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Penultimate predecessors of the 2004 Indian Ocean tsunami in Aceh, Sumatra: Stratigraphic, archeological, and historical evidence

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Abstract We present stratigraphic, archeological and historical evidence for two closely timed predecessors of the giant 2004 tsunami on the northern coast of Aceh, northern Sumatra. This is the first direct evidence that a tsunami played a role in a fifteenth century cultural hiatus along the northern Sumatran portion of the maritime silk route. One seacliff exposure on the eastern side of the Lambaro headlands reveals two beds of tsunamigenic coral rubble within a small alluvial fan. Radiocarbon and Uranium-Thorium disequilibrium dates indicate emplacement of the coral rubble after 1344 ± 3 C.E. Another seacliff exposure, on the western side of the peninsula, contains evidence of nearly continuous settlement from ~1240 C.E. to soon after 1366 ± 3 C.E., terminated by tsunami destruction. At both sites, the tsunamis are likely coincident with sudden uplift of coral reefs above the Sunda megathrust 1394 ± 2 C.E., evidence for which has been published previously. The tsunami (or tsunami pair) appears to have destroyed a vibrant port community and led to the temporary recentering of marine trade dominance to more protected locations farther east. The reestablishment of vibrant communities along the devastated coast by about 1500 CE set the stage for the 2004 disaster.

1. Introduction

One reason that recent giant earthquakes and tsunamis have been extremely devastating is that their predecessors occurred in the very distant past. Such events had thus been considered extremely unlikely, if they had been considered at all. Events that occur every few hundred to thousands of years seldom capture the attention of those faced with much more immediate social, political, and economic matters.

In the case of the 2004 M_w9.2 Aceh-Andaman earthquake and attendant tsunami, records of predecessors existed neither in the cultural memory or written records of communities along the coasts of the Indian Ocean nor in the scientific literature. Thus, the devastating waves came without warning to coasts that had developed without any hint of the potential for disaster on such a grand scale.

Investigations after the disaster showed that the tsunami resulted from sudden rupture of a 1500 km section of the Sunda megathrust [*Chlieh et al.*, 2007; *Meltzner et al.*, 2006]. Slip on the giant undersea fault raised the seafloor and sea surface as much as 6 m, which then led to the propagation of tsunami waves across the Indian Ocean (Figure 1).

Soon after the disaster, geologists began to search for evidence of prior tsunamis in coastal sediments. Two teams independently discovered sand sheets on the western coasts of Thailand and northern Sumatra, beneath those deposited by the 2004 tsunami [*Jankaew et al.*, 2008; *Monecke et al.*, 2008]. Radiocarbon dates from material just below these sand sheets constrained the date of occurrence of this penultimate tsunami in Thailand to between about 1300 and 1450 C.E. and in Sumatra to soon after a date in the range 1300 to 1460 C.E. Others found evidence for tsunamis along the Sumatran coast thousands of years in the past [*Grand Pre et al.*, 2012].
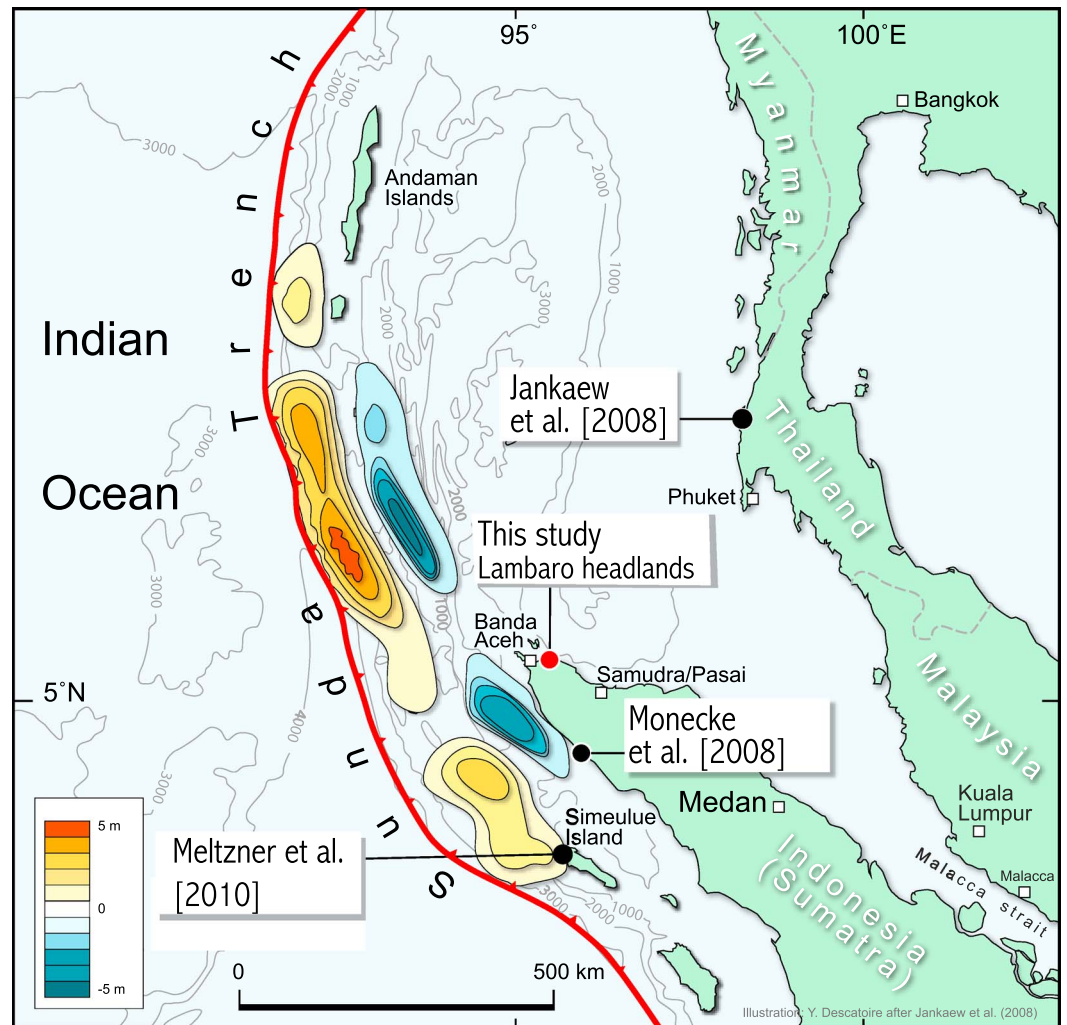
Figure 1. Uplift and subsidence of the seafloor during the great earthquake of 2004 led to tsunami inundation along the coast of the Andaman Sea and northern Sumatra. Black dots indicate three sites that record prehistoric uplift [*Meltzner et al.*, 2010] and tsunamis [*Monecke et al.*, 2008; *Jankaew et al.*, 2008] In this study, we document new evidence of ancient tsunami inundation. Coseismic uplift and subsidence contours courtesy of M. Chlieh, based on Model G9.15 of *Chlieh et al.* [2007]. Figure adapted from *Jankaew et al.* [2008]. Bathymetry is drawn at 1 km intervals.

Geologists also found evidence for the *source* of the penultimate paleotsunami—two sudden uplifts of coral reefs on Simeulue island, above the southern tip of the 2004 rupture, a hundred or so kilometers off the coast of northern Sumatra [*Meltzner et al.*, 2010]. Together the uplifts totaled about twice the uplift produced there in 2004. Uranium-Thorium (U-Th) disequilibrium dating of the dead coral reefs revealed that both uplifts occurred within the ranges indicated by the radiocarbon-dated tsunami-sand layers—the first within 2 years of 1394 C.E. and the other within 3 years of 1450 C.E. Which of these two uplifts produced the tsunami documented from the sand sheets was unclear.

In the six centuries between these ancient events and 2004, at the current rate of plate convergence, about 20 m of potential slip on the Sunda megathrust would have accumulated at the latitude of northern Sumatra. Large parts of the megathrust in the vicinity of Aceh province experienced far less slip than this in 2004, however [*Chlieh et al.*, 2007]. The close timing of the penultimate megathrust ruptures, in about 1394 and 1450 C.E., and the failure of the 2004 rupture to relieve much of the strain accumulated through previous centuries raise the specter that a partial rerupture of the Aceh section of the Sunda megathrust could produce yet another large Indian Ocean earthquake and tsunami within this century.
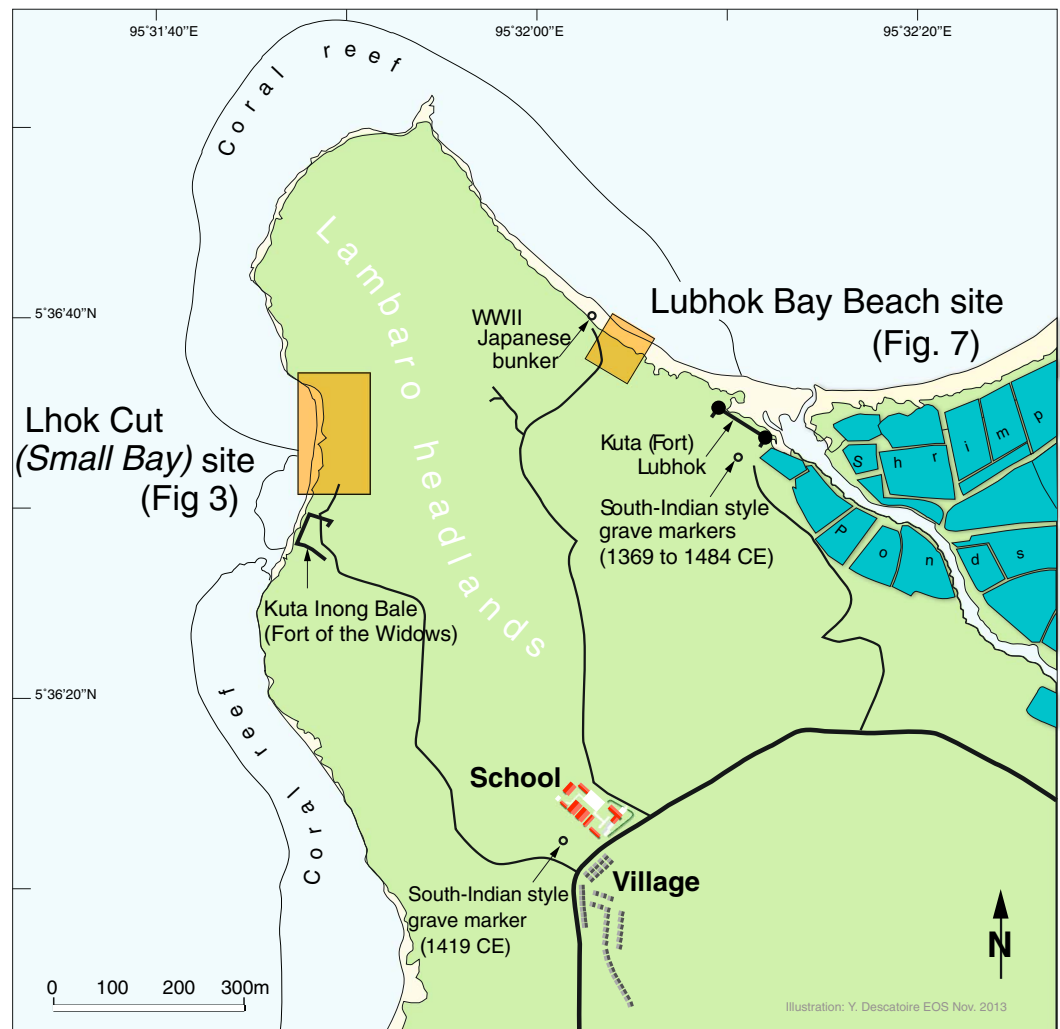
Figure 2. Map of the Lhok Cut and Lubhok Bay Beach paleotsunami sites on the Lambaro headlands. Fifteenth century grave markers, the remains of sixteenth century defensive structures and a WWII Japanese bunker attest to many centuries of occupation. Along at least portions of this coast, tsunami flow depths in 2004 were several meters. The village shown was moved to the location shown following destruction in 2004 at its coastal location on the west side of the headlands.

Here, we document geological and archeological evidence for ancient tsunamis in small seacliffs on the Lambaro headlands about 40 km east of Banda Aceh, the capital of Aceh province (Figures 1 and 2). Precise U-Th dating of coral rubble deposited by the tsunamis, foraminiferal assemblages that confirm a marine source for the deposits, and archeological and geologic evidence for destruction constitute strong evidence for the occurrence of two tsunamis more than 550 years before 2004. At Lhok Cut ("Small Bay"), we found twelfth to fourteenth century archeological deposits capped by a probable tsunami layer of terrestrial and marine sediment, mixed with material culture. At Lubhok Bay Beach, we found two tsunami deposits within a small alluvial fan. The tsunami layers post-date the mid fourteenth century, consistent with *Meltzner et al.*'s [2010] precise dates of raised coral reefs far to the west.

2. Lhok Cut

On the west coast of the Lambaro headlands is a small alluviated valley nestled between low hills and truncated at a low seacliff (Figure 3). Based upon an analysis of historical records, and reinforced by extensive surface finds of South Asian, Chinese, and local archaeological material, *Edwards McKinnon* [1988] posited

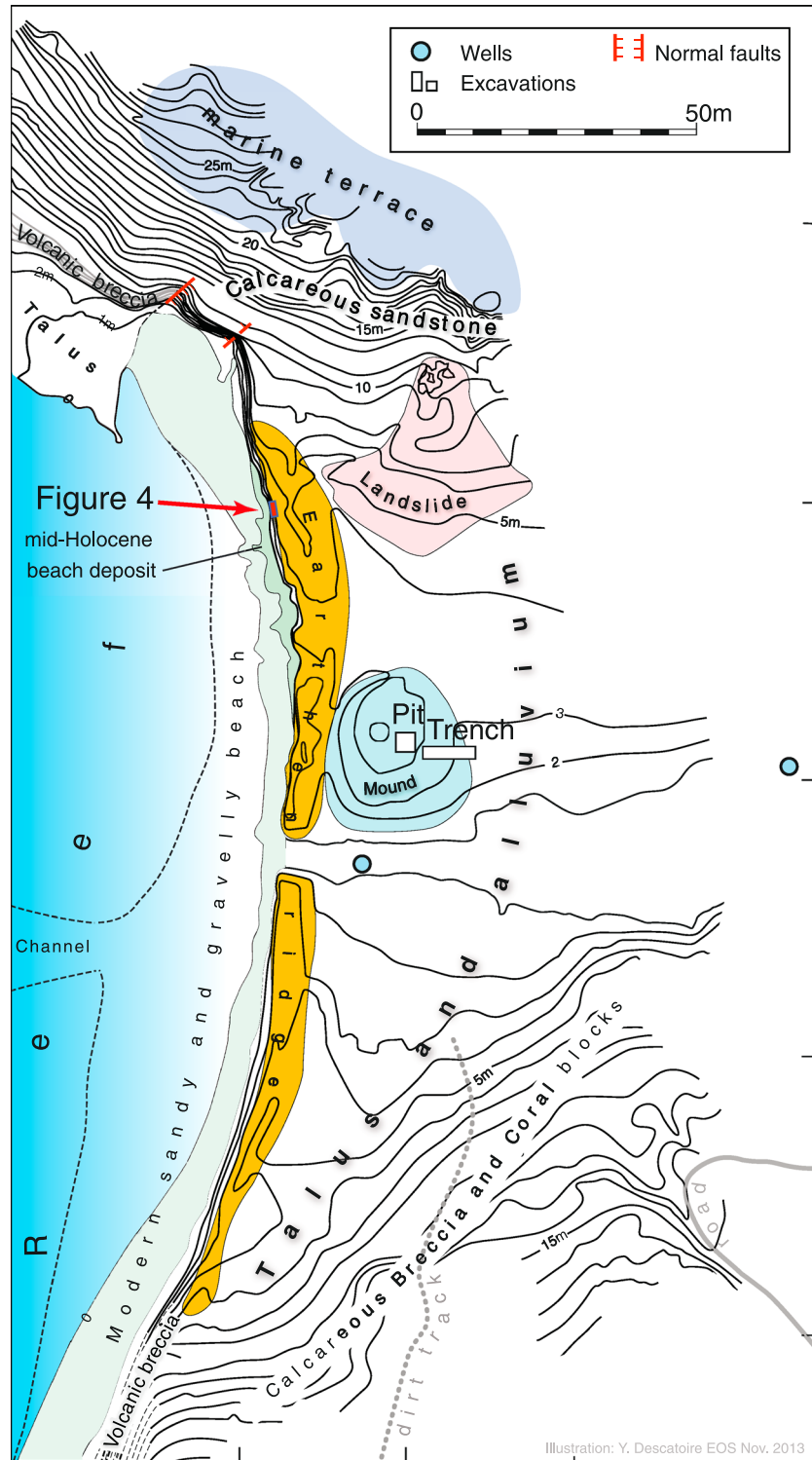**Figure 3.** Geologic and topographic map of the Lhok Cut seacliff exposure along the coast of a small alluviated valley. Lime-plaster floors in the seacliff exposure and beneath a manmade mound indicate occupation of the valley between about 1240 and 1366 ± 3 C.E. The earthen ridge and mound built on top of the floors may be part of defensive works built in the mid sixteenth century [*Edwards McKinnon*, 2009].

that the headlands are the location of the historic trading port of Lamreh, which has been verified by historical records as a nexus of Indian Ocean and East Asian trade [*Edwards McKinnon*, 2006; *Tibbetts*, 1971].

Faulted, gently to moderately dipping, indurate volcanic breccias are well exposed in the seacliffs that flank the valley. Lying atop them are gently dipping calcareous sands and massive limestone breccias that contain rounded rare volcanic clasts and occasional strongly recrystallized coral heads. Immediately north and south of the valley, these beds underlie gentle surfaces about 20 m above sea level. We speculate that these surfaces represent the seafloor during Marine Oxygen Isotope Stage 5e, about 125,000 years ago. A rate of merely about 0.1 mm/yr, which is very plausible so close to the strike-slip Sumatran fault, would be required to lift a bed of this age to its current elevation.

Buttressed into this bedrock across the mouth of the valley and near the modern high-tide mark is an indurated pebbly, cobbly calcareous sandstone layer (Figure 3). The majority of clasts are rounded volcanic rocks from the underlying volcanic breccias, but rounded coral fragments are also present. The overlying deposits in the seacliff are not indurated and are highly erodible, so this gently south-dipping beach deposit forms a resistant marine platform along the northern part of the bay.

The seacliff rises 2–4 m above the hard beach platform and consists primarily of three unconsolidated deposits, each of which range up to about a meter in thickness. The lowest of these is a loose, well-sorted deposit that in most places consists of a pebbly, cobbly shingle of well-rounded volcanic and coral clasts. Atop this is a bed that is locally faintly bedded. It consists principally of a massive pebbly, cobbly loam that contains an abundance of cultural material. Locally, traces of thin sandy beds are preserved within it. The upper part of the seacliff exposure is a cobbly, bouldery loam, which forms an earthen ridge atop the seacliff. The uneroded landward side of this feature rises a half meter to a meter above the alluvial surface of the valley.

We found no eyewitnesses to the 2004 tsunami at Lhok Cut. Nor did we see extensive deposits of the tsunami landward of the earthen ridge on the modern surface of the alluvial plain there. This is not unexpected, though, given the tenuous nature of thin 2004 deposits elsewhere around the Indian Ocean [*Szczucinski*, 2012; *Nichol and Kench*, 2008]. A comparison of the appearance of the site before and after the tsunami implies, however, that the tsunami did have a substantial effect seaward of the seacliff and earthen ridge. In 1995, during our first visit to the site (by EEM), the indurated rocky shelf above the intertidal zone was covered with soil and grasses to a depth of about 1 m. Two Islamic tombstones of the *plang pleng* type were also lying on the beach close to the breach in the earthen ridge (Figure 3). One of these tombstones was removed in 1995 and taken to the Museum Negeri Aceh in Banda Aceh. During our visits after the tsunami, the remaining tombstone and the soil and grass were nowhere to be seen. We assume that they were stripped away by the force of the tsunami. The destruction of a coastal village a km or so south of Lhok Cut is another indication of the force of the 2004 tsunami (see caption, Figure 2).

2.1. The Pit and Lime-Plaster Bed

Cut into the indurate beach platform and the younger deposits at one location is a nested set of pits filled with loamy debris that includes much archeological material (Figure 4). The material in the oldest pit is almost entirely a homogenous dark brown sand, probably derived from the loose well-sorted sand that the pit penetrates. It contains unabraided cultural material, including an almost complete earthenware vessel and animal bones. A younger pit that overlies the first pit contains three distinct fills. The lowest is a dark-brown silty sand, with less than 10% coral pebbles. A next consists of small (~0.5 m) boulders in a poorly sorted matrix of dark brown silty sand and coral pebbles. The uppermost part consists of numerous coral pebble clasts in an unsorted brown silty sandy matrix. All three of these deposits contain large amounts of material culture, including both earthenware and stoneware ceramics and animal bones. In all, over 570 ceramic fragments were collected from these three nested deposits, the majority of them unabraided South Asian styles of earthenware. Stoneware fragments of Chinese (Yuan) origin, as well as a single Chinese coin minted between 1111 and 1118 C.E., accompany these materials. Animal bone and one tooth from the deposits yielded ^{14}C dates ranging from 1200 to 1280 in the lowest pit to 1220 to 1390 in the uppermost layer (Figure 4).

A thick, poorly sorted deposit of pebbly brown loamy sand covers the pits and well-sorted sand and extends north and south in the seacliff. This is the middle of the three deposits that extend along most of the width of
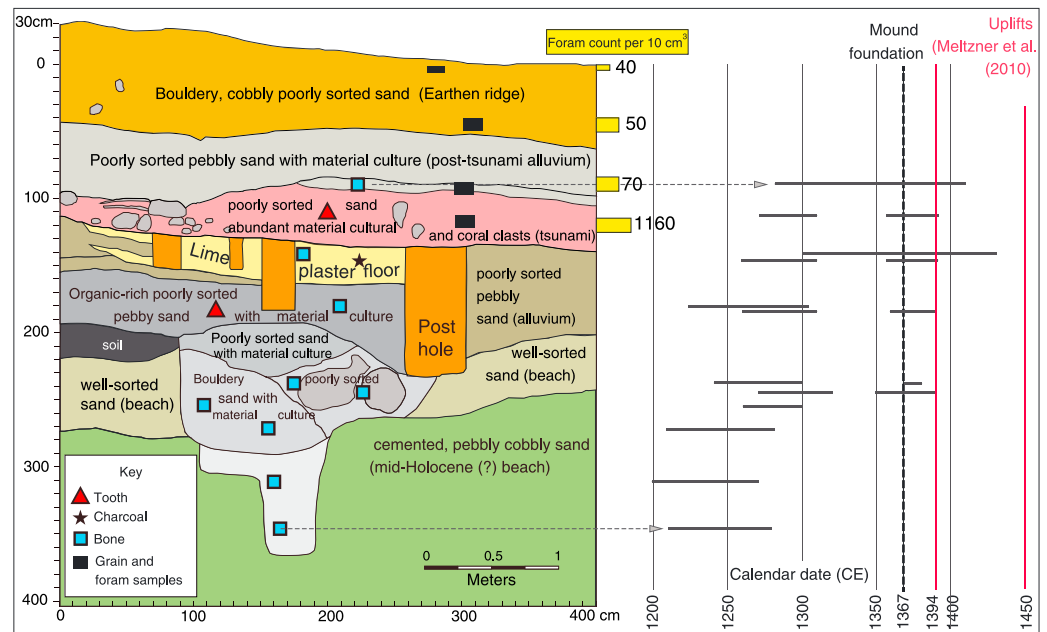
Figure 4. Map and chronology of cultural layers and natural deposits in the Lhok Cut seacliff at location shown on Figure 3. A fourteenth century lime plaster floor (yellow) covers a thirteenth to fourteenth century rubbish pit (gray). A layer rich in foram tests and coral (LC4, pink) overlies the floor. The uppermost layer (LC2) is a man-made earthen ridge built parallel to the seacliff. Interpretations of the units are in parentheses. Samples (blue squares, red triangle, and black star) correspond to ages (black horizontal lines) at corresponding levels on right. Details of exposure, grain-size, foraminifera, and radiocarbon analyses appear in the supporting information, sections 1, 2, 3, and 5.1, respectively.

the valley floor. As noted above, this deposit is also rich in material culture, including ceramics and animal bones. Tooth and bone samples from this deposit yielded age ranges of 1260 to 1310 or 1360 to 1390 and 1220 to 1300 C.E., indistinguishable in age from material in the lower pit fills.

These deposits are partially overlain by a distinctive, compact pebbly layer of lime plaster perforated vertically by round holes (Figure S1.1 in the supporting information). A radiocarbon date from a bone indicates deposition sometime after a date in the range 1300 to 1435 C.E.

2.2. The Coral- and Foram-Rich Layer

Directly atop the lime-plaster layer and extending beyond it through the entire mapped exposure is a 0.3–0.7 m thick, very poorly sorted clay loam that contains abundant coral pebbles and angular coral cobbles, foraminfera and shells (LC4; details in Figures S1.2, S2.1, and S3.1, and Tables S2.1 and S3.1 in the supporting information). Similar types of coral (including *Porites sp*) currently live on the reef directly offshore of the seacliff.

Also within the layer are potsherds and bone fragments from the occupation site like those in the underlying pits. Small limey clasts within the coral- and foram-rich layer consist of material that is similar to the composition of the lime-plaster bed, which appears to be eroded locally. A tooth from the coral- and foram-rich layer yielded radiocarbon date ranges of 1270 to 1310 and 1360 to 1390 C.E.

Our analysis of foraminifera tests within LC4 (supporting information, section 3) reveals that their concentration is relatively high (116 tests/cm^3), and that nearly half (44%) of them are unabraded and unweathered (Figure 4). Most of the foram species currently live in water depths of less than 10 m [*Debenay*, 2013], but 14% of the sample analyzed live in Indonesian waters at depths greater than 20 m [*Cleary and Renema*, 2007].

2.3. Uppermost Layers

Following the deposition of the coral- and foram-rich layer, a predominantly massive, very poorly sorted silty layer covered the site (LC3). Pebbly clasts include sparse, highly abraded ceramics, broken shells, subangular to angular corals and volcanics. Foraminiferal tests are very rare within this unit, and where

present, they are predominantly abraded and corroded. Within the otherwise massive unit are sparse, thin discontinuous pebbly beds.

The uppermost unit in the exposure is a very poorly sorted, massive, pebbly, cobbly silt (LC2). This 0.5–0.8 m thick unit constitutes an earthen ridge that follows the top of the seacliff and is clearly visible in the topography (Figure 3). *Edwards McKinnon* [2009] posits that this is a defensive structure associated with nearby Kuta Inong Bale, which historical evidence suggests was built in the late sixteenth century (see supporting information, section 5 introduction, section on Kuta (Fort) Lubhok, and Table S5.3 for details). Capping this sequence is a thin silty soil (LC 1).

2.4. Earthwork Mound

Centered about 20 m landward from the seacliff is a 20 m wide mound of earth that rises about 1.5 m above the level of the alluvial plain and to the same level as the top of the earthen ridge at the seacliff (Figure 3; supporting information, section 1.1). Two excavations into the mound revealed a 0.2–0.4 m thick, void-rich cobbly and bouldery bed (EM6), which rests at about the elevation of the surrounding alluvial fan surface. The cobbles are predominantly rounded volcanic clasts but include corals as well. Upon this bed lies a 0.15–0.25 m thick lime-plaster layer (EM5). This limey layer differs slightly from the one exposed in the seacliff—it consists of a stark-white lime plaster, nearly free of pebbly debris (Figure S1.3). We found no indications of round holes in the surface, but this could be the result of our exposing only two small portions of the floor.

The limey bed is buried by about 1.1 m of loose, rubbly debris, which form the bulk of the mound. At one location (Figure S1.3B), a small boulder of *Porites sp* coral was imbedded within the debris and rested directly upon the limey layer. The bulk of the earthwork was constructed after creation of the lime-plaster bed, since it consists of a round mound of debris atop the limey layer that rises well above the surface of the alluvial fan.

One coral cobble in the framework-supported bed beneath the mound's lime-plaster layer exhibited no evidence of erosion or weathering (Figure S1.4). Even the submillimeter pali and costae of individual corallites were pristine, which implies that the coral was taken alive from the reef just before creation of the bed in which it was found. This large-corallite head yielded an exceptionally precise U-Th date—1366 ± 3.2 C.E. (details in Table S5.4). This very precise date falls within the broader range of the radiocarbon dates from the deposits beneath the lime-plaster floor in the seacliff. The similarity of the two lime-plaster beds implies that they are contemporaneous.

Cultural material in the mound deposits is consistent with construction of the mound after the fourteenth century. These comprise mixtures of earthenware and stoneware ceramics and animal bone fragments. Age-diagnostic sherds range in age from the twelfth to fourteenth century and, like the beach section, include material of South Asian, Chinese, and perhaps local origin.

3. Lubhok Bay Beach

On the other side of the Lambaro headlands is another small alluvial fan that contains evidence of marine inundation (Figure 2). As at Lhok Cut, the sediments that have formed the alluvial fan consist predominantly of debris from volcanic breccia and calcareous beds, washed down from the surrounding hills. Unlike the Lhok Cut site, however, cultural material is very sparse and not diagnostic. The small alluvial fan slopes seaward between two steep bedrock hillslopes (Figure 5). An abandoned track cuts into the hillslope on the west. Alluvial debris and talus from the track cut cover the northernmost part of the alluvial fan and a WWII Japanese bunker (Figure S1.5). Exposed in a low seacliff cut across the alluvial fan are older alluvial deposits intercalated with two deposits of angular coral rubble (Figure 6).

The oldest exposed bed (Unit 7) is a well-sorted medium to coarse sand that contains abundant small fragments of marine shells and lies at about the elevation of the top of the modern beach. A charcoal fragment near the top of this bed (LMR10-7a) yielded a radiocarbon date range of 890 to 1030 CE (Table S5.2).

Overlying this sand is a predominantly massive, pebbly silt (LB6). The pebbles are calcareous clasts like bedrock in the surrounding hills. Rare lenses of sandy, small-pebbly beds exist within the otherwise massive unit. Radiocarbon analysis on fragments of charcoal yielded ranges from 980 to 1280 C.E. near the base to 1310 to 1440 C.E. at the top.
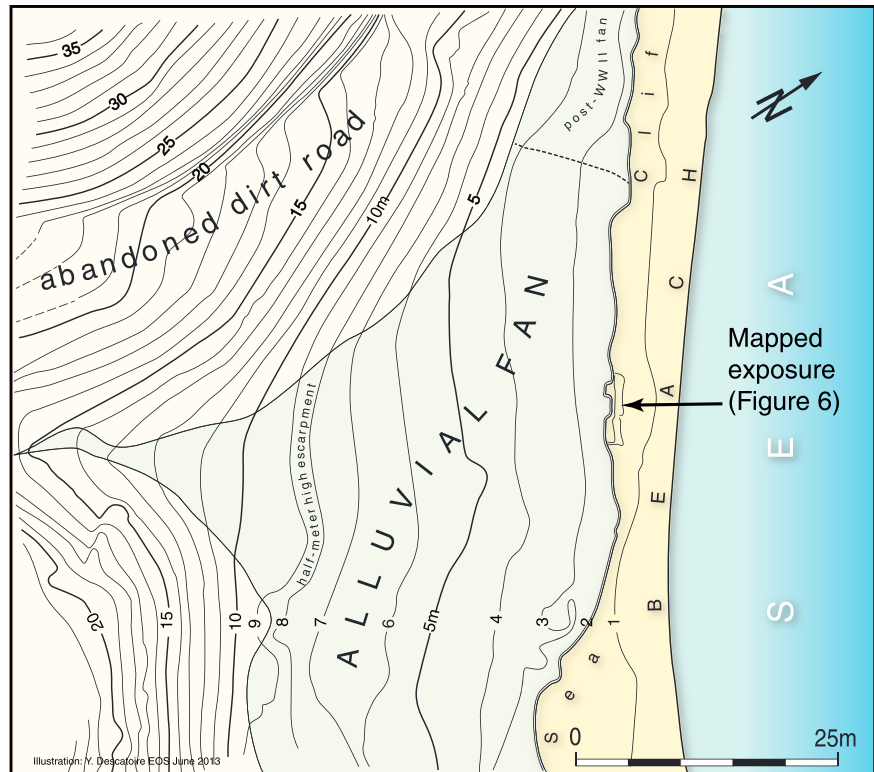
Figure 5. Topographic and geologic map of the Lubhok Bay Beach Site. The modern beach buttresses the alluvial fan at a small seacliff, in which appear older beach, tsunami and alluvial deposits.

Cut into this bed is a 6 m wide, 0.5 m deep channel. A 0.1 m thick sandy black organic deposit with relatively high organic matter (LB5b) covers the base of this broad, shallow swale (supporting information section 4.2). Bulk samples of the black organic sediment yielded a radiocarbon date range of 1030 to 1170 C.E., significantly older than the dates from charcoal in the underlying alluvium. This is the only date that is out of stratigraphic order, so we believe the carbon derives from sources older than the soil (Figure 7).

Three sharp- and steep-sided small channels cut into the swale's peaty basal layer. These channels extend upstream under the alluvial fan, nearly perpendicular to the seacliff exposure.

Filling these small channels is a heterogeneous deposit of pebbly *Porites sp* coral rubble (LB5a). In many places, this coral rubble lacks matrix and is framework supported. Elsewhere, the coral fragments sit in a matrix that is nearly equal parts clay, silt, and sand. In places along the base of the deposit, especially where it lies atop the basal peat, a light-colored calcareous matrix has infused the rubble. X-ray diffraction
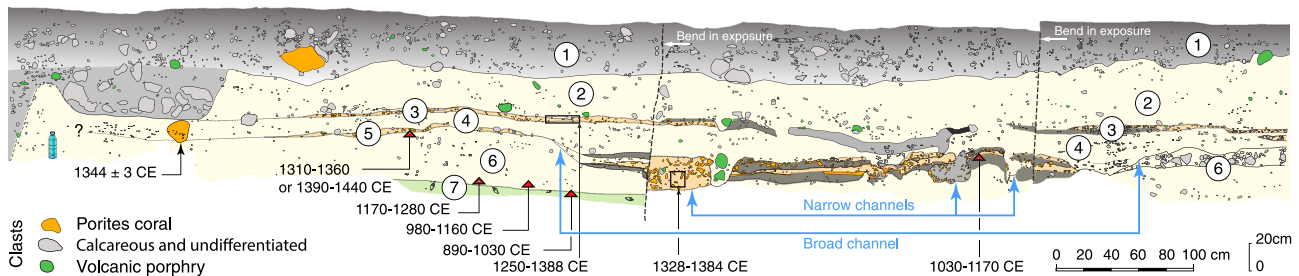

Figure 6. Highly simplified drawing of the seacliff exposure at Lubhok Bay Beach (Figure 2). A beach sand at the base of the exposure (LB7) is overlain by an alluvial bed (LB6) that is, in turn, cut by a broad channel. The channel is filled by a sequence of peaty organic material (black), coral rubble (orange, LB5), and another alluvial deposit (LB4). The upper half of the exposure consists of two massive alluvial fan beds (LB1 and LB2). Pebbles, cobbles, and boulders are drawn to scale. Figure S1.6 is a larger, much more detailed version of this figure.
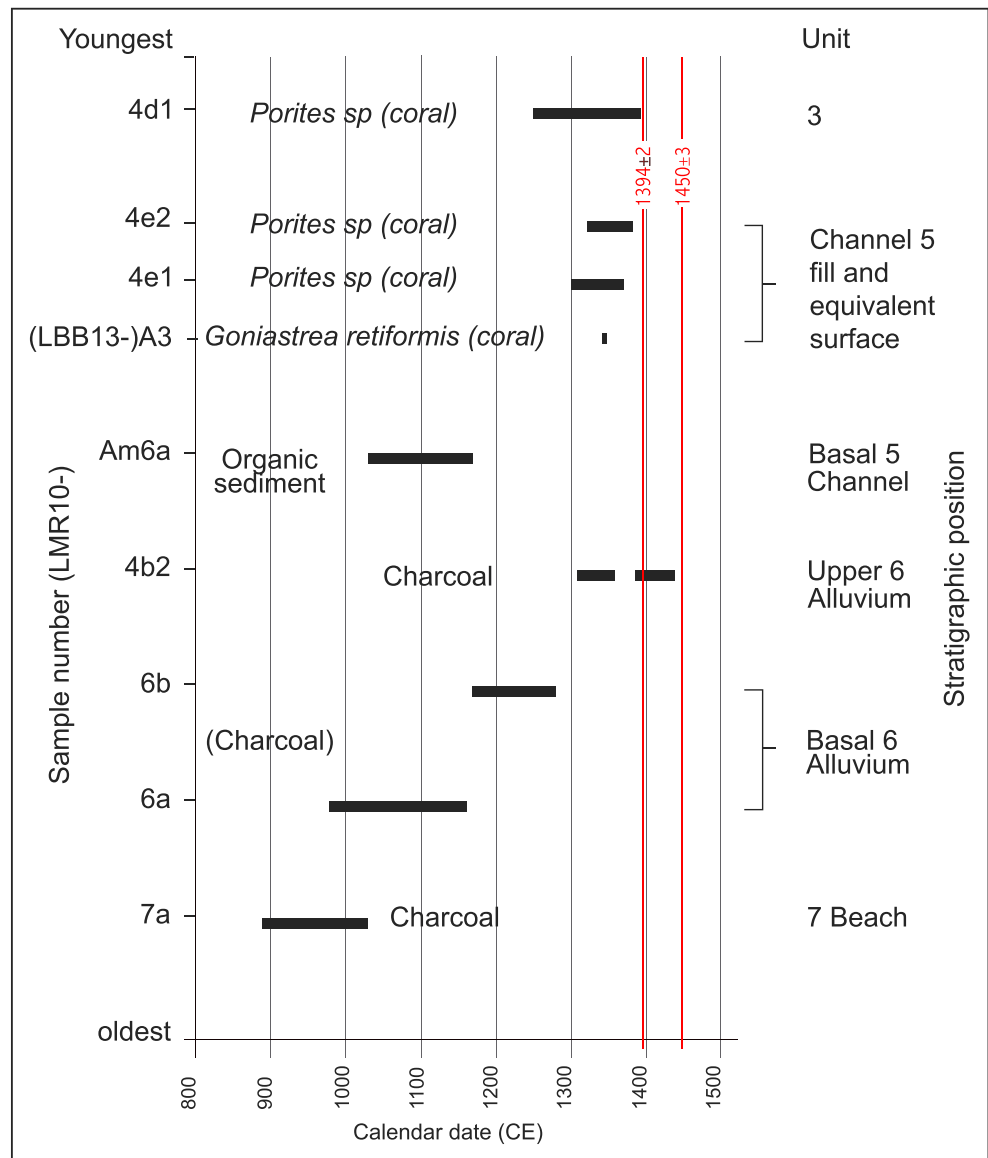
Figure 7. Radiometric ages from Lubhok Bay Beach site as a function of stratigraphic position. The oldest deposit yielded a tenth century radiocarbon date. Both coral-rubble deposits yielded fourteenth century U-Th dates. See Table S5.2 for details of the radiocarbon analyses. Red lines show dates of uplift on Simeulue island [*Meltzner et al.*, 2010]. Details in Tables S5.2, S5.5, and S5.6.

analysis of this pale matrix indicates that it comprises about 95% calcite carbonate and a small amount of sodium chloride.

The sharpness of the broken edges of the coral pebbles shows that the clasts were not abraded or weathered between the time they were created and the time they came to rest in the deposit (Figure 8). Many of the coral fragments display one face that was the living outer perimeter of the coral head from which it was broken. None of these surfaces show even the slightest indication of abrasion or weathering. Even the sub-millimeter-sized architectural details of individual corallites remain.

Charcoal just below the layer of coral rubble yielded date ranges of 1310 to 1360 and 1390 to 1440 C.E. (Figures 6 and 7, sample 4b2). In an attempt to narrow the range of uncertainty in the age of the rubble deposit, we performed five U-Th analyses on each of two samples of pristine coral clasts. These yielded isochron ages of 1334 ± 37 and 1356 ± 28 C.E., more precise than the radiocarbon age but still with large uncertainties (samples LMR10-B-4e1 and 4e2, Table S5.6).
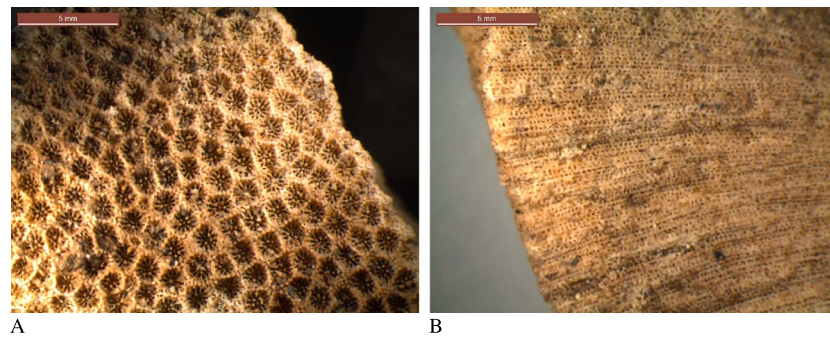
A   B

Figure 8. Photomicrographs of (a) perimeter and (b) broken side of a coral fragment in the channel fill. The unabraded and unweathered surfaces strongly imply that the corals were shattered and deposited while still alive. Their U-Th age should therefore date the tsunami that emplaced them.

An intact *Goniastrea sp.* coral head from near the left side of the cut at the level of the bed of *Porites* rubble yielded a far more precise date of 1344 ± 3 C.E. (Figure 6 and Table S6.1). Unlike the Porites rubble in the same layer, the outer perimeter of this head shows clear signs of weathering or abrasion, in that the submillimeter pali and costae have been removed.

Atop the coral rubble bed is LB4, which filled the parts of the channel not already filled by the coral rubble. Similar to LB6, this deposit is a pebbly, sandy silt (Table S2.2). The pebbles are clasts like the bedrock in the surrounding hillslopes, except in the lowest parts of the bed and very locally elsewhere, where coral clasts are mixed in. For the most part, the unit is massive. There is a shallow swale in the upper part of the alluvial deposit and an organic darkening of the bed below the swale.

Immediately overlying the alluvium is a thin, discontinuous bed of pebbly coral rubble (LB3). The unit is so thin that in most places the matrix of overlying and underlying beds has been mixed in with it. The coral fragments are angular and unabraded, at first glance identical to those in the lower coral-rubble deposit. However, in contrast to those in the lower coral-rubble deposit, these coral fragments are stained a medium brown color and appear under the binocular microscope to have a surficial glaze (Figure 9). In fact, no coating is visible in thin section under a polarizing microscope. The apparent glaze is a manifestation of smoothing caused by slight dissolution of the surfaces of the clasts during weathering.

Five U-Th analyses from one clast (sample LMR-10-B-4d) yielded a weighted-average age of 1319 ± 69 C.E. (Table S5.6), which is indistinguishable from the ages for two clasts from the underlying coral rubble. The five samples failed to produce an isochron, so we used the initial ^{230}Th/^{232}Th ratio determined from the analyses of the other two samples in calculating this age.

The uppermost meter of the seacliff exposure consists of two distinct beds. The lower bed is very much like LB4, whereas the upper bed is far richer in cobbles and small boulders. Both are about 0.5 m thick.
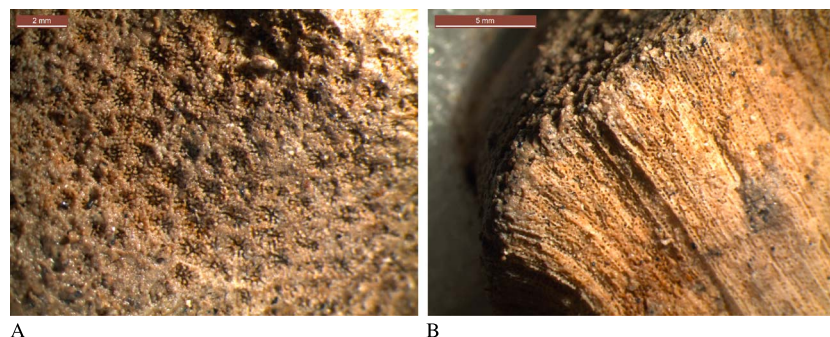

A   B

Figure 9. Photomicrographs of the (a) weathered growth surface and (b) broken side of a representative angular coral fragment in the second rubble layer. Unlike coral clasts in the lower coral-rubble Unit 5 (Figure 8), these fragments show evidence of slight dissolution of their surfaces during exposure to weathering.

The lower of the two beds (LB2) is a massive pebbly, sandy silt (Figure S2.2 and Table S2.2). Its lowest ~0.1 m consists of subangular to subrounded pebbles and cobbles of volcanic and calcareous bedrock. Near the northern edge of the seacliff is a concentration of large cobbles and small boulders within a cut into the alluvium. The uppermost deposit in the seacliff (LB1) is a dark sandy, silty, clayey bed with a high concentration (~25%) of volcanic and calcareous pebbles, cobbles, and small boulders.

4. Discussion

We turn now to interpretations of our observations at both Lhok Cut and Lubhok Bay.

4.1. Seacliff Deposits at Lhok Cut

The sandstone conglomerate that is buttressed into the bedrock across the mouth of the valley and near the modern high-tide mark represents a former beach (Figure 3). The presence of coral fragments and the highly rounded character of the clasts indicates deposition in a high-energy beach environment, not unlike that of the present beach. The induration and elevations of the deposit suggest it is mid-Holocene in age and tectonically tilted southward.

The unconsolidated nature of overlying deposits exposed in the seacliff implies that they are considerably younger (Figure 4). The well-sorted nature of the lowest of the three deposits and the predominance of well-rounded coral and volcanic cobbles and pebbles indicate that it is a beach deposit. The heterogeneous, poorly sorted nature of the second deposit, its abundant scattered material culture, and the locally preserved wisps of sandy laminae indicate that it formed by slow accumulation of alluvium during a time of human occupation. The fact that material culture is abundant in this bed across the entire valley exposed in the seacliff indicates that a community extended across the valley floor during deposition. The massive, heterogeneous character of the third and uppermost of the beds and the fact that it constitutes the geomorphologically obvious ridge across the entire width of the valley floor indicates that it is a man-made earthen embankment.

The regular shape of the pits cut into the lower of these beds, the penetration of the lowest one into the hard, cemented conglomerate, and the abundance of artifacts indicate that they are cultural features. The domestic nature of the material culture assemblage in both the pits and the overlying bed—including fragments of cooking, serving and storage vessels, as well as possible food debris—suggests these deposits were part of a midden spread that is evidence for a settlement on the small alluvial plain. The large size and good surface condition of most of the ceramic sherds, and only minor attrition of material in both the pits and the overlying bed, imply deposition soon after breakage. Thus, we conclude that the hollows are rubbish pits. Radiocarbon date ranges of 1200 to 1280 C.E. in the lowest pit and 1220 to 1390 C.E. in the uppermost part of the pit indicate at least a couple decades but no more than a couple centuries of infilling.

The limey deposit that overlies the rubbish pits and midden spread appears to have been the floor or foundation of a timber-frame structure. The round holes that penetrate it vertically are likely holes dug through the floor to support vertical wooden beams of a small structure. As expected in a warm, moist tropical environment, none of these wooden members have survived the centuries [*Weedon et al.*, 2009]. The varied abundance of material culture in the seacliff exposure and the clear extension of archaeological remains inland suggest a coastal site that consisted of robust timber structures, with a mix of local, Indian, and Chinese trade ceramics and other material culture that implies both domestic and commercial purposes.

The coral- and foraminifera-rich layer that overlies the limey bed (Figure 4) contains a mixture of both marine debris and terrestrial cultural material. We suggest this deposit is the result of a tsunami. The marine debris includes coral pebbles and cobbles as well as abundant foraminifera tests and shells. Most of the foraminifera tests belong to species that live at depths of less than 10 m [*Debenay*, 2013] (see detail in supporting information, section 3). However, 14% of the population belongs to species that live at depths greater than 20 m [*Cleary and Renema*, 2007]. This implies deposition by a tsunami rather than a storm, because the storm wave base along the northern coast of Aceh, well south of the latitudes of cyclonic storms and attendant storm surges, is probably much shallower than 20 m. The pristine character of nearly half of the foraminifera present in LC 4 argues for their rapid deposition and a deep offshore scour of marine sediments from the seafloor [*Goff et al.*, 2011; *Pilarczyk and Reinhardt*, 2012]. Redeposition from either littoral or aeolian deposits

seems untenable for much of the deposit, due to the high percentage of pristine foraminifera relative to those that are abraded and corroded [*Berkeley et al.*, 2009; *Pilarczyk et al.*, 2011].

The abundance of coral, marine foraminifera, and shells implies an offshore origin for LC4. Moreover, the large size of some of the coral clasts indicates that very substantial hydraulic forces brought them onto the lime-plaster floor, which one can reasonably presume would have been above high tide and inland from the seashore at the time of its burial. Similarly, the presence of fragments of lime-plaster floor within the deposit and the evidence of local erosion of the floor imply substantial erosional forces. However, the presence of terrestrial debris in LC4—material culture similar to that in the underlying rubbish pits—implies that part of the unit derived from onshore sources.

One might argue that the lack of building rubble in the layer (other than pebbles of lime-plaster floor) suggests the deposit is not tsunamigenic, given that other geoarcheological sites contain such materials [*Goodman-Tchernov et al.*, 2009; *Reinhardt et al.*, 2006]. This is not a strong argument in this case, because rapid rotting of timber would be expected in a warm, humid environment such as this [*Weedon et al.*, 2009].

A tsunami origin for the coral- and foraminifera-rich bed at Lhok Cut is the only viable interpretation. The mixing of both cultural and marine materials may be explained by the landward and seaward flows associated with the onshore and offshore flows of tsunami waves [*Hawkes et al.*, 2007]. We posit that the run-up phase or phases lifted coral, foraminifera, and shells from below and within the intertidal zone and moved them onland and that return flows entrained and deposited cultural debris from the surface of the alluvial fan.

We described the bed directly overlying the tsunami layer as a predominantly massive, very poorly sorted silty layer that contains pebbly clasts and sparse, highly abraded ceramics, broken shells, subangular to angular corals and volcanics, and a very few foraminiferal tests. These characteristics, combined with the presence of sparse, thin discontinuous pebbly beds, are best explained by bioturbation of a sequence of thin alluvial beds deposited by small flows on the alluvial fan that picked up cultural and tsunami debris in the decades to centuries after the tsunami. The significantly lower density of material culture in this layer implies that the settlement associated with the rubbish pits and midden spread beneath the lime-plaster floor was substantially more robust than any that occupied the site after the tsunami.

Excavations into the earthen mound at Lhok Cut, inland from the seacliff, establish that it is a human construct. The void-rich cobbly and bouldery bed and its overlying lime-plaster bed were built on the surrounding alluvial fan surface and represent a well-drained foundation and overlying lime-plaster floor.

The presence of a boulder of *Porites sp* coral near the base of the earthwork mound and directly atop the lime-plaster floor suggests a high-energy depositional event. This is most plausibly the same tsunami that deposited marine debris directly onto the same stratigraphic horizon—directly atop the lime-plaster floor—in the seacliff exposure a few tens of meters away.

The concentration of small boulders in the uppermost part of the mound, well above the floor, may represent a collapsed stone structure or just the use of stones to raise the surface of the mound. We speculate that this earthwork mound and the earthen ridge atop the seacliff and across the valley floor are defensive constructs and are contemporaneous with Kuta (Fort) Lubhok on the other side of the headland. If so, they were likely built between 1490 and 1650 C.E. (see details on Kuta (Fort) Lubhok in supporting information, section 5).

U-Th analysis of the pristine coral cobble within the stone foundation below the lime-plaster floor of the earthwork mound provides a precise date of 1366 ± 3 C.E. for construction of the lime-plaster floor and a maximum limiting date for the overlying tsunami layer. This maximum limiting date falls within the broader range of the radiocarbon dates on charcoal and a tooth within the seacliff lime-plaster floor and permits correlation of the tsunami with the uplift of Simeulue island in either 1394 ± 2 or 1450 ± 3 C.E. Moreover, the U-Th date is consistent with the radiocarbon dates from the rubbish pit, which range from 1200 to 1390 C.E. We further evaluate the plausibility of this correlation, after the following discussion of the Lubhok Bay Beach site.

4.2. Tsunami Deposit at Lubhok Bay Beach

We interpret the shelly sand at the base of the Lubhok Bay Beach exposure to be a beach deposit (LB7, Figure 6). Its characteristics are similar to the modern beach just a few meters seaward from the exposure, and its elevation is within the modern intertidal zone.

The massive, poorly sorted nature of the overlying LB6 and the similarity of its clasts to the bedrock in the hills above indicate that it is an alluvial deposit. Local thin lines of pebbles imply either thin alluvial lenses between massive debris flows or extensive bioturbation of thin alluvial beds. If this stratum was deposited as thin alluvial beds over a century or two, it is reasonable to expect that bioturbation would have rather thoroughly mixed the thin beds into a nearly structureless unit.

Cut into the LB6 is a broad channel with an organic layer at its base. The diffuse nature of its basal contact indicates that the layer formed in situ as a soil, with decaying organic material filtering into the substrate over years or decades. The presence of the soil indicates that years of stability passed before the broad channel was incised by the three smaller channels that are filled with coral rubble. The steepness of the small-channel walls implies that scouring of the loose substrate by flow of water and filling of the channels with the coral rubble (LB5) occurred in very rapid succession, before the loose material of the channel walls could collapse. Perhaps they are even contemporaneous, with seawater containing the coral rubble first eroding and then filling the small channels.

The nearly monolithologic coralline nature of the rubble requires that it originated in shallow offshore waters. The angularity of the clasts and their pristine nature implies that they spent little or no time either in the sea or on land prior to deposition in the channel and on the uneroded surface of the alluvial fan. We contend that it is most probable that these coral fragments were separated from the coral reef by great percussive force while alive, then rapidly brought onshore and deposited. The calcareous material that locally forms a matrix around the coral rubble, usually just above the base of the broad channel, is best interpreted as a post-tsunami precipitate from groundwater that percolated through the rubble in subsequent years or decades.

The layer that buries the tsunami rubble and fills most of the broad channel with debris from the surrounding hills (LB4) is similar to the alluvial bed beneath the tsunami rubble. It is a pebbly, sandy silt and its pebbles are bedrock clasts from the surrounding hillslopes, except in the lowest parts of the bed and very locally elsewhere, where coral clasts from the underlying rubble are mixed in. For the most part, the unit is massive, although thin concentrations of pebbles hint that it consisted of distinct layers that have been extensively bioturbated. The shallow swale in the upper part of the alluvial deposit is evidence that slight re-incision of the channel occurred after deposition of most of this alluvium. Organic darkening of the alluvium below the swale suggests that the swale persisted long enough for organic detritus to form a weak soil on its surface.

The upper coral-rubble layer (LB3) is quite distinct from the lower one. Nonetheless, we interpret it to be tsunamigenic as well. The similarity of its coral age to the dates of the samples from the lower coral-rubble layer and the stained and weathered nature of the samples suggest that the upper rubble layer consists of reworked clasts from the lower one.

If this is the case, it is important to contemplate where these clasts resided while they were weathering. If they had been sitting at a higher elevation on the surface of the alluvial fan, one might expect the alluvial deposit between this and the first coral-rubble bed (LB4) to contain pieces of coral scattered throughout. Since this is not the case, it seems most likely that the coral clasts of LB3 were resting seaward of the mapped exposure, in a place where they could not be deposited on the alluvial fan and could avoid abrasion. We favor the hypothesis that they were sitting in an embankment of debris in shallow water, well below storm wave base and protected from the intense bio-erosion that is common in the intertidal zone. If so, then this deposit represents a second tsunami.

However, one cannot conclusively dismiss the alternative hypothesis that the weathered coral clasts were resting higher up on the alluvial fan and were washed down, since there are rare places within the underlying alluvial unit where coral fragments are present. In favor of this hypothesis, one might argue that weathering would not be likely to occur in a subtidal environment. However, the very thin nature of this second bed of coral rubble allows another interpretation: The coral rubble in this second layer could have weathered in place, after deposition, in the shallow, acidic soil, before and even during the slow deposition of overlying alluvial layers. Thus, although we cannot be altogether certain that the stratigraphic evidence indicates a tsunamigenic origin for the second, thinner bed of coral rubble, it is our strongly favored interpretation.

Immediately above the second coral layer is another alluvial layer (LB2). The concentration of subangular to subrounded volcanic and calcareous pebbles and cobbles along its base suggests a short period of

concentrated erosion of large clasts from surrounding hillslopes. We speculate that this was induced by the tsunami inundation that produced LB3. The lack of any hint of finer bedding in the rest of LB2 suggests that it comprises at least one additional debris-flow bed.

Near the northern (left) edge of the seacliff is a concentration of large cobbles and small boulders within a cut into the alluvium (Figure 6). We tentatively interpret these as a manmade assemblage of uncertain purpose. Perhaps it dates to the same period as the wall that skirts the seacliff at the Lhok Cut site and the early Sultanate defensive structures elsewhere on the peninsula [*Edwards McKinnon*, 2009]. If so, our radiocarbon dates of charcoal in the mortar of the fort wall indicate creation sometime between 1490 and 1650 C.E., during the first century or so of the Aceh Sultanate (see supporting information, section 5).

The massive, poorly sorted, cobbly, bouldery character of the uppermost deposit in the seacliff (LB1) means that it too must be a debris-flow deposit or an amalgamation of more than one. The high concentration of pebbles and cobbles suggests that the bed formed after exceptional disturbance of hillslopes upstream, but it clearly antedates the construction of the road leading to the WWII Japanese bunker, since the bunker is built upon it and its stony foundation cuts into it. Perhaps that road follows the path of a more ancient track, also associated with Acehnese defense of the peninsula within the period 1490 to 1650 C.E.

Several dates constrain the date of the first tsunami at Lubhok Bay Beach. The radiocarbon age of a charcoal fragment in LB6, just below the first tsunami bed, is 1310 to 1360 C.E. or 1390 to 1440 C.E. (Figure 6). These broad spans of maximum limiting dates allows a correlation of the first tsunami with the either the 1394 or 1450 C.E. dates of sudden uplifts of Simeulue island. All three of U-Th ages related to the first coral rubble deposit fall within or overlap the earlier of these two broad ranges and thus are older than the 1394 C.E. uplift. The dates determined for two pristine *Porites sp* clasts from the deposit are 1334 ± 37 and 1356 ± 28 C.E. One plausible explanation for why these ages are three to six decades older than the date of the island uplift is that the initial Thorium in the samples might be slightly greater than we assumed in calculating the ages. As we show in the supporting information (section S6.2), even slight errors in using the initial Thorium concentrations derived from isochron calculations can lead to U-Th ages that are a few decades older than the real ages of the samples.

The date from an intact *Goniastrea sp.* coral head at the level of the first tsunami yielded a far more precise date of 1344 ± 3 C.E. (Figure 6 and Table S6.1). The precision of this date does not allow us to speculate that an erroneous assumption about the initial Thorium has yielded a date a few decades older than the 1394 C.E. uplift of *Meltzner et al.* [2010]. However, unlike the angular *Porites sp* clasts, the outer perimeter of this head shows clear signs of weathering or abrasion—the sub-millimeter pali and costae are absent. Thus, this sample died some time before it was emplaced on the alluvial fan, so its date constrains the date of the first tsunami to sometime after about 1344 C.E. This maximum limiting date from the Lubhok Bay Beach site is consistent with the maximum limiting date of 1366 ± 3 C.E. from the Lhok Cut site on the other side of the headland. We favor the interpretation that the first tsunami recorded at the Lubhok Bay Beach site and the only tsunami recorded at the Lhok Cut site are one and the same and that they correlate with uplift of northern Simeulue island in 1394 ± 2 C.E.

Unfortunately, we have no direct constraint on the date of the second tsunami deposit at Lubhok Bay Beach. Since the one U-Th date from a weathered coral clast within LB3 yields a date of 1250–1388 C.E., the tsunami must post-date a date within that range. The 1366 and 1344 C.E. U-Th dates from the two sites further limit its oldest plausible date of occurrence.

If we assume that the first tsunami occurred in 1394 C.E., then the stratigraphic position of the second bed suggests that it occurred some decades later, given that deposition and extensive bioturbation of intervening alluvial LB4 would likely have spanned decades. A plausible date is Meltzner et al.'s 1450 C.E.

4.3. Comparison of the Deposits of the Paleotsunamis With Those of 2004

At both the Lhok Cut and the Lubhok Bay Beach sites, the deposits of the 2004 tsunami are less impressive than the ancient tsunami deposits. This relative meagreness of the 2004 tsunami deposits raises the possibility that the penultimate tsunamis on the Lambaro headlands might have been larger than the 2004 tsunami and that their sources might not have been the same as the 2004 source. The plausibly greater age of the Lambaro headlands tsunamis also raises the possibility that they do not correlate with

Meltzner et al. [2010]'s 1394 and 1450 C.E. uplifts above the Sunda megathrust. We argue below that each of these hypotheses is less likely than a Sunda-megathrust cause and temporal correlation with *Meltzner et al*. [2010]'s uplifts.

The 2004 tsunami did not leave a large deposit on the floor of the Lhok Cut valley. This does not necessarily imply that the 2004 tsunami was smaller than its predecessor. First, studies of the 2004 tsunami have shown that thin deposits commonly are destroyed in the years following their deposition [*Szczucinski*, 2012; *Nichol and Kench*, 2008]. Second, the 2004 tsunami had a higher seacliff to wash over than did its predecessor. The units atop the seacliff add about a meter to the height of the ground surface. At Lhok Cut, the uppermost of the two younger layers may have served not only as a defensive wall against potential sixteenth century attackers but also, unexpectedly, against the 2004 tsunami! Third, the shape of the seafloor and seacliff might have been different in 2004 than during the penultimate tsunami. This might have restricted the availability and/or delivery of sand and coarser rubble onto the valley floor during the 2004 inundation. Another ad hoc argument would be that the tides might have been higher during the ancient tsunamis than during the 2004 event. Tides during the earlier events could have been a meter or so higher, because the 2004 tsunami struck when the sea was near mean tide and not during a time of spring tides. If the tides were indeed higher, then the earlier tsunamis would have been able to deliver more water and debris onto the valley floor.

There is abundant evidence that the 2004 tsunami swept this side of the Lambaro headlands and was several meters high. Local resident Abdullah reported to us that the tsunami inundation extended at least as far as the road bridge that crosses the stream shown on Figure 2. This point is farther east than the extent of the figure, about a kilometer inland from the coastline. He also reported that the tsunami in the valley of Lubhok Bay (east side of Figure 2) made marks about 3 m above the ground on coconut trees behind Kuta (Fort) Lubhok. This is consistent with our own observations. Heavy, sixteenth century *plang pleng*-style gravestones landward of the Fort (marked on Figure 2) were not moved greatly by the tsunami, but a large chunk of masonry from the front of the circular, landward bastion of the fort was torn off by the waves and carried inland to the edge of the river bank. Sand and stones from the fort cover much of the ground behind the fort.

The Lubhok Bay Beach exposure itself does not have a 2004 tsunami bed at its top. However, sand from the 2004 tsunami does still exist locally on the surface of the alluvial fan a few meters landward of the exposure, similar to the spotty nature of LB3 in the exposure. Judging from the height of the tsunami at and inland from nearby Kuta (Fort) Lubhok, the height of the 2004 tsunami at the exposure must have been several meters, well above the 1.5 m height of the seacliff. Perhaps the half-meter high escarpment at the 8 m contour on the fan (Figure 5) is an expression of erosion caused by the tsunami. This would imply that the surface of the fan was substantially eroded rather than aggraded.

In any case, the expression of the older of the two paleotsunamis in the seacliff is more pronounced than any expression of the 2004 tsunami at the site. As at the Lhok Cut site, however, greater deposition during this paleotsunami might well be due to the surface of the fan being a meter or so lower and closer to the elevation of the sea then. Perhaps there was also no seacliff then to serve as a barrier to transport of large clasts onto the surface of the fan or into its channels.

The lack of historical evidence for other large destructive tsunamis along this coast is another argument that the sources of the two ancient tsunamis are indeed the 1394 and 1450 C.E. uplifts above the Sunda megathrust. First, none of the lesser earthquakes of the twentieth century, including the events of 1907 [*Newcomb and McCann*, 1987], 1881 and 1941 [*Briggs et al*., 2006] produced a significant tsunami along this part of the Acehnese coast. Moreover, 2004-sized events, with about 20 m of slip on the megathrust, should occur about every 500 years on average, because plate convergence across the megathrust at this latitude is about 40 mm/yr. Thus, if there are no large tsunamis along this coast since before the beginning of the Aceh Sultanate about 1500 C.E. [*Meltzner et al*., 2010, Figure 17], would it not be most probable that the ancient deposits of the Lambaro headlands are evidence for the penultimate giant failures of the Sunda megathrust offshore Aceh? If one proposed that the two tsunamis were caused by another source, such as the Aceh Basin backthrust [*Singh et al*., 2011], then the penultimate 2004-like rupture of the Sunda megathrust would need to have occurred even further back in time. This seems implausible in light of the stratigraphic records of both *Monecke et al*. [2008] and *Jankaew et al*. [2008] which show only two earlier, 2004-like tsunami deposits along the western coasts of both Aceh and Thailand in the past millennium.

4.4. Historical and Archeological Context

There is textual and archeological evidence that one or both of the tsunamis we have documented profoundly affected habitation and commerce along the northern shores of Sumatra and in the Malacca Strait. Below, we summarize this evidence for significant disruption between the time of the first tsunami and about 1500 C.E. Within that period of a century, more or less, the culture represented by our settlement at Lhok Cut disappeared from written and archeological records, and settlements on the more protected coasts of the Malacca Strait became dominant. But by no later than 1520 C.E., the Sultanate of Aceh had appeared and established dominance along the devastated northern coast.

The thirteenth to late fourteenth century settlement at Lhok Cut is contemporaneous with an ancient settlement along the northern coast of Aceh known as Lamri or Lambri, an important node in transregional maritime trading routes that linked South Asian, East Asian, and local traders [*Edwards McKinnon*, 1988]. Lamri was flourishing just before the Lhok Cut record begins, that is, by the end of the twelfth century [*Tibbetts*, 1979, pp. 138–140, 247]. It was sending tribute missions to China late in the thirteenth century [*Hall*, 1985, pp. 213], a time during which the rubbish pit at Lhok Cut was being filled. Also by the late thirteenth century, a Tamil-language guild inscription at Neusu, Banda Aceh, demonstrates that the trade for local pepper and forest material had reached a high level at Lamri [*Subbarayalu*, 2009, pp. 529–32]. Moreover, obelisk-shaped *plang pleng* Islamic grave markers that are indigenous to the northern coast and very common on the Lambaro headlands (Figure 2) are also contemporaneous with the filling of the rubbish pit and the destruction layers [*Edwards McKinnon*, 2009; *Lambourn*, 2003, 2004; *Guillot and Kalus*, 2008].

Lamri disappears from written records and the focus of trade moved further east, into the Malacca Strait, sometime between the late thirteenth and late fifteenth centuries. By the early fifteenth century, the previously established settlement of Samudra-Pasai (Figure 1), near present-day Lhokseumawe, had grown in size and influence and become the primary port for north Sumatran pepper exports [*Hall*, 1985, pp. 218]. The prosperity of this Muslim port polity facilitated its emergence as a leading centre of Muslim culture in the Indonesian Archipelago, a position that it maintained for a century or so, until 1524 C.E., when the Acehnese conquered it. If this expansion of trade and culture farther east reflects destruction of the northern coast of Aceh, then that destruction would have occurred before the early fifteenth century, consistent with an 1394 ± 2 C.E. date for the first tsunami, followed by a second tsunami of as yet uncertain effects in about 1450 C.E.

Records show a gradual return of trading settlements along the north and west coast of Aceh, when Arabic ships were calling at a port in the area called Mandara. These textual records imply that Mandara had replaced Lamri after a long hiatus in activity there [*Tibbetts*, 1971, pp. 493]. This economic and political reestablishment around what is now Banda Aceh likely occurred no later than the early sixteenth century, during which time Sultan Agi Mugharat Syah, buried near Banda Aceh in 1530 C.E., expanded the control of the sultanate westward. A string of fortifications between Banda Aceh and the Lambaro headlands and associated with the rise of the sultanate of Aceh appeared in the mid sixteenth century [*Edwards McKinnon*, 2009] (see comments in supporting information section 5 about Fort Lubhok dates). From the early seventeenth century, this port polity a few tens of kilometer west of the earlier Lamri settlements became the most powerful center in northern Sumatra.

All this is consistent with the destruction of settlements along the northern coast of Aceh during the tsunami of 1394 ± 2 C.E. and thereafter in 1450 ± 3 and with a recentering of trade at Samudra-Pasai, Malacca, and even Singapore, on the more-protected shores of the Malacca Strait, in the decades that followed. By the beginning of the sixteenth century, new settlements had arisen in the region devastated by the tsunami.

The dates of the *plangpleng* gravemarkers on the Lambaro headlands suggest another interesting aspect to the story. The date inscribed on the youngest of these is equivalent to 1483/1484 C.E., about a century after the 1369 or 1389 C.E. date marked on the oldest. This implies that some members of the culture that witnessed both the 1394 and 1450 C.E. tsunamis survived them and remained in the area, even if they ceded their commercial vitality and prominence to protected communities to the east and eventually to the sultanate of Aceh.

Although we can as yet only speculate about the magnitude of its effect on any remaining populations, the evidence for the second, 1450 C.E. tsunami is clear at Lubhok Bay. Its deposits at our sites on the Lambaro headlands are far less prominent than those of the earlier tsunami. Still, it does not necessarily follow that the tsunami was smaller or had less impact, since we have explored only two sites and since local conditions at our

sites could have produced a lesser display of evidence for the second event. For example, the near-shore settlement at Lhok Cut does not appear to have been rebuilt after its initial destruction; thus, evidence of the second tsunami might not show up as a stratigraphically discrete bed. One ad hoc argument for the meagerness of the tsunami bed at the Lubhok Bay Beach site is that the coral reef broken by the 1394 C.E. tsunami had not been replaced by new growth in the decades before 1450 C.E.

5. Conclusions

Strata exposed at Lhok Cut, on the west side of the Lambaro headlands, record inundation and destruction by a tsunami late in the fourteenth century. U-Th and radiocarbon analyses constrain that tsunami's date to soon after 1366 ± 3 C.E. On the eastern side of the Lambaro headlands, at the Lubhok Bay Beach site, at least one and likely two tsunami layers are evident within a succession of beach and alluvial deposits. U-Th dates on coral associated with the first of these constrain its deposition to sometime in the decades after 1344 ± 3 C.E.

The simplest interpretation is that the tsunamis recorded at Lhok Cut and at Lubhok Bay correspond to the 1394 ± 2 C.E. uplift of northern Simeulue Island documented by *Meltzner et al.* [2010]. Coral fragments in a higher layer at Lubhok Bay were remobilized from the first layer and cast upon the alluvial fan as a thin and discontinuous bed. We suggest that this resulted from a tsunami in 1450 ± 3 C.E.

The tsunamis of 1394 ± 2 and 1450 ± 3 were surely not the first tsunamis, nor is their 2004 successor the most recent tsunami to have caused a major, even permanent disruption in human societies. The tsunami caused by the great eruption of Santorini in the eastern Mediterranean about 1628 B.C.E. may well have initiated the profoundly consequential transition from Minoan to Mycenean domination of the Mediterranean [*Bruins et al.*, 2008]. The destruction of Port Royal, Jamaica, by a large earthquake and tsunami in 1692 C.E. initiated its permanent decline as an important port city [*Lander et al.*, 2002]. The 2011 Japanese tsunami laid waste to communities and agricultural land along hundreds of kilometers of Honshu's eastern coast, and current demographic and economic circumstances seem to be dictating that much will not be rebuilt. By contrast, the nearly complete destruction of Lisbon by the earthquake, tsunami, and fires of 1755 had no such effect and is even seen as a salutary event in the history of the Enlightenment [for example, *Shrady*, 2008; *Braun and Radner*, 2005].

The tsunami of 1394 C.E. appears to have had an effect on the northern coast of Sumatra similar to the effect of the 1692 C.E. earthquake on Port Royal, Jamaica—the center of commerce moved elsewhere in the decades that followed. By contrast, the response to the devastation of Aceh in 2004 is more akin to Lisbon's response to its debacle in 1755—Aceh's devastated communities are rebuilding rapidly, due in no small part to outpouring of assistance from outside the region [*Daly et al.*, 2012].

Too little is known about the millennial patterns of tsunamis along the northern coast of Sumatra to know whether the next tsunami will devastate a generation centuries removed from us or one that will occur in our lifetimes. The occurrence of the 1394 C.E. to 1450 C.E. pair suggests that the latter is possible, but such pairings may be the exception rather than the rule. Records extending still farther back in time would be helpful in refining forecasts there. Paleotsunami deposits extending back thousands of years in a cave along the western coast of Aceh are a good start in that direction [*Pilarczyk et al.*, 2013].

Regardless of whether tsunamis strike the Aceh coast regularly every many hundred years or not, the issue we raised at the beginning of this paper warrants more serious attention: Who would prioritize planning that makes accommodations for once-in-a-millennium events, with so many other pressing social, political, and economic issues at hand? Surviving fifteenth century traders and their progeny seem to have opted for a rather common-sense measure, perhaps necessitated by economic and environmental devastation—they did not rebuild their ports in precisely the same locations. However, with time, and presumably the recession of memory and direct experience, trade and population did move back to Aceh—setting the stage for the eventual destruction of 2004. After 2004, there was no hiatus—large-scale relief and reconstruction processes funded by the international humanitarian community rebuilt much of what was destroyed by the tsunami directly in areas that will almost certainly be devastated by the next.

From this and other examples, one can only conclude that adaptation to very rare events, like 500 or 1000 year tsunamis, will always tend to take second seat to more pressing social, economic and political activities, such as those that faced Aceh in the decades preceding the tsunami of 2004.

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