Discovery of Possible Paleotsunami Deposits in Pangandaran and Adipala, Java, Indonesia Using Grain Size, XRD, and $^{14}$C Analyses

Kevin L. Stuart
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Discovery of Possible Paleotsunami Deposits in Pangandaran
and Adipala, Java, Indonesia Using Grain Size,
XRD, and $^{14}$C Analyses

Kevin L. Stuart

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Discovery of Possible Paleotsunami Deposits in Pangandaran and Adipala, Java, Indonesia Using Grain Size, XRD, and \(^{14}C\) Analyses

Kevin L. Stuart
Department of Geological Sciences, BYU
Master of Science

Grain size, \(^{14}C\) age, and X-ray diffraction (XRD) analyses of sediments indicate possible tsunami deposits on the southern coast of Java near Pangandaran and Adipala. Previous studies that have described known recent and paleotsunami deposits were used for comparison. Fining-upward grain size trends, interbedded sand and mud, sediment composition, and trends in heavy mineral abundances are among the characteristics used for tsunami deposit identification.

At Batu Kalde, an archaeological site south of Pangandaran, a layer of aragonitic sand with marine fossils was found atop a layer of archaeological fragments at an elevation of \(\sim 2-5\) m. It is likely this layer was deposited by a tsunami, potentially generated by a mega-thrust earthquake. Archaeological material remains suggest that the tsunami occurred \(\sim 1300\) years ago. A bivalve with an age of 5584-5456 cal YBP was buried within the deposit, perhaps long after its death. At Goa Panggung, a cave east of Batu Kalde, fining-upward grain size trends, composition of sediments, and radiocarbon ages suggest the presence of at least one tsunami deposit. A 5040-4864 cal YBP piece of charcoal overlying modern organic matter suggest that the tsunami first scoured the cave floor, reworking existing material and making interpretation difficult. At Adipala, in western Central Java, fining-upward grain size, upward decrease in heavy mineral abundances, and lateral continuity of sand layers revealed the existence of two possible tsunami deposits buried within the sediments in a swale \(\sim 1.6\) km from the ocean. Age of the deposits is undetermined.

Keywords: Java, Pangandaran, Adipala, Indonesia, tsunami, earthquake, deposit, x-ray diffraction, XRD, paleotsunami, grain size
ACKNOWLEDGEMENTS

First, I must thank my wife, Ann, and my nine children. Without their help, this would have been impossible. Returning to school has been a long and arduous task and an enormous sacrifice, more so for them than for me. I also want to thank my parents for their support and enthusiasm, and for teaching me that, “If it is to be, it is up to me.”

Many people helped me with several different aspects of my research, and I could never list everyone. However, I want to thank Chelsea Samuelson and Torri Duncan. Their help in analyzing samples was invaluable and saved me countless hours. Hanif Sulaeman, Bondan Ramadhan, Sumi, Irfan Islamy, Carolus Prasetyadi, Eko Yulianto, and Purna Putra showed me where to go and what to do in Java. I would have been lost without them. I am grateful to my advisor, Ron Harris, for accepting me as a graduate student, for his enthusiasm (which oftentimes was what pulled me from my discouragement and helped me believe that I could do this), and for bringing me to beautiful Indonesia. I also thank Stephen Nelson, John McBride, Sam Hudson, and Kevin Rey for answering dozens of questions and for hours of help in the lab. I thank Kathryn Tucker and Kris Mortenson for their countless hours of behind-the-scenes work. I want to express heartfelt appreciation to many other friends, fellow students, and the staff and faculty in the Department of Geological Sciences at Brigham Young University and in the Department of Earth Sciences at Utah Valley University. Visiting Indonesia with professors from both schools was awesome. Finally, I thank the people of Indonesia for their welcoming kindness. I was fortunate to be in Pangandaran on the 10-year anniversary of the 17 July 2006 tsunami. As I participated in programs, visited the grave site of the victims, and lit candles with the people who had lost friends and family members, I was able to genuinely experience the effect it had on the people there. I hope that this research and more like it can help lessen such loss in the future.
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1 Introduction

Southern Indonesia is one of the most seismically-active places in the world. Records have been kept by Dutch colonists since at least the sixteenth century, documenting 61 earthquakes and 36 tsunamis between 1538 and 1877 (Harris and Major, 2016; Wichmann, 1918; Wichmann, 1922). Many recent studies have been published about earthquake risk in Indonesia, focusing on efforts to improve disaster mitigation and the resilience of people living in hazard-prone environments (Irsyam et al., 2010; Irsyam et al., 2013; Harris and Prasetyadi, 2002; Reese et al., 2007). Such research and planning are vital. Earthquakes and related hazards have killed tens of thousands in Indonesia in recent years, including over 730 in the July 17, 2006 Pangandaran tsunami (Lavigne et al., 2007) and over 130,000 during the 26 December 2004 Indian Ocean tsunami and earthquake (Muhari et al., 2007). Indonesia is the fourth most populous nation on Earth (United Nations, 2017; Current Population, 2018). With an exploding population, large earthquakes and tsunamis like those that have occurred in the region in the past could cause hundreds of thousands of casualties.

Perhaps because of the 2004 Indian Ocean earthquake, much of the earthquake research in Indonesia has focused on the Sumatra region. However, Java is located next to what may be a seismic gap capable of producing a severe earthquake and tsunami (Hanifa et al., 2014). Java is the most populous island in the world (Most Populous Islands, 2018) and one of the most densely populated areas in Indonesia (Indonesia Population, 2018). Further, over half of the Indonesian population living in absolute poverty is on the island of Java (Urban & Rural Poverty in Indonesia, 2016). An earthquake and tsunami on the scale of the 2004 event could lead to catastrophic death tolls in the crowded coastal communities on the southern part of the island.
Pangandaran and Adipala are centrally located on the southern coast of Java, next to the Sunda trench (Figure 1). The area was inundated by a moderate tsunami in 2006 and has likely experienced many earthquakes and tsunamis in the past. At least 5 earthquakes have occurred south of Java since 1840 (Newcomb and McCann, 1987; Yudhicara et al., 2013; Harris and Major, 2016). Because of its proximity to the trench, low-lying coastal areas, and topography marked by ridges and swales, the area has been considered to have high potential for the deposition and preservation of tsunami deposits. Many studies have been done in the area to explore for and examine both recent and paleotsunami deposits in low-energy environments such as swales and marshes (Rizal et al., 2017; Yudhicara et al., 2013; Hébert et al., 2012; Moore et al., 2011; Spiske et al., 2010; Lavigne et al., 2007; Reese et al., 2007; Marami and Tinti, 1997; Dawson et al., 1996).

The author and research team conducting this study visited Pangandaran and Adipala from 15 July to 1 August 2016. This timing was significant as the ten-year anniversary of the 2006 Pangandaran tsunami was commemorated on 17 July, and members of the team organized and participated in surveys, programs, and interviews to help improve resiliency of the people in Pangandaran and elsewhere. This study used data from the studies mentioned previously to search for possible tsunami deposits and address the question of whether there is evidence for large tsunamis—potentially related to mega-thrust earthquakes—in this area of southern Java. It combined the use of exploration (trenching and coring), grain size analysis, mineralogical analysis, and optically stimulated luminescence (OSL) and \(^{14}C\) dating techniques to identify and correlate possible paleotsunami deposits.

In some cases, such as with the 2006 Pangandaran “tsunami earthquake” where some people felt no shaking at all before the waves came (Reese et al., 2007; Fritz et al., 2007), the
tsunami may be far more devastating than the earthquake itself. Identification of paleotsunami deposits is an important part of developing a better understanding of the nature, frequency, and intensity of tsunami events in this area. This understanding is important for creating inundation maps and realistic vulnerability assessments (Rubin et al., 2017) and will help develop effective disaster mitigation plans that will save lives.

1.1 Geology of Java

The island of Java is located in southwest Indonesia and is part of the volcanic island arc behind the Sunda trench (Figure 1). Bedrock is composed dominantly of Cenozoic volcanic and carbonate rocks that are widely covered in Quaternary sediments and volcanism (Steinshouer et al., 1999; Karnawati et al., 2006). Southern Java is less well-known geologically than other areas of the island due to the scarcity of oil exploration (Java geology and evolution, 2017). However, a general Cenozoic history of sedimentation, tectonic evolution, and volcanism has been described by Bolliger and DeRuiter (1975), and is summarized in the following 2 paragraphs.

Pangandaran and Adipala are located on the northern edge of the Java forearc basin (Figure 1). The surrounding region (on- and offshore) is a series of Neogene sedimentary basins filled with Neogene and Quaternary sediments. Topographic lows were filled with deep marine facies, and highs are composed of Neogene shallow marine limestones. Structural characteristics of the area are defined by Late Oligocene tectonics and volcanism. The same tectonics also produced an extensive angular unconformity beneath the Neogene sediments that reaches at least from west of Pangandaran to south of Yogyakarta. The unconformity is less than 760 m below the surface at Pangandaran and between 760-1500 m below Adipala. Offshore is a basin filled with over 3000 m of undeformed sediment, composed mostly of volcanic material of variably-
sized clasts as well as deep marine clastics and clay with some turbidites. Figure 2 shows a schematic cross section, oriented N-S through the Sunda trench, central Java, and the southernmost Sunda shield.

The Late Oligocene tectonic event involved faulting, subsidence of the Sunda shield, and widespread volcanism. Following this event were three more tectonic events. The first, during the Early Miocene, was weakly expressed and involved subsidence, faulting, and volcanism. The second, during the Mid Miocene, caused regional uplift and emergence, with simultaneous block tectonics and tilting that caused local rapid subsidence. Volcanism was concentrated in present-day inland Java. Subsequent regional subsidence led to widespread cover of deep marine Late Miocene to Early Pliocene sediments. The third tectonic event, during the Late Pliocene, caused major updoming of Java and extreme volcanism that persists today.

Figure 1. Google Earth imagery of the region around Pangandaran and Adipala. Locations of study sites are marked with yellow triangles and text.
1.2 Historic seismicity of the Sunda trench

Java is part of the Sunda arc-trench system, which extends from Sumatra in the west to Timor in the east, where the Indo-Australian plate subducts beneath the Eurasian plate with a convergence rate of roughly 7 cm/yr, orthogonal to the trench (Tregoning et al., 1994; Hanifa et al., 2014). Historic seismic activity near West Java has not been enough to account for measured convergence rates (Tregoning et al., 1994). Newcomb and McCann (1987) suggested that this is because movement occurs aseismically and earthquake potential is low. However, Tregoning et al. (1994) warned that the 1994 earthquake suggests otherwise, as may the 2006 earthquake. Abercrombie et al. (2001) concluded, based on seismic analysis, that the 1994 earthquake occurred from slip over a subducting seamount that acted as a locked area in an otherwise decoupled subduction zone. Similarly, Raharja et al. (2016), based on an analytical approach of logarithmic and exponential functions to model GPS data, concluded that the 2006 rupture likely occurred in a less-rigid region that tends to slip continuously for long periods, lessening the
threat of a mega-thrust event. Additionally, Okal (2012) concluded that the 1921 tsunamigenic earthquake was an intraplate earthquake on the subducting slab and not a mega-thrust event.

Okal (2012), however, stated that it is possible that the Sunda trench south of Java produces occasional, if rare, mega-thrust events. Rubin et al. (2017) found correlations between tsunami deposit thickness and time between deposits in a cave in Aceh, Sumatra. The correlations suggest that very long seismic dormancies indicate strain is accumulating on the Sunda arc, and such dormancies precede very large earthquakes comparable to the 2004 Sumatra event. This could be the case for the trench south of Java (McCaffrey 2008). Furthermore, Hanifa et al. (2014) claimed that GPS measurements of convergence, uplift, and shortening considered together suggest that the subducting Indo-Australian plate is at least partially locked, with a coupling ratio of 70-82% at a depth of 20-45 km beneath Pelabuhan Ratu (240 km west of Pangandaran), and a coupling ratio of 75-80% at a depth of 37-45 km beneath Pangandaran. They added that strain accumulated over a 300-year absence of mega-thrust events in the area could result in either a future single large earthquake and associated tsunami, or several future slow-slip “tsunami earthquakes” similar to the 2006 Pangandaran earthquake. Potential is high for large tsunamis with either scenario.

If the Sunda trench near Java is indeed locked and strain is accumulating, then Java is located next to two large seismic gaps (Figure 3) that may not have produced a mega-thrust earthquake since at least 1584-87 (Harris and Major, 2016). With a possible accumulated slip of up to 30 m, these seismic gaps are potentially capable of producing M 9.18 and M 8.87 earthquakes, based on calculations using linear regression formulae (Equations 1 and 2) from Wells and Coppersmith (1994) and rupture zones of earthquakes given by Yeats (2012). Tsunamis generated by such earthquakes could produce run-up heights as high as 20-30 m and
inundate huge swaths of low coastal areas. Coulomb stress transfer modeling (Figure 3) of earthquakes that have already occurred next to these gaps (the 1994 and 2006 earthquakes) suggests that little stress was released by these earthquakes, indicating that there may instead be one very large gap over 2000 km long.

\[
\text{Eq. 1} \quad M_0 = \mu D_{\text{avg}} A
\]

\[
\text{Eq. 2} \quad M = \frac{2}{3} \log(M_0) - 10.7
\]

\(M_0\) = seismic moment  \(D_{\text{avg}}\) = average surface displacement = \(D_{\text{max}} / 2\)

\(A\) = fault surface rupture area  \(M\) = moment magnitude

\(\mu\) = shear modulus (3 \(\times\) 10^{11} dyne/cm² for crustal faults)

Figure 3. Map showing seismic gaps for the Sunda arc, based on rupture zones of past earthquakes given by Yeats (2012). Magnitude and other data for past earthquakes are from usgs.gov. Potential magnitudes for seismic gaps are calculated from slip rate between the Eurasian plate and the Indo-Australian plate and an estimated 400 years since the last event in each area, using formulae from Wells and Coppersmith (1994). Coulomb stress transfer was modeled using USGS’s Coulomb 3.4 software in MATLAB. Input data are shown in the figure.
Newcomb and McCann (1987) and Yudhicara et al. (2013) report that five tsunamigenic earthquakes have been recorded for the south coast of Java: 4 January 1840, 20 October 1859 (MMI VII from Harris and Major, 2016), 11 September 1921 (M 7.5 from Newcomb and McCann, 1987), 3 June 1994 (M 7.6 from Tsuji et al., 1995, or M 7.9 from Hébert et al., 2012), and 17 July 2006 (M 7.8 from Moore et al., 2011). Of these, the Pangandaran and Adipala study areas were affected by tsunamis from the 2006 earthquake and the 1921 earthquake (Newcomb and McCann, 1987). Yudhicara et al. (2013) reports that the 1994 tsunami affected Pangandaran and Adipala, but from Tsuji et al. (1995), that does not seem to be the case.

The tsunami caused by the 2006 Pangandaran earthquake arrived at land about 40 minutes after the shaking (Reese et al., 2007). Flow depths at Pangandaran were mostly 2-4 m (Reese et al., 2007). At Adipala, depths averaged 5 m for a distance approximately 100 km to the east (Moore et al., 2011). Inundation reached as far as 1 km inland (Moore et al., 2011). Average run-up (the maximum elevation reached by tsunami inundation) was about 5 m, with a maximum run-up of 21 m at Permisan prison (Fritz et al., 2006; Hébert et al., 2012). Even though the shaking of the earthquake was generally not felt, the recession of the ocean was noticed by witnesses and was as much as 300-500 m (Reese et al., 2007). Panic upon seeing the waves led to death and injury as people fled in vehicles in inconsistent directions. Wells were contaminated by saline sea water, buildings were severely damaged, and about 10% of the exposed population were killed (Reese et al., 2007).

1.3 Tsunamis and tsunami deposits

Tsunamis associated with convergent plate boundaries, such as the Sunda trench, are caused by vertical movement of the seafloor. This movement displaces a rectangular-shaped
column of water. The column collapses perpendicular to the strike of the fault, forming waves of very low amplitude and long wavelength. As these waves approach land, wave height can increase significantly, while the long wavelength provides enough energy to drive the tsunami far inland. Tsunamis often arrive at land as multiple waves, or as multiple pulses in one wave, often with the second pulse being the largest (Reese et al., 2007; Dawson and Stewart, 2007). Each wave or pulse may erode and/or deposit sediments, depending on location and other factors, and even remove sediment left by previous waves or pulses.

Discovering deposits in the geologic record is difficult, due largely to the fact that tsunamis affect high-energy environments with frequent reworking, such as coasts and floodplains (Dawson and Stewart, 2007). Thus, preservation is often impossible. Challenges to identification and preservation include reworking by mechanical or biological processes, high water table levels, cultivation, lack of accommodation (Kelsey et al., 2015), fluvial influence, soft sediment deformation, and lack of lithological or textural differences between tsunami-transported and local sediments (Costa et al., 2014). Lowe and deLange (2000) suggest that a minimum inundation height of 5 m is needed to leave a recognizable deposit in the onshore sedimentary record.

Tsunami deposits are potentially identified by various characteristic features that have been described in many different studies. Identification of historical tsunami and paleotsunami deposits is generally done by comparison with recent known tsunami deposits. Basic features include an unconformable basal contact where the tsunami may have scoured the ground surface, sand layers that mimic existing topography and in which sand grains fine upward (normal grading), mud drapes atop a sand layer or between sand layers from multiple pulses, and mud rip-up clasts (Figure 4; Morton et al., 2007; Moore et al., 2011). Additionally, sand sheets may
fine landward (Morton et al., 2007; Moore et al., 2011; Costa et al., 2014). Tsunami sediment grains may have more fresh surfaces and a greater number of percussion marks (Costa et al., 2014). Tsunami deposits may contain broken shells, coral, or microfossils (Yudhicara et al., 2013; Rizal et al., 2017; Rubin et al., 2017), and may display certain mineralogical trends, specifically a decrease in heavy minerals upward within the bottom portion of a deposit (Figure 4; Moore et al., 2011; Costa et al., 2014). Tsunami deposits may also contain anthropogenic material and wood or plant debris. Deposits left by tsunamis are generally less than 25 cm thick (Morton et al., 2007). In places where multiple tsunami deposits have been preserved, deposits are often separated by organic-rich beds with lower abundances of microfossils (Rubin et al., 2017; Jankaew et al., 2008). Sand layers interbedded with other sediments (e.g. clay or peat) are perhaps the most important feature for initial discovery of potential tsunami deposits. Tsunami deposits appear to be best preserved in low-energy environments such as swales, coastal lakes, marshes, and caves (Rizal et al., 2017; Rubin et al., 2017). Paleostunami deposits within swales have been identified as far as 3 km from the coast (Rizal et al., 2017) and from as much as 8200 years ago (Costa et al., 2014).

Severe storms can also create sandy deposits similar to those made by tsunamis, and distinguishing between the two types can be challenging. Cyclones do occur (Dua Bibit Badai, 2018), though Java is sufficiently close to the equator and the Coriolis Effect is weak enough that cyclone exposure is limited (Figure 5; Rubin et al., 2017; Anthes, 1982; Rohde, 2018). Research has shown that there are differences between tsunami deposits and storm deposits (Morton et al., 2007; Engel and Brückner, 2011). Storm deposits generally lack internal mud layers or rip-up clasts, exhibit no inland fining, are commonly thicker than 30 cm, and have many layers or laminae, but Engel and Brückner (2011) point out that contradictory examples have been
encountered for each of these and other characteristics. Differences between storm and tsunami deposits are summarized from Morton et al. (2007) in Table 1.

Figure 4. A) Graph from Moore et al. (2011) showing grain size distribution and density data for the 2006 Pangandaran tsunami. Magnetite was present at the base of the two sub-deposits (one from each wave pulse). Heavy mineral abundance decreases upward within the bottom portion of each sub-deposit, while grains fine upward within the upper portion of each sub-deposit. B) Photo from Morton et al. (2007) of an exposure of a deposit from the 23 June 2001 La Quinta, Perú tsunami, showing grain size trends, rip-up clasts, and a mud drape between sub-deposits.

Figure 5. Image from Rohde (2018) showing the tracks of nearly 150 years of tropical cyclones. Map is based on all storm tracks available from the National Hurricane Center and the Joint Typhoon Warning Center through September 2006.
Table 1. Table summarized from Morton et al. (2007) listing differences in flow and deposit characteristics between tsunamis and storms.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Tsunamis</th>
<th>Severe coastal storms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of coast impacted</td>
<td>10–10,000 km</td>
<td>100–600 km</td>
</tr>
<tr>
<td>Potential wave run-up</td>
<td>Most are 10’s of meters</td>
<td>A few meters</td>
</tr>
<tr>
<td>Number of overland waves</td>
<td>Normally &lt;10</td>
<td>Normally &gt;1000</td>
</tr>
<tr>
<td>Inundation depth</td>
<td>0–20 m</td>
<td>&lt;5 m</td>
</tr>
<tr>
<td>Active flow duration</td>
<td>Minutes to hours</td>
<td>Hours to days</td>
</tr>
<tr>
<td><strong>Deposit characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum clast size</td>
<td>Boulders</td>
<td>Boulders</td>
</tr>
<tr>
<td>Internal mud layers</td>
<td>May be present</td>
<td>Not reported</td>
</tr>
<tr>
<td>Vertical grading of entire deposit</td>
<td>Normal or no grading,</td>
<td>Normal or inverse grading</td>
</tr>
<tr>
<td></td>
<td>rare inverse grading</td>
<td></td>
</tr>
<tr>
<td>Lateral grading</td>
<td>Inland fining</td>
<td>No trend or inland fining</td>
</tr>
<tr>
<td>Average deposit thickness</td>
<td>Usually &lt;25 cm</td>
<td>Commonly &gt;30 cm</td>
</tr>
<tr>
<td>Sedimentary structures</td>
<td>None or rare laminae</td>
<td>Planar laminae, some foresets</td>
</tr>
<tr>
<td>Number of layers/laminasets</td>
<td>Few</td>
<td>Many</td>
</tr>
<tr>
<td>Rip-up clasts</td>
<td>Common</td>
<td>Rarely present</td>
</tr>
<tr>
<td>Basal contact</td>
<td>Abrupt, erosional or</td>
<td>Abrupt, erosional or</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Deposit elevation</td>
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<td>Commonly &lt;4 m</td>
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2 Materials and Methods

2.1 Preliminary investigation and exploration

The general area of Pangandaran was chosen because it was the site of the 2006 tsunami, and because of characteristics favorable to the preservation and study of tsunami deposits (Moore et al., 2011). Google Earth was used to locate coastal swales, marshes, and floodplains that were promising locations for preservation. Advice from local Indonesians was also sought. Many villagers suggested places to dig and were able to recount where the 2006 tsunami had reached. During an earlier reconnaissance visit to Pangandaran, Ron Harris discovered possible tsunami deposits at Goa Panggung and Batu Kalde. Purna Sulastya Putra, a scientist from the Indonesian Institute of Science (LIPI), suggested investigating the swale east of Adipala. These locations were the most promising that were visited and were the sites that were used for this study.

2.2 Sample collection

The candidate deposit at the Batu Kalde archaeological site was identified based on a calcareous sand layer containing fragments of coral and shells above a layer of cultural material remains. One bulk sediment sample was collected from a pit dug at this location. Potential tsunami deposits at Goa Panggung cave were identified based on sediment composition and grain size variation, geometry of bedding, and ages of radiocarbon samples. Five samples were collected from this site. They were collected from thin (~1 cm) layers at different depths in a pit dug in the cave floor.

Twenty-four cores were examined from a broad region in eastern Adipala. Care was taken to avoid influence from nearby rivers. Rice paddies within swales were usually flooded,
which led to loss of sample in the water, so coring was done on or next to the berms between paddies. The cores were extracted using a 1-inch split-core sampler with 1-meter extensions. Advance and recovery were done by hand. Core length ranged from 2-4 meters. Stratification and sediment grading were well-preserved in the cores. Grain size variation was the key feature used in identifying potential tsunami deposits, particularly the presence of interbedded sand and clay. Based on this feature, samples were collected from eight of the cores and were divided into 214 subsamples of 1 or 2 cm thickness for effective analysis of vertical grain size variation. Upon returning to the lab, sediment samples were freeze dried to prevent organic growth or oxidation. Bottles were then shaken to disaggregate and homogenize samples.

2.3 Grain size analysis

A sieve analysis was done to determine the particle size distribution/gradation curve for 187 of the subsamples taken from Adipala. US standard sieve numbers 10 (2 mm), 18 (1 mm), 35 (0.5 mm), 60 (0.25 mm), 120 (0.125 mm), and 230 (0.0625 mm) were used. Subsamples were weighed three times. A percent error (the difference in the mass of the sediment sample before and after sieving) of within ±2% was considered acceptable. Percentage of soil particles finer than each sieve size versus the log of the particle diameter were plotted. Median grain size was determined from the 50-percentile line on a cumulative curve, where half of the particles by weight were larger and half were smaller. Mean grain size was determined using the formula by Folk (1968): \[ M = (\varphi_{16} + \varphi_{50} + \varphi_{84})/3 \], where \( \varphi_{16} \), \( \varphi_{50} \), and \( \varphi_{84} \) represent phi values at 16%, 50%, and 84%. Mean and median values were reported in millimeters and in phi units. Sorting, skewness, and kurtosis were not determined. Basic grain size analyses were also done on the
samples from Batu Kalde and Goa Panggung, but vertical grain size variation could not be determined because of the paucity of samples collected.

2.4 Mineralogic analysis

After grain size analyses were completed, a small portion of each sample (sufficient for XRD analysis) 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. Six of the samples had an additional small portion washed to remove organics and clays in order to aid in XRD pattern analysis. These sample portions were boiled in hydrogen peroxide and then nitric acid (each for 1 hour), and then rinsed and centrifuged in deionized water six times.

X-ray diffraction (XRD) analysis was done using a Rigaku MiniFlex 600 instrument. Unwashed 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. Other measurement conditions are shown in Table 2.

Table 2. Optical conditions used in XRD analysis of sediment samples.

<table>
<thead>
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<th>Slit condition</th>
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<tr>
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<td>10.0 millimeters</td>
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<tr>
<td>SS</td>
<td>Soller (rec.)</td>
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<tr>
<td>1.250 degrees</td>
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Pattern analysis was done using Rigaku’s 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 Autosearch option in PDXL2, as long as those minerals were reasonable. Aragonite was also searched for. Minerals regularly searched for include albite, oligoclase, andesine, labradorite, anorthoclase, augite, enstatite, magnetite, kaolinite, vermiculite, montmorillonite, 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. Determination of a good analysis was based on several things:

- Closeness of the match between the calculated pattern and measured pattern
- Presence only of minerals that could be reasonably present
- Presence of carbonates or iron oxides only if the sample effervesced or had magnetic material (confirmed using a magnet)

2.5 Age analysis

Several pieces of coral and various gastropod and bivalve shells were collected from the test pit at Batu Kalde. Seven pieces of datable organic material were found in the pit at Goa Panggung. Of these, one bivalve (Batu Kalde) and two pieces of charcoal and two root sheaths (Goa Panggung) were processed to determine radiocarbon ages. Ages were determined by the Center for Applied Isotope Studies at the University of Georgia, and were then calibrated using
the online version of Calib 7.10 at www.calib.org/calib/ (Stuiver et al., 2017). Ages were calibrated (cal YBP) to a 2σ (95% probability) error range, where zero age is 1950 AD. The non-marine (charcoal and root sheath) sample ages were calibrated using the SHCal13 curve (Hogg et al., 2013), and the marine sample (bivalve shell) age was calibrated using the Marine13 calibration curve (Reimer et al., 2013). Reservoir correction was determined by averaging ∆R data from nearby locations in northwestern Australia and western Java (Southon et al., 2002; O’Connor et al.; 2010, and Bowman 1985). Locations were chosen with consideration for proximity and ocean circulation. The value used for calibration was ∆R = 53 ±16, with a lab error multiplier of 1.

2.6 Optically stimulated luminescence

An optically-stimulated luminescence (OSL) sample was collected from the Batu Kalde archaeological site. 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. Dose rate and water content samples were also collected. The OSL age analysis of this sample is being conducted by Hanif Sulaeman at the Utah State OSL laboratory and will not be completed for several months.

3 Batu Kalde archaeological site

3.1 Batu Kalde Results

Batu Kalde (“Kalde Stone”) is located in the Cagar Alam Nature Reserve south of Pangandaran (Figures 2 and 6). It is the site of a Hindu temple that the locals say was destroyed circa 700 AD by an “invader from the sea that destroyed the temple and then left.” The elevation
of the site is not definitely known because of reproducibility problems encountered when performing the survey, which was done via Jacob’s staff method using a measuring tape, rod, and clinometer. The topographic map in Figure 6 suggests an elevation of 40 m, but this is too high, and elevation is likely ~5-10 m, with higher topography between the site and the beach to the east (Bunds, Harris, and Horns, personal commun., 2018). The area is forested, with loose, dry sediments and soil covered in a thin layer of undergrowth and plant debris. The 2006 tsunami did not reach the site.

Two test pits were dug at this location (Figure 7). The first was located about 30 m to the northwest of the site and was dug to a depth of 40 cm before reaching a layer of cultural material remains (earthenware and building material) that researchers were not allowed to disturb. The material remains are believed to be from the circa 700 AD destruction of the temple. The second pit, about 100 m to the east, was dug to a depth of 55 cm before the cultural material was reached.

Both pits were essentially the same, with a top layer of dark brown, organic-rich silty sand and soil above a layer of light brown calcareous sand with abundant fragments of branching coral, bivalves, and gastropods (Figures 8 and 9). Below the calcareous sand and fossils was the archaeological layer. Fossils were mostly uniformly spread throughout the layer of calcareous sand in the first pit, but were concentrated at the top of the same sand layer in the second pit. The OSL sample, sediment sample, and fossils were collected from the second (east) pit. Stratigraphy, average grain size, and mineralogy are shown in Figure 8. Average grain size was fine to medium sand. Determination of vertical grain size gradation was not possible because only one sediment sample was collected. XRD analysis determined the light brown sand to be nearly 80% aragonite and 12% calcite. Quartz and dolomite were also present at low abundance.
The age determined for the bivalve found at 30 cm (radiocarbon sample Pang16-15, Appendix A) was 5584-5456 cal YBP (5212 ±25 14C YBP). Age analysis for the OSL sample, collected from 35 cm, is still in process. Photos of the test pit and fossils are shown in Figure 9.

Figure 6. Map showing the locations of the Batu Kalde archaeological site and Goa Panggung cave within the Cagar Alam Nature Reserve. Contour interval is 20 m. However, as mentioned in the text, the elevation of Batu Kalde is lower than 40 m, and the contour data is likely inaccurate. Map data ©2018 Google. Accessed through http://www.maphill.com/indonesia/detailed-maps/terrain-map/ January 2018.
Figure 7. Map of Batu Kalde archaeological site, created from UAS imagery captured by Michael Bunds, Utah Valley University. Two pits were dug near the site. The first was approximately 30 m to the northwest. The second pit, from which the sediment and fossil samples were collected, was located 100 m to the east.
Figure 8. Stratigraphy (based on field description), locations of radiocarbon samples, ages, grain size variation, and mineralogy of samples at Batu Kalde (Pang16-15). Two pits were dug near the archaeological site. The first was to the northwest of the fenced area (left stratigraphic column in figure). The second was to the east (right column in the figure). Grain size and mineralogy data are from the east pit. West pit: A) Organic-rich dark brown silty sand and soil. B) Light brown silty calcareous sand with abundant branching coral, bivalve, and gastropod fragments. C) Silty sand with archaeological fragments. East pit: D) Organic silty sand with roots. E) Dense layer of coral, bivalve, and gastropod fragments in a calcareous sand. F) Poorly-graded, light colored fine calcareous sand. OSL sample collected at 35cm. G) Archaeological fragments and apparent earthenware, buried (according to locals) ~1300 years ago.
Figure 9. Top: photo of the pit dug to the east of the archaeological site, showing the organic-rich dark brown silty sand above the light brown calcareous sand. Bottom left: photo of the area around the pit to show density of vegetation and ground cover. Bottom right: photo of bivalve, gastropod, and coral fragments collected from the calcareous sand layer in the east pit.
3.2 Batu Kalde Discussion

Determining the age of the calcareous sand layer is difficult. The bivalve shell returned an age of 5584-5456 cal YBP (relative to 1950), or ~5600 years ago. However, the cultural material buried beneath the sand and fossils is believed by the locals to be ~1300 years old. The bivalve shell may have already been very old when it was deposited with the sand on top of the archaeological fragments 1300 years ago, or the archaeological fragments may be far older than believed. It is also possible that the bivalve shell and the other fossils in the pit were deposited separately from the sand at a later time (e.g. by human or animal activity). However, the fossils were found along with the sand in both test pits (~130 m apart) at the same depth, and were also found at approximately the same depth near a road some distance west of the site. The simplest explanation is that the sand layer and fossils were deposited together above the archaeological fragments ~1300 years ago, and that the analyzed bivalve was already old at the time of burial.

Sediment accumulation rates for the dark silty sand and soil deposited above the calcareous sand cannot refute either a ~5600 yr or ~1300 yr age for the calcareous sand layer. Minimum sedimentation rate if the bivalve was alive at or shortly before burial is 30 cm in 5600 years, or ~0.05 mm/yr. Maximum sedimentation rate based on burial of the archaeological fragments 1300 years ago would be 30 cm in 1300 yrs, or ~0.23 mm/yr. Either of these rates are potentially high for the location, but not unreasonable.

Because only one sample was taken from this site, it is impossible to analytically determine whether or not there are any trends in grain size that would be characteristic of a tsunami deposit. There was no evidence for multiple waves or wave pulses, nor were any rip-up clasts or mud drapes seen. However, the presence of a continuous layer of sand of appropriate thickness (~15-22 cm), especially an aragonitic sand containing large fragments of shells and
coral deposited on top of a layer of archaeological fragments, is substantial evidence of a tsunami deposit. Considering the density of vegetation, elevation of the site, its distance from the shore (over 300 m at its closest point), and the presence of higher topography between the deposit and the coast, the deposit was probably not produced by storm waves. Therefore, it is likely that the layer of calcareous sand and marine shells is a tsunami deposit, unless its existence at Batu Kalde can be explained by significantly higher eustatic or relative sea level at the time of deposition.

Mitrovica and Milne (2002) claim that late Holocene sea level highstands of ~3 m are characteristic of equatorial oceans, and Lessa and Masselink (2006) state that sea levels had to have been at least 1 m higher 2720 YBP based on the radiocarbon age of a sedimentary layer near Broome, Australia (~1850 km southeast of Pangandaran). However, abundant research has shown that sea level has not fluctuated more than a few meters (Lambeck and Nakada, 1990) or even only centimeters (Lambeck et al., 2014) in the last 6000 years. According to Horton et al. (2005), sea level ~5600 years ago may have been 0.5-1 m lower than current sea level, reaching a maximum of 4.87 m ±0.57 above current sea level at 4850-4450 cal YBP, and sea level ~1300 years ago was comparable to today. Thus, higher eustatic sea level in the past likely cannot account for deposition of the sand layer at Batu Kalde if the layer was made 5600 years ago, and certainly not if it was deposited 1300 years ago.

Another possibility is that a relative sea level drop (i.e. uplift of the coast) could explain the high elevation of the sand layer. Andreini et al. (2016) determined a late Quaternary uplift rate of 0.17 mm/yr on the south coast of Java, based on handheld GPS measurements, real time kinematic (RTK) GPS profiles, and 5 cm/pixel digital surface modeling of a 17 m terrace from Marine Isotope Stage 5e. How the age of the terrace was determined was not stated. Measurements were done at 4 locations from West Java to East Java, including at Pangandaran.
Even in 5600 years, this uplift rate would have produced only ~1 m of uplift, and far less in 1300 years. Considering the sea level and uplift data mentioned and the elevation and topography of the site and surrounding areas, it seems highly unlikely that even a combination of sea level drop and coastal uplift over the last 5600 years or less could account for deposition of the sand at Batu Kalde by storm waves. This study concludes that the layer of calcareous sand and fossils was deposited by a large tsunami, and that this deposit is strong evidence for a mega-thrust event south of Java likely 1300 years ago or shortly thereafter, or possibly 5600 years ago. The layer of dark silty sand and soil may also be partially comprised of tsunami sediments that have been mixed with plant litter and sediment eroded from higher topography to the east. This could explain the high deposition rate mentioned previously.

The source area for the calcareous sand is unknown. Unfortunately, no samples from the beaches nearby were collected, so composition could not be determined. Although most tsunami deposits differ from nearby beach sands because the source is dominantly from offshore (Hudson, personal commun., 2016), comparison could still be important. Moore et al. (2011) found that the 2006 tsunami deposit sediments were very similar to beach sediments and determined that the tsunami deposit sediments were likely beach sediments moved landward. Beaches to the west of Cagar Alam have medium brown to gray sand with very few shells. The beach on the east side of Cagar Alam is named Pasir Putih (white sand). It is very different from any other beach near Pangandaran, and the sand there is white with small pieces of coral. Fritz et al. (2007) state that the 2006 tsunami deposited fresh coral rubble on Pasir Putih, but they do not mention coral deposits elsewhere. The calcareous sand buried at Batu Kalde and the sand and coral on Pasir Putih may be from the same source, perhaps somewhere east of Cagar Alam.
4 Goa Panggung cave

4.1 Goa Panggung Results

Goa Panggung is a cave located a short distance to the northeast of the Batu Kalde archaeological site (Figure 6). The name means "stage cave," and was given to the cave because of its shape. The lower cave entrance is located on the northeast coast of Cagar Alam and faces roughly to the east. The cave curves to the west and south while continuously widening and rising in elevation. Near the top of the cave, it abruptly narrows before opening again to an upper entrance that is the grave site of Embah Jaga Lautan, a legendary Indonesian figure who was assigned to keep the sea (Jaga Lautan means "take care of the ocean") and to safeguard the Indonesian coast (Legenda Goa Panggung, 2018; Legend Gua Panggung, 2018). Interestingly, this may be a reference to tsunami threat. A rough map of the lowest part of the cave is shown in Figure 10. Near the lower entrance is a sinkhole that is approximately 1.6-2 m deep and perhaps 4 m across. Most of the cave floor near the lower entrance is covered in semi-lithified ripple marks except for around the sinkhole. Distance between ripple marks was not measured, but ripples were perhaps 10-20 cm apart. There was no sand in the sinkhole, but it did contain several large coral boulders. The test pit is located at an elevation of approximately 3.3 m, determined by Jacob's staff method using a measuring tape, rod, and compass clinometer.

Figure 11 shows stratigraphy, grain size, and mineralogy for the pit. Vertical grain size gradation within individual layers could not be determined analytically because of the paucity of sediment samples collected. The top layer of sediment (layer A) was a brown medium sand with mud, composed mostly of plagioclase with possibly some olivine or epidote and quartz (based on field description). This top layer was not continuous, exposing the second layer at the surface in some areas (Figure 12).
The second layer (layer B) was a fine white or light brown calcareous sand that was also discontinuous and may have filled in topographic lows. The bottom contact of this layer was sharp and highly convoluted (Figure 12 right). The sample taken from the base of the calcareous layer had a medium median grain size and a very coarse mean grain size. Composition determined by XRD was various clays (42%, including chlorite), calcite (22%), sulfates (17%, including bassanite and gypsum), quartz (10%), and pyroxene (9%). Magnetic material was found in the sample using a magnet, but in such a small amount that it was not detected by XRD.

Figure 10. Illustrated map based on the author's field note sketch of Goa Panggung cave around the test pit. Scale is provided only for rough reference, as exact distances between cave walls and between the test pit and the sinkhole are unknown.
Figure 11. Stratigraphy (based on field description), locations of datable samples, ages, grain size variation, and mineralogy of samples at Goa Panggung cave (Pang16-14). A) Medium grained sand with a muddy matrix. The sand is composed mostly of plagioclase (95%), with olivine or epidote and quartz. B) Fine white calcareous sand with a little brown silty sand, visible only in some areas and may have filled in topographic lows. This layer is exposed at the surface in some areas, and both top and bottom contacts are non-horizontal (Figure 12). May represent the 2006 tsunami. C) Silt and coarse non-carbonate sand that may represent normal cave deposition. D) Uppermost of 3 possible layers of fining-upward sands. Top boundary is not easily identifiable. Datable material was found throughout the 3 layers. E) Middle of 3 possible fining-upward sand layers. F) Lowest of 3 possible fining-upward sand layers. Layers D-F may represent a tsunami deposit. G) Thick, sticky clay that was very difficult to dig through, extending down to at least 80 cm.
Below the white sand layer was a brown layer of silt and coarse sand (layer C). A sediment sample from the base of this layer was medium to coarse sand, composed of clay (41%), sulfates (34%), quartz (19%), and magnetite (6%), supported by the presence of magnetic material in the sample.

Below layer C was a series of three brown medium to coarse sand layers (layers D, E, and F in descending order, Figure 11) that each appeared in the field to have a fining-upward trend in grain size. Sediment and radiocarbon samples were taken from the base of each layer. All three layers were composed mostly of clays and sulfates, with smaller amounts of quartz and magnetite and minimal calcite, with the exception of the bottom layer, which had more calcite and less clay. Charcoal (radiocarbon sample Pang16-14I, Appendix A) from the base of the top layer (28 cm) had an age of 5040-4864 cal YBP (4425 ±24 ^14C YBP). The age of a root sheath (sample Pang16-14J) from the base of the middle layer (33 cm) was modern (post-1950 AD). A root sheath (sample Pang16-14K) found at the boundary between layer F and underlying layer G
(38 cm) also returned a modern age. There was no plant growth in the cave or signs of bioturbation in the pit. Pieces of root sheath were isolated and appeared to have been transported from elsewhere and deposited with surrounding sediments.

Below the three fining-upward layers was a layer of thick, sticky clay (layer G) that was very difficult to dig through. No grain size variation was visible. This layer extended to at least 80 cm. Charcoal (sample Pang16-14B) found at 70 cm had an age of 5556-5473 cal YBP (70.3%) or 5606-5571 cal YBP (29.7%) (4856 ±25 ¹⁴C YBP).

4.2 Goa Panggung Discussion

This study suggests two possible interpretations for the sediments in the cave (Figure 13). The first, which was the initial field interpretation, is that the white sand of layer B was deposited by the 2006 tsunami, evidenced by the significant difference in composition of this layer, by a possible fining-upward trend in grain size, and by the convoluted basal contact, possibly from rip-up of the existing cave floor by the tsunami wave. Layer A above is from normal cave deposition (i.e. storm wave deposition and deposition from material eroded from higher in the cave) that filled in topographic lows. Layer C below also likely represents normal cave deposition. A piece of white material found at 14 cm within layer C (Figure 12, right) was originally interpreted to be a rip-up clast, indicating that this layer could be another tsunami deposit. This is unlikely because no lower sediments match the material. It is more probable that this is a piece of cave chalk that was deposited along with the surrounding sediments. This situation was frequently experienced by Rubin et al. (2017). If this is not a tsunami deposit, the presence of magnetite in the sample is at first confusing. Magnetite, found in all layers from B to F, was expected as a constituent of tsunami deposits, as it had been found at the base of deposits.
from the 2006 tsunami (Moore et al., 2011; Fritz et al., 2007), but was not expected as a product of normal cave weathering and deposition. However, magnetite has been found as a constituent of cave sediments, potentially from both sedimentary and chemical origin (Pospelova et al., 2007; Šroubek et al., 2007). Magnetite is also a component of beach sands beneath the 2006 deposit in Adipala (Moore et al., 2011), so it is possible that magnetite was transported to the cave by storm waves that may periodically inundate the cave.

In this first interpretation, layers D-F are from multiple waves from the 1921 tsunami. Vertical grain size gradation could not be determined because of the paucity of sediment samples collected. As such, interpretation of layers D-F as a tsunami deposit is based on the field description of sediment grading and on the presence of modern organic material buried at 30-35 cm, with significantly older (~5000 yr) material above. Layer G is from normal deposition. The major problem with this interpretation is that the radiocarbon ages don’t support this conclusion. Modern ages for material at the base of layers E and F suggest that they were deposited after 1950 and therefore could not be a deposit from the 1921 tsunami.

The second possible interpretation for the sediments in the cave is that layers D-F are from three waves or pulses from the 2006 tsunami. This interpretation is supported by witness accounts. Witnesses in Adipala said there were two waves associated with this tsunami (Moore et al., 2011), while witnesses in Pangandaran mentioned two to three waves (Fritz et al., 2007). All layers above and below layers D-F are the result of normal cave deposition, requiring the 2006 tsunami to have first eroded away any deposit left from the 1921 tsunami. The white calcareous sand (layer B) may have been from a particularly severe storm that first scoured and ripped up areas of the cave floor, producing the sharp, convoluted basal contact of that layer. Potential storms occurred in 2002 and 2007 (Yudhicara et al., 2013; Dua Bibit Badai, 2018).
Periodic inundation and deposition of sediment by storm waves could also explain the high sedimentation rate above layers D-F.

Figure 13. Two interpretations for sediments in Goa Panggung cave. Left: initial field interpretation that there are two tsunami deposits preserved in the cave. Right: age supported interpretation that there is only one preserved deposit. In both interpretations, layers D-F are three fining-upward sand layers that may represent three wave pulses from one tsunami.
Several questions arise when considering these interpretations. The first is the question of why the modern radiocarbon samples at the base of layers E and F are beneath the much older sample at the base of layer D. It is very likely that the tsunami first scoured the existing cave floor, reworking old sediments and organic material. As deposition progressed, younger material brought to the cave by the tsunami was deposited first, and the older sample was re-deposited above.

The charcoal sample found at 70 cm in layer G may have been transported by a strong storm or tsunami, or perhaps from the higher entrance of the cave by overland flow or gravity, or by an animal. There is no grain size variation or other evidence for a tsunami deposit within layer G, suggesting that it was brought to the cave by one of these other methods.

Another concern is that the compositions of layers D-F (mostly clay minerals and sulfates) are significantly different from the composition of the 2006 tsunami deposits (primarily magnetite, olivine, and ilmenite, with minor portions of quartz, amphibole, lithics, and glass) studied at Adipala by Moore et al. (2011). If layers D-F were also deposited by the 2006 tsunami, they could be expected to have similar compositions. An explanation is that the tsunami deposited layers D-F largely by reworking and re-deposition of material already found in the cave.

The questions of sedimentation rate for and time represented by layer G depend on radiocarbon sample Pang16-14K. This sample is on the boundary between layers F and G and has a modern age. If the sample was deposited with layer G, then layer G represents roughly 5600 years of deposition. This is unlikely as it would have required extensive erosion elsewhere in the cave to unbury the 5000-year-old sample Pang16-14I that was found at the bottom of layer D, while eroding virtually nothing at the location of the test pit. If the sample was deposited with
layer F as this study interprets, then the amount of time represented by layer G is not definitely known because we do not have an age for the top of the layer. However, if radiocarbon sample Pang16-14I was eroded by the tsunami from near the current top of layer G, then layer G represents roughly 600 years. There is no evidence of a tsunami deposit in layer G, which is all thick clay. 600 years is a more reasonable time for no tsunami deposit to have been made than 5600 years. If the sample had eroded from much higher in the original sediment column, then layer G would represent an even smaller amount of time and a larger sedimentation rate.

If layer G represents 5600 years or even 600 years, then there is a large difference in sedimentation rates above and below layers D-F (above: ~20 cm in 10 years if D-F were deposited by the 2006 tsunami, or ~30 cm in as much as 66 years if D-F were deposited some unknown time after 1950; below: ~35 cm in as many as 5600 years). As mentioned previously, periodic inundation and deposition by storm waves could help explain the high sedimentation rate above D-F. However, it is also likely that a very large amount of sediment was removed by one or more tsunamis before deposition of layers A through F. Rubin et al. (2017) noted that the 2004 tsunami in Sumatra had likely eroded a significant amount of material deposited by previous tsunamis from the floor of the cave in Aceh before depositing new sediment. Erosion of existing sediments may be a significant challenge in the study of tsunami deposits preserved in caves.

5 Adipala swale

5.1 Adipala Results

The Adipala study area is located 60 km east of Pangandaran (Figure 1). Twenty-four cores were examined from several swales (Figure 14). No tsunami deposit indicators were found
in the top ~20 cm of soil because of cultivation. Interbedded sand and clay layers were found in 8 of these cores, all located in a swale 1.6 km from the ocean (Figures 15, 16, and 17). Thickness of sand layers found in the swale in Adipala ranged between 1 cm and about 20 cm, except for a very thick layer of sand that was found at the bottom of almost all cores and may represent an ancient beach. There was usually very little or no contrast in color between the sand and clay, except for a layer of yellow sand that was useful in correlation (Figure 17). Rip-up clasts were not seen in the cores. No shells were found in any samples that were collected, which matches both local beach sands and findings from others who studied the 2006 tsunami deposit ~5 km to the west of this study area (Moore et al., 2007). No apparent useful datable material was found in any of the cores.

214 subsamples were collected, with varying numbers of subsamples from each core, and 187 subsamples were analyzed in the lab for mineralogy and grain size. Figures 18-25 show stratigraphy, grain size, and mineralogy for each core. In general, grain size was slightly smaller than 0.5 mm, and rapid variation in grain size was not common. More variation was seen in mineralogy, especially in pyroxenes and feldspars, the abundances of which were often but not always inversely related. Carbonates were absent, and iron oxides (mainly magnetite) were rare. There was some variation in the abundance of clay within cores, though levels were generally less than 40% and often less than 20%. Abundance of quartz was very constant at 10%. This composition differs significantly from that determined by Moore et al. (2007) for both tsunami sediments and underlying sand 5 km to the west: mostly olivine, magnetite, and ilmenite, with small abundances of lithics. However, this study found as Moore et al. (2007) did in that lithics make up the bulk of the coarse grains, while oxides were all fine-grained. No aragonite or amorphous silica were identified, so microfossil analyses were not performed on the samples.
Specific details of sedimentology and mineralogy will be more easily discussed along with interpretations in the following section.

Figure 14. Top: topographic map of Adipala. Contour interval is 20 m. Map data ©2018 Google. Accessed through http://www.maphill.com/indonesia/detailed-maps/terrain-map/ January 2018. Bottom: map showing locations of the 24 cores retrieved from various swales in Adipala. General stratigraphy at each site is shown. Core locations shown in yellow are those at which samples were collected.
Figure 15. Top: map of core locations at which samples were collected. Bottom: topographic profile generated from Google Earth showing elevations, locations, and depths of cores. Vertical exaggeration x10.

Figure 16. Top: map of central five core locations at which samples were collected. Bottom: topographic profile generated from Google Earth showing elevations, locations, and depths of cores. No vertical exaggeration.
Figure 17. Top: photo of the swale from which sediment samples were collected. Because rice paddies were flooded, cores were pulled from the berms or next to berms to prevent sample loss in the water. Bottom: photo of a sample collected using a 1-inch split core sampler and divided into 2 cm subsamples. This sample includes the yellow layer found in cores 15, 16, 20, and 21 below a layer of clay.

5.2 Adipala Discussion

The cores from which samples were collected were all located close to each other in the swale behind the ridge closest to the coast (Figures 14 and 15). Correlations between cores 1 and 21 on the west (Figures 26 and 27) and between 10 and 9 on the east (Figure 28) were difficult because of the distance between. The five inner cores (21, 20, 16, 15, and 10) were perhaps the most interesting. They were also more easily correlated because of a distinct yellow sand layer
Consideration of elevation variation between cores is important when comparing sediment layers. An elevation profile created using Google Earth across all eight cores had a maximum variation of 10 m (Figure 15). A profile across the five central cores showed a maximum variation of 4 m (Figure 16). However, these profiles are certainly at least somewhat inaccurate as they showed features that were not existent in the field, such as an abrupt 4-meter drop and areas that were shown as lower than surrounding topography but were actually higher. The area around the five central cores was dominantly flat and likely had a maximum elevation variation of no more than ~1 m. Variation between distant cores is more difficult to tell, but there were no abrupt or significant changes in elevation within the swale. The gradual, minor changes in elevation between the cores may not be a significant issue as studies have found that tsunami deposits generally mimic landscape (Morton et al., 2007). Figures 26-28 show correlations between the eight cores.

There is evidence for two potential tsunami deposits in this area. The first is represented by the yellow sand layer found at a depth of ~90 cm (Figure 27). This sand layer is found in cores 21, 15, 16, and 20, but pinches out before reaching core 10. The yellow layer is ~18 cm thick in core 16 (Figure 23). Grain size at the base of this layer is coarser than in the layer below, and grain size slightly and gradually fines upward through the layer. The portion of heavy minerals varies throughout the layer, though there is a higher abundance at the bottom of the layer. There is also a small amount of magnetite near the bottom and about half way up in the layer. As mentioned previously, Fritz et al. (2007) and Moore et al. (2011) found that deposits from the 2006 tsunami often had thin layers of magnetite at the bottom. The magnetite midway through the layer roughly coincides with a small increase in grain size, and these factors together may indicate a second wave or pulse in a tsunami.
To the west, the yellow layer in core 21 (Figure 25) is ~9 cm thick. Grain size is very constant within the layer, but there is a high abundance of heavy minerals near the base of the layer, and a smaller peak also appears about midway through the layer, supporting the interpretation of a second tsunami pulse. Magnetite is minimal within this layer, with only a small peak in the middle of the layer. Magnetite abundance is actually higher at the top of this layer and at the bottom of the overlying layer. Layers I-K from core 21 were also sand layers. However, grain size and mineralogy analyses did not suggest that these were tsunami deposits.

In core 15 (Figure 22), the yellow layer is 20 cm thick. Grain size shows only a slight fining upward in the bottom half of the layer before rapidly coarsening and then fining substantially throughout the top half of the layer, again suggesting a possible second tsunami pulse. Heavy mineral abundances show a minor peak at the bottom of the layer and then decrease upward through the bottom half of the layer. However, they then increase gradually but significantly through the top half of the layer before dropping sharply at the top of the layer and abruptly rising again. This abundance pattern and high abundance value may reflect some unknown condition (sedimentary or hydrodynamic) on an extremely local scale because similar conditions do not show up in core 16, which is only 20 m away. The abundance pattern does not support the likelihood of a tsunami deposit, but it does not refute the possibility either, so no further interpretation was made.
Figure 18. Stratigraphy (based on field description), grain size variation, and mineralogy of samples at Cila16-1. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Light brown clay. B) Silty brown clay, darkens with depth. C) Organic brown clay with some sand. D) Dark gray brown sand that appears to be moderately well-sorted, fine grains. Good basal contact. E) Organic clay with some sand like 174-191 cm. F) Dark brown organic clay. G) Dark gray brown clayey sand. H) Dark brown/gray clay with sand, alternating sandy clay and clayey sand. I) Dark brown/gray medium sand with higher magnetic content that extends down to at least 280 cm and may represent an ancient beach. See figures for Cila16-9 or Cila16-10 for legend.
Figure 20. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-9. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Dark gray clay, with a soft contact at the bottom. B) Light brown clay. Still no sand or organics. C) Mix of brown clay above and darker brown clay with organics like below. D) Darker brown clay with organics, no sand. E) Layer of (gray?) sand. Described from bottom: coarser grains fining-upward, organic at 157-158cm and maybe clay. Then above that are coarser grains that fine upward to around 140 cm. Difficult to tell without disturbing sample. Then coarser grains above again that may fine at top. F) Brown clayey sand or sandy clay. G) Coarser cleaner sand. H) Interbedded sandy clay and very clayey sand, with very thin layers of cleaner grey sand. I) Dark gray cleaner sand, medium grained, that continues down to at least 280 cm. Still has a little clay, with higher amounts in some areas. May be a continuation of the same environment above. The sand continues to at least 282 cm. It gets cleaner and coarser gradually with depth, but there is a very thin layer of clay at ~260 cm and some other areas with a little more clay. There are also a few organics throughout the sand. Sample below 282 cm was very wet and fell out of the split core sampler.
Figure 21. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-10. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Dark gray fine clayey sand with a soft contact at the bottom. B) Brown clay. C) Brown clay with some organic pieces, interpreted as recent organics/roots. D) Sandy brown clay with organic pieces. E) Dark gray sand. Mostly all coarse to very coarse, poorly sorted. Scattered organics. F) Non-horizontal mud layer. G) Clean, coarser sand. H) Dark gray sand, like 100-175 cm, that extends down until at least 400 cm. May represent an ancient beach. Small, horizontally discontinuous sand and clay lenses at 245-300 cm.
Figure 22. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-15. Stratigraphic column unit descriptions: A) Thick dark gray clay. B) Brown clay with recent organics. C) Fine grained, well-sorted sand. Mixture of light brown and yellow brown, with dark brown below 82cm. No visible vertical grain size variation. D) Coarser, darker sand, brown to dark brown. Black under hand lens. Moderately poorly sorted. Lithics or mafic grains with little clay except between 133-135 cm. This sand extends down to at least 170 cm and probably to 230 cm, but the sample fell out below 170 cm. May represent an ancient beach.
Figure 23. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-16. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Clay with recent organic material. B) Wet medium-grained sand with a little clay. C) Brown clay with silt and/or very fine sand. D) Dark brown clay with silt and/or very fine sand. E) Transition with a mix of sediment from above and below. F) Yellow and light brown sand. Fine grained. Looks like the same sand as at Cila16-15 but finer grained and/or clay or silt included. G) Brown clay with some fine sand that may have been pulled down to this layer from above when we cleaned the core sample with the knife. H) Sand with a little clay. The sand becomes cleaner (less clay) with depth and matches the description from Cila16-15 at this depth. Sand probably continues below 96 cm but the sample fell out below this. See figures for Cila16-15 or Cila16-20 for full legend.
Figure 24. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-20. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Brown clay. B) Brown clay with sand. C) Brown clay. D) Sandy clay that looks different from what we see above and the yellow and brown clay below. E) Yellow and brown sand similar to what we have seen in other cores. F) Dark gray sand that appears to get cleaner and coarser downward. Similar to the sand that is common at the bottom of other cores. Extends below 100 cm.
Figure continued on next page
Figure 25. Stratigraphy (based on field description), grain size variation, and mineralogy of core at Cila16-21. Notes on right side of stratigraphic columns indicate interpreted correlations with other columns. Stratigraphic column unit descriptions: A) Brown clay with very little or no sand. B) Sandy brown to dark gray clay. Sand percentage increases below 25 cm. C) Medium brown clay, with very dark gray clay at 62-64 cm. D) Sandy brown clay. E) Mixture of brown and gray sand with clay, with some yellow that might match the yellow and brown sand seen in other cores. F) Dark gray sandy clay with sparse recent organics. G) Brown clay with a little sand. H) Dark gray sandy clay or very clayey sand. I) Dark gray clayey to clean sand that is coarser than the sand above. Some recent organics. J) Dark gray sandy clay. K) Clean to clayey dark gray coarse sand like that at 111-120 cm. May slightly fine upward, but difficult to tell in hand lens. L) Brownish dark gray clay. Distinct hard contact above and below. M) Poorly sorted medium to coarse dark gray sand. Very little clay. N) Layer with gravel. Fines upward and downward from center. Coarse sand, then gravel up to 8 mm diameter, then coarse sand again. O) Medium to coarse dark gray sand with little clay with recent organics. P) Dark gray clay. Q) Dark gray medium grained sand with some clay down to at least 300 cm. May represent an ancient beach. Heavy clay at 210-215 cm.
Figure 26. Fence diagram of Cila16-5 and Cila16-1, showing stratigraphy and possible correlations. See Figures 18 and 19 for more detail.
Figure 27. A) Fence diagram of Cila16-21, 20, 16, 15, and 10, showing stratigraphy, distances between cores, and interpreted correlations. Note the distances and directions to adjacent cores 1 and 5 (to the west) and core 9 (to the east). B) Exposed stretch between cores 20 and 16. The yellow layer at ~90 cm and the coarse layer at ~160 cm represent possible tsunami deposits. For greater detail, see Figures 21-25.
Figure 28. Fence diagram of Cila16-10 and Cila16-9, showing stratigraphy and possible correlations. See Figures 20 and 21 for more detail.
The yellow layer is 13 cm thick in core 20 (Figure 24). Coarsest grain size occurs near the bottom of the layer before then fining gradually upward throughout the layer. Heavy mineral abundances vary within this layer. They exhibit a general decrease upward through the layer, but the highest abundance occurs as a peak just above midway through. These grain size and heavy mineral trends are opposite those for core 15. These differences may be due to local conditions at core 15 as noted previously, or they may simply be due to variation in flow characteristics in different areas. The only evidence for a second tsunami pulse in this core is the heavy mineral peak and a small amount of magnetite half way through the layer.

The second possible tsunami deposit is the coarse layer found at a depth of ~160 cm. The strongest evidence supporting this interpretation is found in 5 cm-thick layer N from core 21 (Figure 25). From the bottom of the layer, average grain size rapidly increases from medium sand with clay to very coarse sand, with gravel grains as large as 8 mm. Grain size then gradually fines upward through the layer back to a medium sand. The tsunami deposit may continue up through layer M. There is also a thin layer of magnetite near the bottom of layer N. Heavy mineral abundance is low at the bottom of the layer. However, it then rapidly increases before decreasing upward through the layer.

The layer of coarse sand and gravel was not discovered in cores 15, 16, or 20 (Figures 22, 23, 24, and 27). Core 15 was advanced to a depth of 230 cm, but the sediment at the bottom of the core was very wet, and no sediment below 170 cm was recovered. All of the sediment 100-170 cm was dark gray sand. Core 16 was advanced beyond 100 cm, but no sediment was recovered below 96 cm. Core 20 was only advanced to a depth of 100 cm. But in core 10 (Figure 21), layer F is a 1cm-thick mud layer above layer G, which is a 1cm-thick layer of coarse sand. Both are slightly sub-horizontal and have sharp upper and lower contacts. It is possible that
layer F is a mud drape and that layer G is a tsunami deposit that potentially correlates with layer N in core 21 (Figure 25). Mud drapes are common above tsunami deposits, but storm wave periods are too short to allow their formation (Shiki et al., 2011). Layer G in core 10 may also possibly correlate with layer G in core 9 (Figure 20).

Core 5 (Figure 19) shows some interesting trends, but correlation even with core 1 is difficult. Layer F was initially of interest because it appeared in the field to be a 1 cm layer of coarse sand. However, grain size analysis actually showed that the average grain size of layer F was not significantly different from surrounding sediments except for a thin layer of finer sediments and very low heavy mineral abundance at the top of layer G. Layer F was not correlatable with any layer in core 1. Layers H, I, and J in core 5 show no significant trend in grain size but do show a decrease in the abundance of heavy minerals upward. These layers may correlate with layer D in core 1.

Core 1 (Figure 18) contained nothing of interest other than sand layer D. Grain size analysis showed a slight fining-upward of sediments, but no significant trend in mineralogy. As mentioned, unit D may correlate with units H-J in core 5. Layers H-J in core 5 and layer D in core 1 considered together show some characteristic features of tsunami deposits, and may potentially correlate with the coarse unit N in core 21. Correlation between these units and those to the east is difficult because of the large distance between (~1.4km, Figure 27).

Core 9 (Figure 20), located 802 m east of core 10, contained thicker and fewer layers and little of interest except near the bottom. Layer E may correlate with layer E of core 10, and as mentioned earlier, layer G may correlate with the sub-horizontal tsunami candidate layer G in core 10. There is nothing to suggest this, however, except that layer G in core 9 appeared in the field as a slightly coarser unit at an appropriate depth.
Why was the yellow sand layer deposited at cores 21, 15, 16, and 20, and not at the other cores? It may be due to particular characteristics of the shape of the ridge. The geometry of the yellow layer (Figure 27) and its nearness to the swale suggest that it may be comprised of traction load sediments that were deposited in a channel eroded by the tsunami as it flowed over the swale. A detailed elevation model of the ridge and swale would be useful in making further interpretations, though current conditions may be different from conditions when the deposit was made. The direction from which the tsunami wave came (i.e. from the south over the ridge or from the west into the swale from the river valley) would also need to be considered, as would the age of the ridge and the deposits in the swale. Ridges may be formed by mega-thrust events. If the swale deposits are old enough, the ridge may have not existed and the depositional environment may have been very different. Finally, it is possible that the yellow sediment is source-related and that the layer correlates with less-obvious layers that were not recognized in the other cores. Whatever the situation, there is evidence that tsunamis have inundated the study area in the past.

6 Conclusion

Based on evidence discovered at Batu Kalde, a very large tsunami inundated the southern coast of Java near Pangandaran to an elevation of at least ~5-10 m high, depositing a 15-22 cm thick layer of calcareous sand and fossils on top of a layer of cultural material remains. Ages associated with this deposit present strong evidence for a mega-thrust earthquake south of Java roughly 1300 years ago, or perhaps 5600 years ago.

This study offers two interpretations for the sediments in Goa Panggung cave. The first is that there are two tsunami deposits in the cave: the earlier deposited as three fining-upward
layers from three pulses of the 1921 tsunami, and the latter as a single deposit of white
calcareous sand from the 2006 tsunami. However, if valid, radiocarbon ages of material found in
the three layers challenge this interpretation. The second interpretation is that the three layers
were deposited by three pulses from the 2006 tsunami. All other sediments studied in the cave
are from normal deposition (i.e. storm wave deposition and deposition from material eroded
from higher in the cave). Interpretation was based on grain size variation, stratigraphy, and
radiocarbon sample ages. Likely erosion of pre-existing cave floor by one or more tsunamis
made interpretation of cave floor sediments difficult, and such erosion could be a significant
challenge when studying tsunami deposits in caves elsewhere. Either interpretation supports the
conclusion that large tsunamis have inundated the southern coast of Java.

Two potential tsunami deposits were identified in Adipala in the swale behind the ridge
closest to the ocean. Identification was based on analytically-determined grain size variation,
continuity of a key yellow sand layer, and trends in mineralogy. However, the ages of the
candidate deposits are not known, nor is the age of the ridge, so the original depositional
environment for the deposits is not certainly known. Nevertheless, findings in Adipala support
the conclusion reached for the other two areas.
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USU OSL Laboratory - Need analyses?: http://www.usu.edu/geo/luminlab/submit.html (accessed April 2016)


Appendix A: Radiocarbon Data

Table 3. Data from radiocarbon analysis, along with calibrated ages and depth in test pit. Ages were determined by the Center for Applied Isotope Studies at the University of Georgia, and were then calibrated using the online version of Calib 7.10 at www.calib.org/calib/ (Stuiver et al., 2017). Ages were calibrated (cal YBP) to a 2σ (95% probability) error range, where zero age is AD 1950. For further information, see text.

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