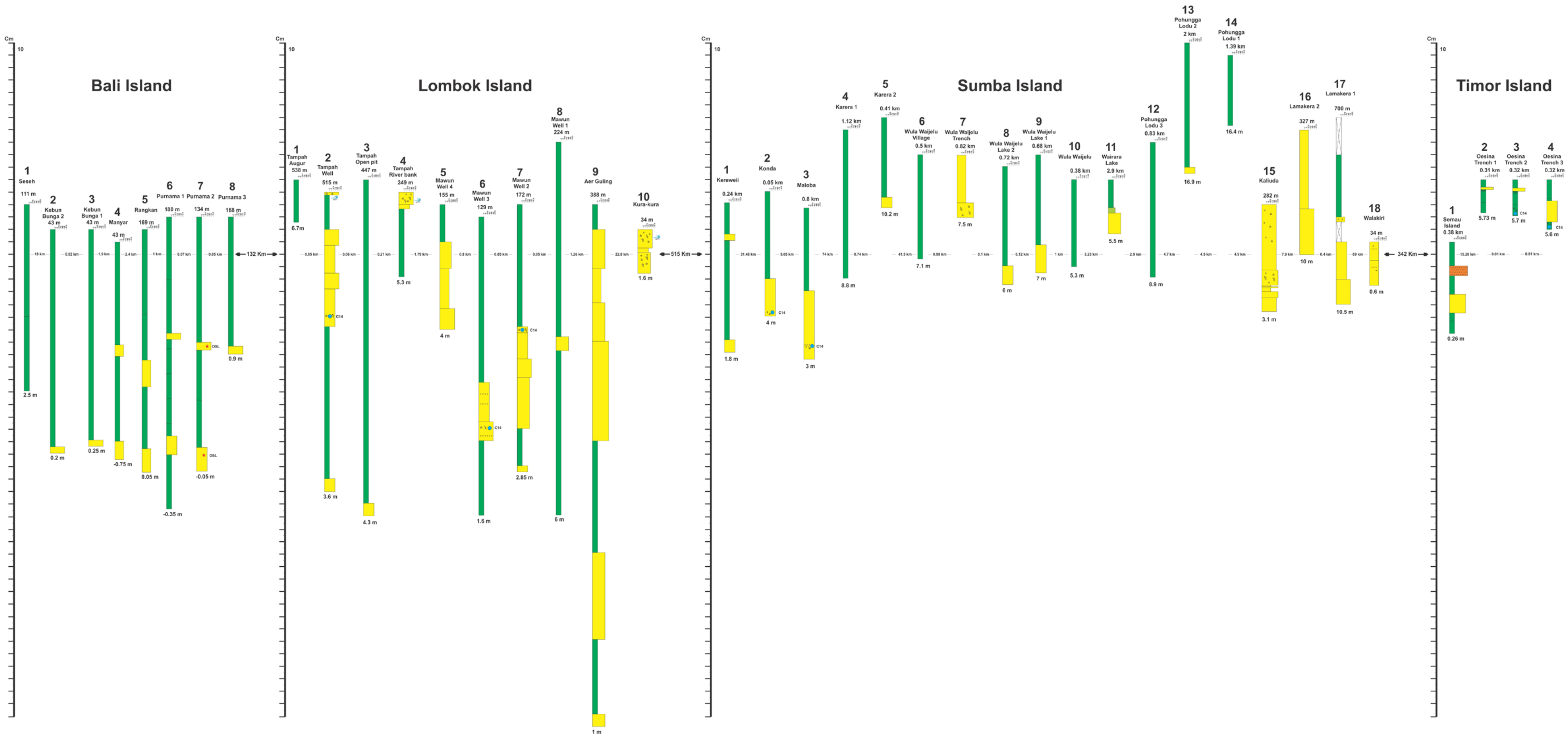


Appendix 1. All stratigraphy column of study area



Appendix 2. Elevation datum for all stratigraphy column of study area