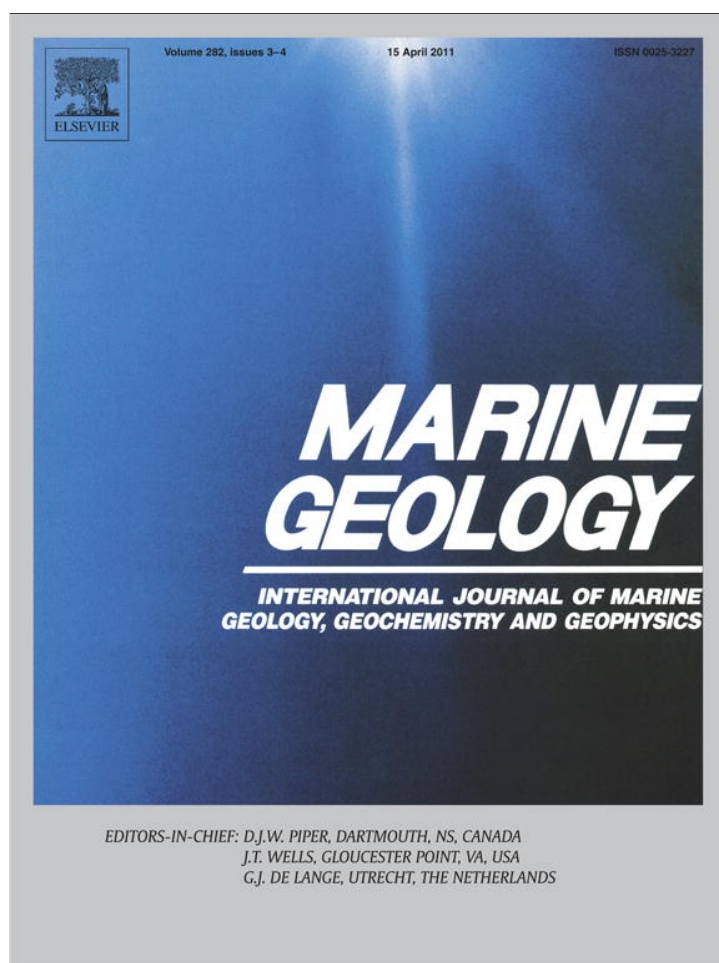


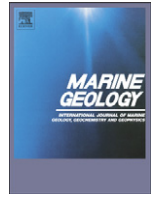


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Evidence for a mid-Holocene tsunami deposit along the Andaman coast of Thailand preserved in a mangrove environment

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ABSTRACT

Klong Thap Lamu, a large mangrove-fringed tidal channel along the northern Andaman Coast of Thailand, provides an ideal location to test the hypothesis that a paleotsunami record can be preserved in the sediments of a mangrove forest. The 2004 Indian Ocean tsunami destroyed local swaths of mangrove forest with highly variable widths — up to 300 m. Left in the wake of the tsunami is a thin mantling of laterally discontinuous sand, macerated shells, and localized coral rubble that is being mixed rapidly into the underlying mangrove peat. Transects across the channel's tsunami-modified shore show that the sand layer thins abruptly at the border of the undisturbed mangroves, suggesting that the energy of the wave dissipated quickly as it entered the forest. The distribution and sedimentology of the 2004 tsunami deposit (Unit tI) suggest that any paleotsunami deposit within this mangrove environment should be spatially restricted and thoroughly bioturbated. Sediment cores collected from within the 2004 tsunami zone penetrate a buried coral-shell peat unit (Unit tIII) that tapers inland. Unit tIII is strikingly similar to Unit tI, except for Unit tIII's diffuse sedimentology, which we attribute to extensive bioturbation. Unit tIII also cross-cuts an identified facies boundary that is traceable across the width of the 2004 tsunami zone. Rather than a facies boundary associated with the regional early-to-late Holocene sea level regression, stratigraphic correlations suggest that Unit tIII represents an event horizon (i.e. tsunami). AMS ¹⁴C dates on material from within Unit tIII combined with an upper bracketing age suggest that the tsunami event occurred sometime between 2720 and 4290 cy BP. If correct, this tsunami predates the 3–4 tsunami events recognized to the north at Koh Phra Thong. Unit tIII is, however, a potential far-field equivalent of a recently recognized paleotsunami deposit on the southwestern Indian coast ca. 3,710 years before present (Nair et al., 2010).

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1. Introduction

The 2004 Indian Ocean tsunami struck the Andaman coast of Thailand without warning (Waltham, 2005). This catastrophic event underscored the absence of data about the frequency of tsunami occurrence along this coast as well as the insufficient preparation of the coastal communities (Rhodes et al., 2006). Our understanding, however, of the frequency of tsunamis capable of impacting the Andaman coast has improved recently with evidence for possibly three pre-2004 events since 2800 cy BP (Jankaew et al., 2008; Monecke et al., 2008; Fujino et al., 2009). The lack of local written historical records leaves the geologic record as the best resource for identifying past tsunamis in Thailand. Finding a paleotsunami record along this section of tropical coast requires the recognition of coastal environments suitable for capturing and preserving tsunami sediment (Atwater, 2007). Elsewhere, many of the well-known paleotsunami

records exist along temperate coasts in salt marshes (Atwater, 1987; Atwater and Moore, 1992; Cisternas et al., 2005; Williams et al., 2005) and coastal freshwater lakes (Bondevik et al., 1998; Grauert et al., 2001; Kelsey et al., 2005), but these environments do not exist along Thailand's Andaman coast. Paleotsunami deposits also lie within the sediment of wide beach plains where they are preserved in swales between progradational beach ridges (Nanayama et al., 2000; Pinegina et al., 2003; Jankaew et al., 2008; Fujino et al., 2009). Although the 2004 tsunami left extensive deposits on the beach plains of Thailand (Hori et al., 2007), finding similarly situated ancient deposits along the Andaman coast is frustrated by the near complete disruption of many beaches by extensive 20th century placer tin mining (Schwartz et al., 1995) and subsequent coastal development.

Mangroves represent the tropical analog of temperate salt marshes (Augustinus, 1995). Extensive regions of mangrove forests characterize Thailand's northern Andaman Coast. Unfortunately, intense bioturbation within the mangrove forests most likely precludes the preservation of "classic" tsunami-deposited sheets of sand like those found in temperate salt marshes and coastal lakes (Nanayama et al., 2003; Cisternas et al., 2005; Kortekaas and Dawson, 2007). Based on recent

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reconnaissance studies of the 2004 tsunami deposit along Thailand's northern Andaman coast, we hypothesize that mangrove forests are potential sites for preserving paleotsunami sediment. Below we describe a coral-shell peat layer (Unit tIII) preserved along the Thap Lamu tidal channel (Fig. 1) in the peaty sediment of a mangrove forest, which we interpret as the oldest paleotsunami deposit so far identified along Thailand's Andaman coast.

2. Regional setting

Thailand's northern Andaman coast reflects approximately 8000 years of sea-level change (Fig. 2). Post glacial, rapid sea level rise ended with an early-middle Holocene high stand (Scoffin and Tissier, 1998; Hassan, 2002; Tanabe et al., 2003; Horton et al., 2005). This high stand produced a submerged, sinuous coastline. A combination of beach progradation and longshore sand drift sealed off large bays fed by relatively narrow tidal channels. Deposition in

these bays accompanied by falling sea level throughout the mid-to-late Holocene, resulted in the progradation of mangroves across the bays (Tanabe et al., 2003). This proposed succession exists in other regions where relative sea level dropped, such as that documented in the Gulf of Thailand and parts of Australia, following an early-middle Holocene sea level highstand (Chappell, 1983; Woodroffe, 1992; Tanabe et al., 2003). The 1 km wide Klong Thap Lamu (Fig. 3), a tidal channel north of Phuket Island, forms the entrance to one such mangrove-filled bay. About 4 km upstream of its mouth, the main channel splits with a southern branch that extends between older beach ridges to the east and the narrow modern beach ridge to the west (Fig. 3B). The 2004 tsunami did not breach the narrow modern beach; the tsunami wave entered the channel only through its mouth. The northern branch feeds a dendritic network of smaller channels that extend over 10 km inland with 1–2 km-wide mangrove forests along their edges (Fig. 3B). A >100 m high, 4 km long north–south trending bedrock ridge guards the mouth of Klong Thap Lamu and

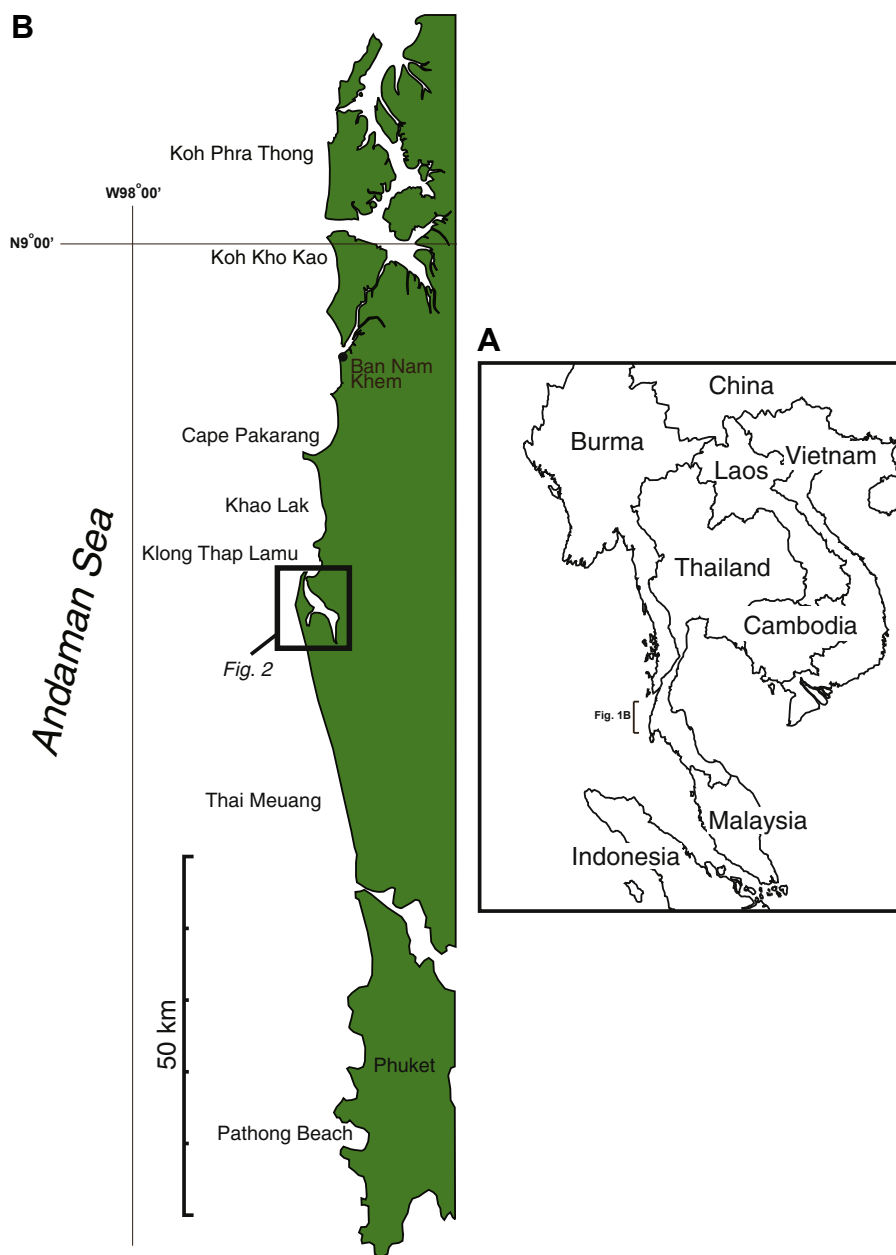


Fig. 1. Index map of Thailand's northern Andaman Coast showing the location of Klong Thap Lamu.

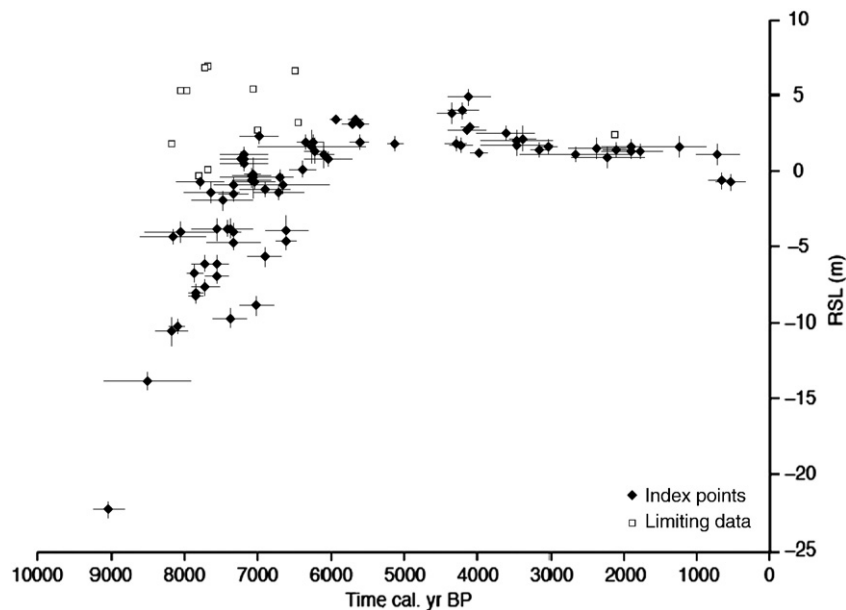


Fig. 2. Holocene sea-level curve for the Gulf of Thailand (simplified from Horton et al., 2005, Fig. 4).

protects it from significant storm-wave energy. We used Klong Thap Lamu to test our hypothesis that sediment beneath a modern mangrove forest could preserve paleotsunami deposits.

2.1. The 2004 tsunami deposit

In order to understand the potential for preserving a tsunami deposit in a mangrove swamp, we examined the sediment deposit from the 2004 tsunami in Klong Thap Lamu. The 2004 tsunami refracted around the headland at the mouth of the channel, washing across the low, wide beach plain to the north of the channel's mouth and continued upstream. The most obvious impact of this tsunami on Klong Thap Lamu is the irregular destruction of the mangroves that fringe the channel (Fig. 3D and E). The extent of destroyed mangroves varies abruptly from almost no damage, to complete destruction (down to ground level) over a width of nearly 300 m. In similar tidal channels and lagoons north of Klong Thap Lamu, post-tsunami high-resolution satellite images document similarly abrupt lateral variations in the degree of mangrove destruction (Fig. 4) (Yanagisawa et al., 2009; Roemer et al., 2010). Lateral variation in the 2004 tsunami's energy suggests that the thickness and landward extent of the tsunami deposit should also vary along its depositional pathway (Hawkes et al., 2007; Hori et al., 2007; Goto et al., 2010). Furthermore, the presence of mangrove vegetation should cause an abrupt landward reduction in the capacity and competency of the wave to transport sediment and diminish backwash erosion (Woodroffe, 1992; Thampanya et al., 2006).

To test these ideas, in March, 2006, we measured the thickness of the 2004 tsunami deposit along 2 transects across the edge of Klong Thap Lamu – from the channel, across the swaths of destroyed mangroves, and into the intact mangrove forest (Fig. 5). The clearing and replanting program conducted by the Thai government in the months following the tsunami facilitated access to these swaths of destroyed mangroves. Along both transects, the 2004 tsunami deposited a veneer of fine-medium-grained sand across the zone of destruction. The thickness of this veneer varies from 0 to 5 cm, and thins abruptly into the mangrove forest. Along transect KTLA3, the sand layer also thins toward the channel – perhaps due to redistribution by tidal currents and/or bioturbation. Thus, the tsunami sand is thickest within the zone of destroyed mangroves, with very

little sand penetrating into the interior of the remaining mangroves (Fig. 5).

These data suggest that a paleotsunami deposit within a mangrove swamp should be discontinuously concentrated along the edge of the tidal channels. Moreover, it is unlikely that a paleotsunami deposit in a mangrove swamp will be a continuous sheet of sand, such as the examples found in temperate salt marshes and coastal lakes (e.g. Atwater and Moore, 1992; Cisternas et al., 2005). In order to find a paleotsunami deposit in this environment it is necessary to search along the paleochannel's edge, not within the interior of the mangrove forest. Additionally, samples must be collected at closely-spaced intervals to account for the extreme discontinuity caused by the lateral variation in the tsunami's energy and the mangrove forest's dissipative affect (Woodroffe, 1992).

Extreme bioturbation represents another challenge to finding a preserved paleotsunami deposit in a mangrove forest. After more than two years, the 2004 tsunami deposit was still distinct, in spite of burrowing, primarily by crabs. Over timescales of decades to millennia the mixture of faunal and mangrove root bioturbation will mix the tsunami deposit with the underlying mangrove peat – this effect is highlighted by our multiple age reversals (see Results and discussion). Consequently, the identification of heavily bioturbated, sandy paleotsunami deposits will require careful examination of multiple lines of evidence.

At the study site within Klong Thap Lamu, the refracted 2004 tsunami hit a mangrove forest along the south edge of the channel, 2 km upstream from its mouth and directly behind (east) of a high, bedrock ridge that guards the channel's mouth (Fig. 3). Here, the tsunami sheared a swath of mangrove forest up to 300 m wide. Along with a thin veneer of sand, the tsunami also stranded an unsorted litter of angular coral fragments and macerated shell debris on the floor of the destroyed mangrove forest (Fig. 6). Coral clasts up to 50 cm in diameter were spread across the destroyed area, although none were found within the intact mangroves. No such coral debris was found at any other location within Klong Thap Lamu. Local fishermen confirmed that this coral debris did not exist prior to the 2004 tsunami. This localized deposit probably resulted from the tsunami crossing a fringing reef along or just offshore of the headland. Moreover, the extent of coral deposition as well as the coral's large size suggests that the tsunami contained sufficient energy to transport

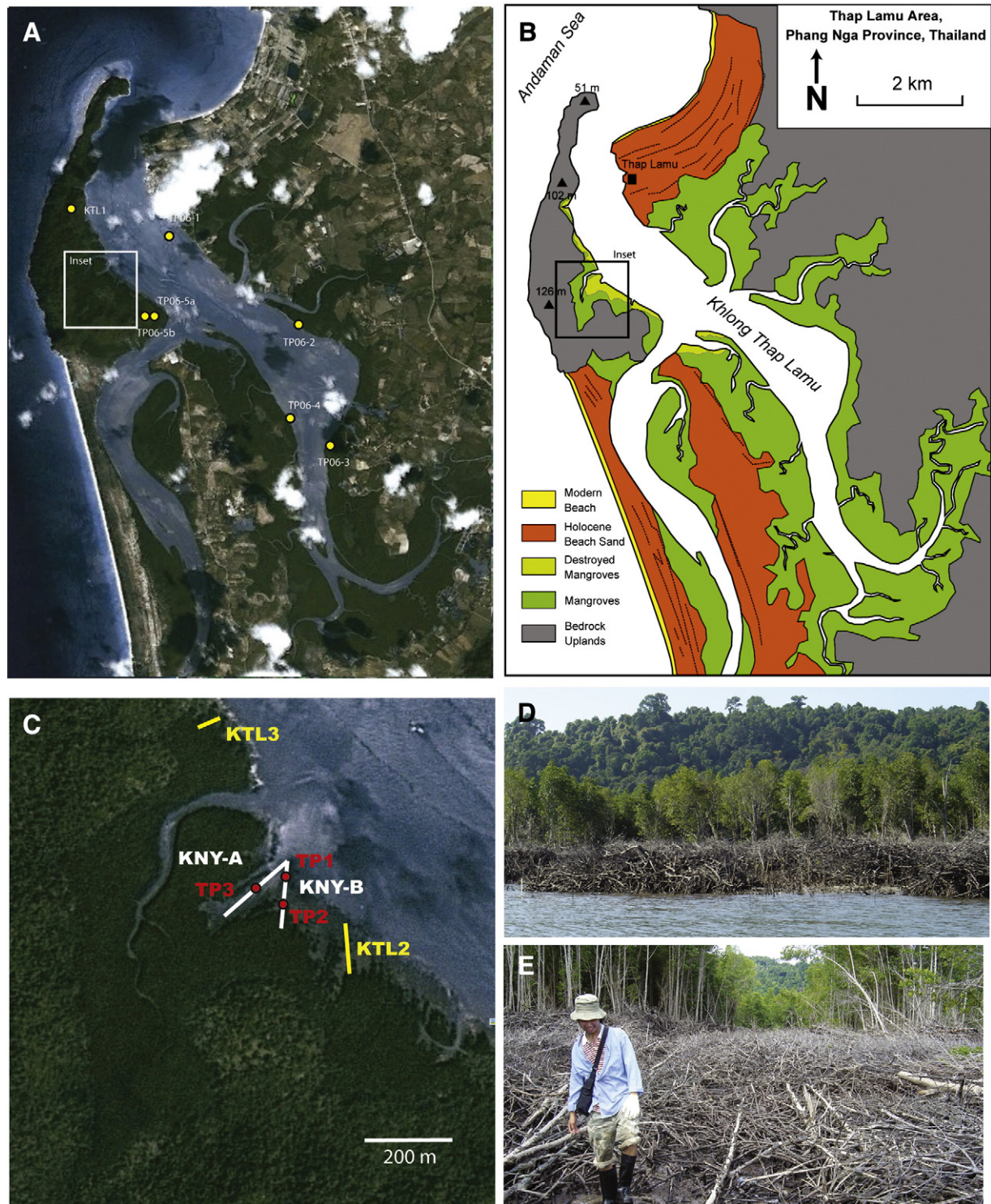


Fig. 3. A. Google Earth Satellite image of Klong Thap Lamu area, area of Fig. 3C, and location of reconnaissance soil-probe cores (see Table 1 for descriptions). B. Map of Klong Thap Lamu area showing distribution of mangrove forests and beach deposits. C. Enlarged Google Earth image of study area showing transects and piston core locations discussed in the text. D. Photo of the eastern shore of Klong Thap Lamu showing extensive mangrove damage. E. Photo showing unusually wide swath of mangrove destruction taken from near the eastern end of transect KNY-B. Fig. 3A and C, ©2011 Cnes/Spot Image, © 2010 MapIt, © 2010 Tele Atlas.

coral debris 2 km upstream into the channel, where it deposited the coral when the wave expended its energy as it entered the mangrove forest. It is worth noting that the coral reefs along the west coast of Thailand felt the impact, although of varied magnitude, of the 2004 tsunami (Phongsuwan and Brown, 2007; Chavanich et al., 2008). In the hope of finding an older, buried deposit, we chose this mangrove location for subsurface exploration.

3. Methods

To begin the study we collected several 1–3 m reconnaissance soil-probe cores along the shores of Klong Thap Lamu (Fig. 3A). Most of these cores contained a variable thickness of mangrove peat overlying sandy channel or paleobeach deposits (Table 1). However in the area that coincides with the distribution of 2004 coral debris,



Fig. 4. Google Earth image showing feathery pattern of extremely variable mangrove destruction in the tidal channel northeast of Ban Nam Khem (see Fig. 1 for location). Image © 2006 DigitalGlobe.

reconnaissance cores intersected, at a depth of approximately one meter, a layer of angular, poorly sorted coral and macerated shell gravel. In order to recover this layer in its context, we collected three 4–6 m square-rod, Livingstone piston cores (Table 2, Figs. 7 and 8). In addition, excavation of a 2 m deep pit allowed a field description of this layer. To fill in the stratigraphy between piston core sites, 15 additional soil-probe cores helped to delimit the location and thickness of the coral-shell unit (Fig. 9). The soil-probe cores came

from two roughly perpendicular transects across the site to include the location of the piston cores (Fig. 9). While in the field, we described and discarded the soil-probe cores, whereas the piston cores were extruded into plastic wrap and aluminum foil lined PVC piping, labeled, and taped for safe transport back to the Cal State Fullerton (CSUF) cold storage facility. Typical of poorly compacted peats, the coring and extrusion process produced compaction of 5–50% of the top 1–2 m of these cores; we assume this compaction is

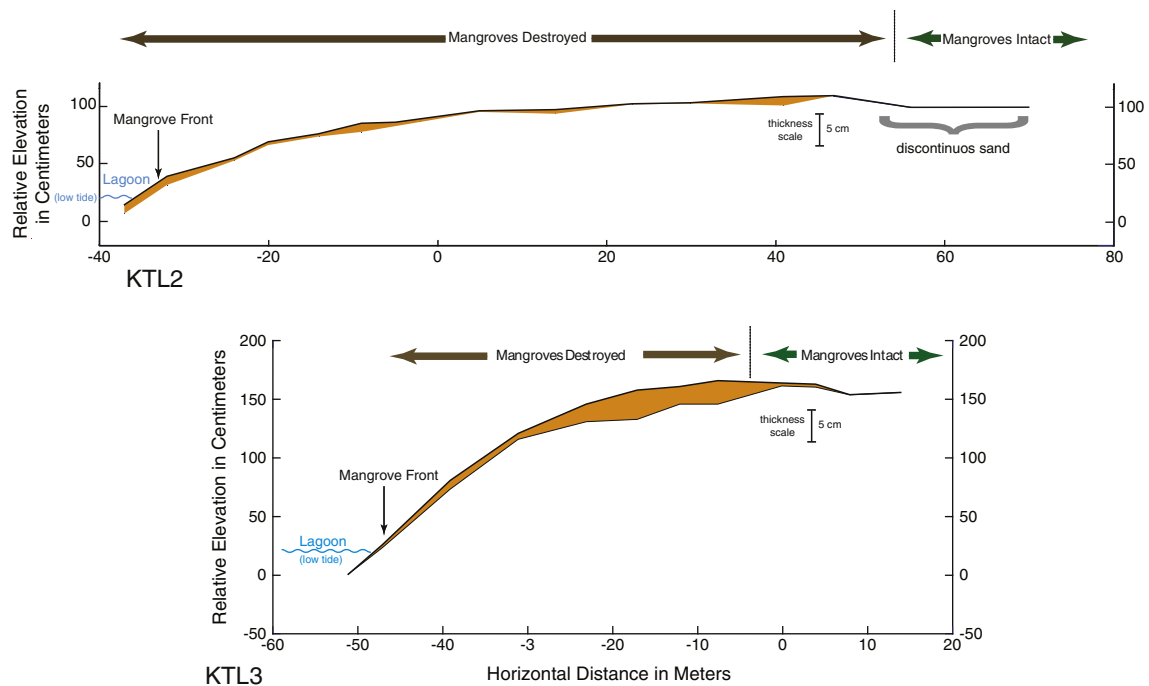


Fig. 5. Two transects across the eastern shore of Klong Thap Lamu showing the distribution of the sand sheet from the 2004 tsunami. See Fig. 3C for locations.

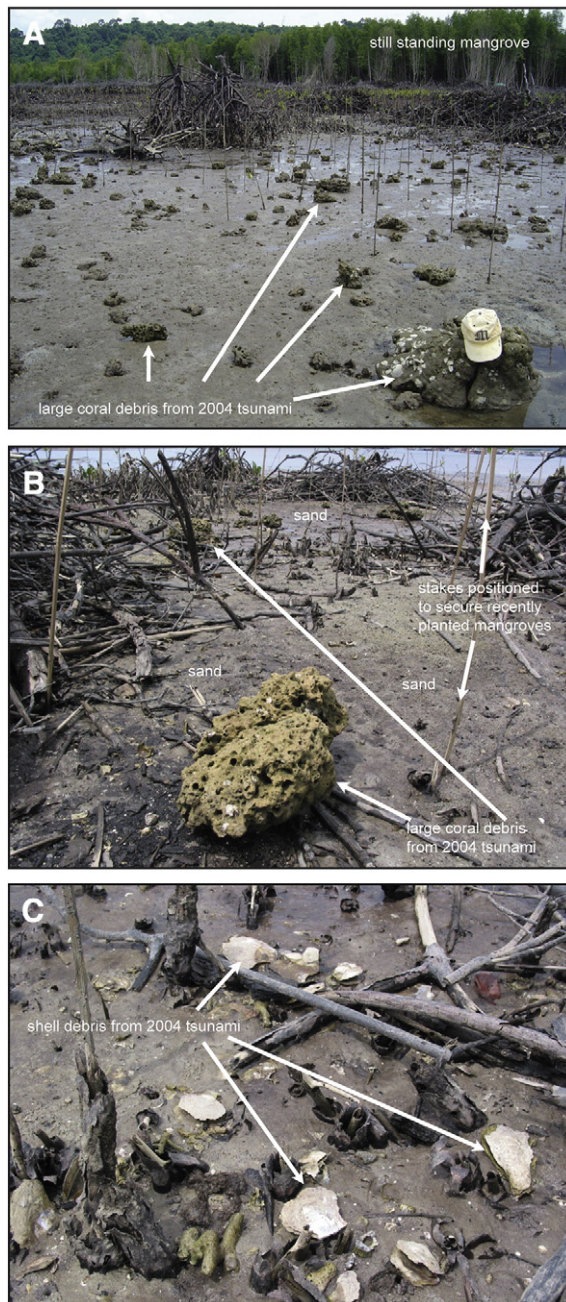


Fig. 6. A. View looking south approximately along the line of transect KNY-B from near the pre-2004 shore of Klong Thap Lamu (Fig. 3C). Photo shows scattered coral debris deposited by the 2004 tsunami. Vertical sticks are poles placed as guides for newly planted mangroves. B. View looking northward in study area with Klong Thap Lamu visible in background. Photo shows close-up of coral boulder and discontinuous sand sheet deposited by the 2004 tsunami. C. Close up view of macerated shells deposited by the 2004 tsunami.

uniform within each drive of the core down to 2 m depth and an appropriate correction was applied to all stratigraphic sections as shown on Figs. 8 and 9.

Back at CSUF, the three piston cores were opened, digitally photographed, and described. Each core was sub-sampled at 1 cm contiguous intervals into 8 cm³ plastic cubes for determination of mass magnetic susceptibility using a Bartington MS2 Magnetic Susceptibility instrument at 0.456 kHz. Measurements were made twice rotating the y-axis 180° to the 0.1 decimal place and reported as mass magnetic susceptibility in SI units ($\times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$). Loss-on-ignition 550 °C (% total organic matter, %TOM) and 950 °C (% total carbonate, %TC) were

measured following the method of Dean (1974). As shown by Dean (1974), three to four percent total weight loss after 950 °C may represent clay de-watering. Therefore, values less than 4% LOI 950 °C are interpreted as containing low to negligible total carbonate.

Grain size was determined at 5 to 10 cm intervals on two of the piston cores. Samples were boiled in DI water combined with 10 mL increments of 30% H₂O₂ until organics were removed. Organic material larger than 2000 μ was removed by wet sieving prior to the addition of hydrogen peroxide. Carbonates were removed using 10 mL or more increments of 1 N HCl and allowed to sit overnight. Finally, biogenic silica was removed using 10 mL or more of 1 N NaOH for 4 h at 50 °C. Following both carbonate and biogenic silica pre-treatments, each sample was mixed with DI water and centrifuged twice at 3000 rpm for 10 min to clean the sample. All samples were run on a 2004 Malvern Mastersizer 2000 laser diffraction grain size analyzer coupled to a Hydr 2000G. To assess the equipment's repeatability and stability, a tuff standard (TS2) with a known distribution between 1.0 and 16.0 μ (avg. $4.56 \mu \pm 0.17$; $n = 5510$ [as of 12/10/10]) was measured twice and compared to past measurements. Thereafter, TS2 was run every 10 samples to verify analytical repeatability and stability and once at the end of the day's analyses for a final assessment. TS2 results are compared to values obtained by measuring known Malvern standards as an additional measure of stability. All data are reported as volume percent and divided into 10 grain-size intervals as well as d(0.1), d(0.5), d(0.9), and mode.

Discrete macro-organic samples were also picked using a binocular scope for AMS ¹⁴C dating (see below).

4. Results and discussion

4.1. Lithostratigraphy and Holocene sea level change

Based on field descriptions of the soil-probe cores as well as lab-based descriptions and sedimentological analyses of the piston cores, seven lithostratigraphic units are identified (Table 3, Fig. 9). These units are cross-correlated between TP-1, -2, and -3 and 15 soil probe cores and interpreted in the context of the early-to-late Holocene regional sea level regression (Sinsakul, 1992).

4.1.1. Unit tI (2004 sand)

Light gray, medium-grained sand forms a discontinuous layer up to several centimeters thick (Figs. 7 and 9). Sand content minus carbonates, organics, and biogenic silica (see Methods) average >90% for Unit tI (Fig. 8). Coarse coral and shell fragments lie within and on top of this sand (Fig. 6). Analyses suggest this sand is carbonate-poor (without the inclusion of large coral and shell fragments) with low, but variable organic content and negligible magnetic susceptibility (Table 3, Fig. 8). The low carbonate values, however, are misleading. The small diameter of the corer could not accommodate the 2004, unweathered large coral and shell fragments, thus the "carbonate" fraction of the sand is relatively low despite the obvious occurrence of significant carbonate material associated with Unit tI (Table 3, Fig. 8). If the large coral and shell fragments were included in the bulk samples, the total carbonate values would be similar to Unit tIII, which is carbonate-rich (Fig. 8). In general, Unit tI forms a sharp boundary with the underlying peat. Unit tI represents the 2004 tsunami deposit.

4.1.2. Unit II (mangrove peat)

Fibrous, reddish-brown to black peat dominates the upper parts of all the cores (Figs. 7 and 8). Red mangrove roots, root fibers, and wood fragments lie within a mostly muddy-sand matrix. Unit II is characterized by the highest average total organic matter, low but variable total carbonate, and negligible magnetic susceptibility (Table 3, Fig. 8). Unit II is interpreted as representing an established mangrove environment.

Table 1

Location and description of soil-probe cores from shores of Thap Lamu tidal channel. Core Locations are plotted on Fig. 1A.

Sample number	UTM location (WGS84)	Mangroves destruction	Depth of core (cm)	Core description
KTL1	Zone: 47 Easting: 413477 Northing: 947273	Destruction zone up to 40 m from edge of channel	90	Indistinct sandy peat at top may represent 2004 deposit. Remainder of core consists of coarse mangrove peat.
TP06-1	Zone: 47 Easting: 415290 Northing: 946562	Mangroves undamaged	263	15 cm of 2004 sand at top, underlain by 2 m of coarse mangrove peat resting on 60 cm of coarsening downward pebbly sand.
TP06-2	Zone: 47 Easting: 417448 Northing: 944666	Destruction zone 50 m wide. Large 1–2 m thick layers of peat were ripped up from edge of Mangrove forest by tsunami	200	5 cm of coarse 2004 sand at top of 1 m of mangrove peat grading into 200 cm of coarse sand interpreted as a beach deposit.
TP06-3	Zone: 47 Easting: 417921 Northing: 942295	Destruction zone limited to <5 m from edge of channel	290	Discontinuous thin veneer of 2004 sand at top, overlying 150 cm of coarse mangrove peat. Peat is underlain by an 85 cm thick interval of interbedded fine-medium grained sand and peaty mud which grades downward into uniform sand.
TP06-4	Zone: 47 Easting: 417288 Northing: 942883	Mangroves undamaged	290	20 cm of medium grained sand from 2004 tsunami overlies 110 cm of coarse mangrove peat which grades into uniform, decreasingly peaty sand to bottom of core. Lower 100 cm contains no peat.
TP06-5a	Zone: 47 Easting: 414936 Northing: 945009	Mangroves destroyed in an irregular zone 50–100 m wide	295	7–8 cm thick fine sand from 2004 tsunami underlain by coarse mangrove peat that grades into peaty sand at about 140 cm depth. Below 140 cm, peat component decreases leaving fine-medium sand in bottom 100 cm of core.
TP06-5b	Zone: 47 Easting: 414873 Northing: 945013		290	No 2004 tsunami deposit visible in core. Coarse mangrove peat extends to 170 cm depth where it grades into decreasingly peaty sand to bottom of core.

4.1.3. Unit tlll (coral-shell peat)

Most of the cores along the two transects penetrated a single coral-shell peat unit (Figs. 7 and 9). Within the small trench and piston cores, this layer consists of matrix supported, disorganized sand to cobble-sized coral clasts and randomly dispersed macerated shells within a matrix of reddish, fibrous mangrove sandy peat. We cannot discount the existence of larger coral fragments because the small diameter soil-probe and piston cores are unable to core material larger than the cores diameter such as large coral fragments. Unit tlll is characterized by the high and variable total carbonate, medium-high organic matter, and negligible magnetic susceptibility (Table 3; Fig. 8). In core TP-1, percent sand is higher in Unit tlll than in the sediment units above and below Unit tlll. In TP-2, Unit tlll is only slightly sandier than the units above and below Unit tlll. The latter observations regarding sand content affirm the contention that sand content is of limited value for identifying paleotsunami units in mangrove environments. The reason for sand's limited value is due both to bioturbation that dilutes the sand and the characteristically sandy environment that define mangrove settings, thus making a biotur-

bated event-sand indistinguishable from background sand content. We interpret Unit tlll as representing a pre-2004 tsunami deposit as detailed in the Results and discussion section.

4.1.4. Unit IV (peaty sand)

In 5 of the cores, Unit IV underlies Unit II (Fig. 9). Unit IV closely resembles the Unit II, but lacks abundant coarse woody material and abundant fine peat fibers. Consequently, Unit IV is characterized by the slightly lower average total organic matter than Unit II. Both total carbonate and magnetic susceptibility are low to negligible (Table 3; Fig. 8). Sand content is high. From these data, especially the absence of coarse woody material, Unit IV is interpreted to represent a successional pre-mangrove environment. This succession of depositional environments in response to falling sea level and progradation of the littoral zone is similar to that proposed for the Gulf of Thailand during the Holocene by Tanabe et al. (2003).

4.1.5. Unit V (sand)

There are several distinct, fine sand layers that appear in the sediment cores midway landward along the two transects (Fig. 9). For clarity, these sand layers are sub-divided into an upper unit and a lower unit. For example, core TP-1 contains 3 thin sand layers, which together comprise the upper unit; two thin sand layers comprise sand unit in core TP-1. Core TP-2 contains a thick upper sand unit while four thinner layers comprise the lower sand unit; TP-3 contains one thick upper unit and five variably thick lower unit sand layers (Fig. 9). On average the upper sand unit becomes thicker landwards (Fig. 9). The upper sand layers in TP-2 and TP-3 are unstructured with sharp upper and lower contacts; they contain variable amounts of shell fragments of sand to pebble size. Sedimentologically, Unit V is characterized by low, but variable magnetic susceptibility, low organic and low to negligible carbonate content (Table 3, Fig. 8).

Table 2

Locations of piston cores.

Core I.D.	UTM (WGS84)	Latitude	Longitude	Core length (cm)
TAPISTON06-1 (TP-1)	Zone: 47 Easting: 414002 Northing: 945692	8° 33' 16.370" N	98° 13' 6.759" E	549
TAPISTON06-2 (TP-2)	Zone: 47 Easting: 413985 Northing: 945620	8° 33' 14.025" N	98° 13' 6.207" E	443
TAPISTON06-3 (TP-3)	Zone: 47 Easting: 413910 Northing: 945662	8° 33' 15.387" N	98° 13' 3.751" E	456

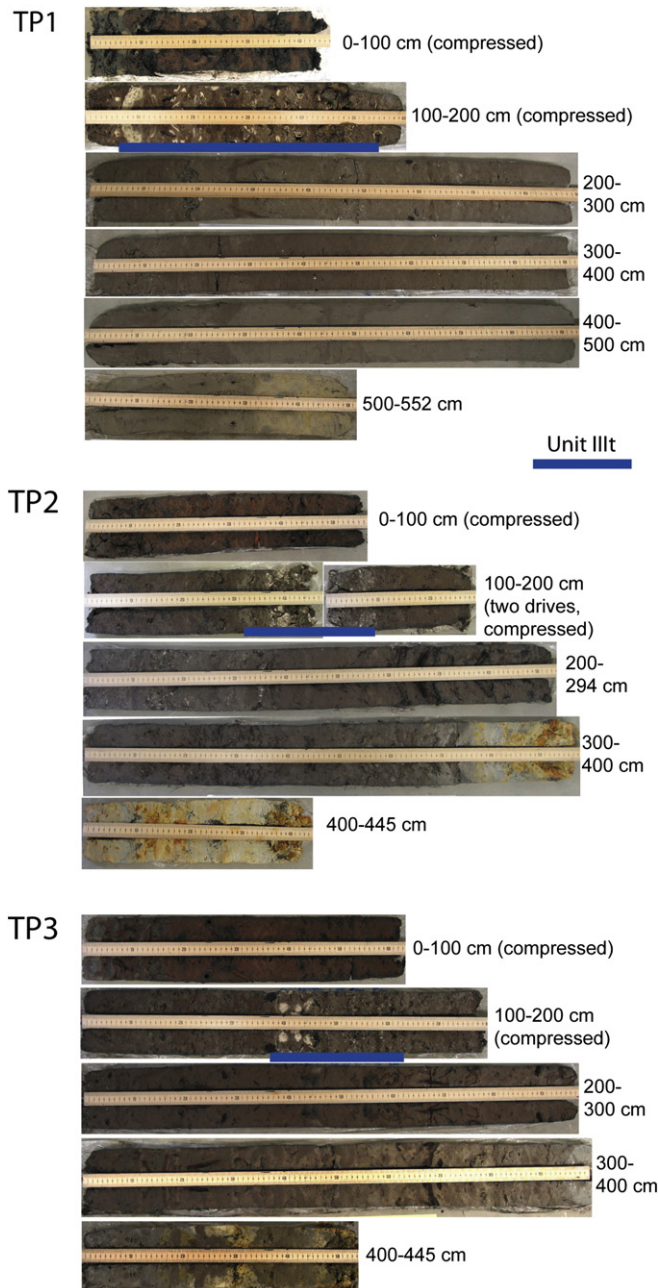


Fig. 7. Photos of the three piston cores collected at the Klong Thap Lamu study area. Locations of cores are shown in Fig. 3C. Scale is in cm. Note the location of the coral debris layer in core TP1 in the second row, in core TP2 spanning the two drives of the second row, and in core TP3 in the center of the second row. Note that all sections (rows) of the cores represent 100 cm precompaction.

Where sampled for grain size, the sand content is high. Core TP-1 and TP-2 show that Unit tIII is separated from Unit V by a thin but distinct intervening layer of Unit II or Unit VI. In no case, does Unit V overlie Unit tIII. In several cases, the upper sands of Unit V are located conformably beneath Unit tIII or are present in the absence of Unit tIII, especially landwards (Fig. 9). As a result, it is equivocal if Unit V represents a lateral continuation of Unit tIII landwards or if Unit tIII and the upper sands of Unit V represent two distinct layers that overlap spatially. It is equally possible that both the upper and lower sands of Unit V represent paleotsunami deposits or simply a sandy tidal channel that migrates across the tidal flat through time. As a result, the interpretation of Unit V remains questionable, and it is not considered in the Results and discussion as a paleotsunami layer.

4.1.6. Unit VI (sandy silt)

Thick gray sandy silt dominates the lower parts of cores nearer the modern tidal channel where it underlies the Unit II or tIII. Unit VI is characterized by second highest average magnetic susceptibility values, moderate organic content, high carbonate content, and moderate sand content (Table 3; Fig. 8). We interpret Unit VI as representing a lagoonal environment soon after the early-to-mid Holocene sea level highstand but before the encroachment of mangroves.

4.1.7. Unit VII (clay)

Unit VII, a light brown, sticky clay, is the basal unit in several cores (Fig. 9). Unit VII is characterized by the highest average magnetic susceptibility values, low organic content, and negligible carbonate content (Table 3; Fig. 8). The presence of angular rock fragments and high magnetic susceptibility are interpreted to represent the contribution of relatively unweathered bedrock, which we postulate underlies Unit VII. Overall, Unit VII is interpreted to represent a lowstand environment (inter-tidal?) before sea level attained its early-middle Holocene highstand ca. 7–8 cal kyr BP (Somboon and Thiramongkol, 1992). An age of 8110 cy BP in Unit VII at the base of TP-1 supports the latter interpretation (Fig. 9).

In summary, the general progression from Unit VI upwards to Unit II is interpreted to represent an environmental response to the early-to-late Holocene regional sea level regression like that recognized in the Gulf of Thailand (Sinsakul, 1992). A general increase in the thickness of Unit II (mangrove peat) along both transects from approximately 1 m near the edge of the pre-2004-tsunami shoreline to 2–3 m inland is consistent with a slowly prograding mangrove forest in response to a sea level regression (Fig. 9). The general increasing sand content trend in TP-1, lesser pronounced in TP-2, also support the progradation interpretation, which should result in an overall sandier environment as sea level falls and the beach front progrades across our core sites. Superimposed on this regressive sequence is Unit tIII, potentially the oldest yet identified paleotsunami in the region.

4.2. Unit tIII: A tsunami deposit?

Any explanation for the origin of Unit tIII must include a mechanism for depositing large (≤ 0.5 m diameter), angular, poorly sorted, coral clasts, various sized shell fragments, and sand into the low-energy environment of the mangrove swamp (Fig. 6). Because mangroves represent a formidable boundary to landward sediment transport, the mechanism required to explain the observations above is also likely rare and characterized by high energy (Thampanya et al., 2006; Teo et al., 2009; Yanagisawa et al., 2009). We offer two viable transport mechanisms: a large storm surge or tsunami wave. It is well documented that large storms are capable of mobilizing and transporting large quantities of sand and other marine detritus inland, even into mangrove environments (Turner et al., 2006; Wang and Horwitz, 2007; Nott et al., 2009; Smith et al., 2009). Thus, making the distinction between a storm deposit and tsunami deposit is a key to interpreting Unit tIII. A large and growing body of literature has discussed methods for distinguishing storm and tsunami deposits (Nanayama et al., 2000; Goff and McFadgen, 2004; Tuttle et al., 2004; Morton et al., 2007). Most comparisons rely on differences in the sedimentology, stratigraphy, and inland height and extent of the deposit. Severe bioturbation, however, characteristic of mangrove environments, makes the application of the recommended criteria untenable in application to Unit tIII because Unit tIII is diffuse and retains no demonstrable original internal stratigraphy. Research by Jankaew et al. (2008) on deposits from Koh Phra Thong Island, ~65 km north of Klong Thap Lamu, addresses the storm versus tsunami issue. They argue, based on modern climatology and historical storm tracks, that large storms are not a viable mechanism for mobilizing and transporting large quantities of sand and other marine detritus inland along Thailand's western coast. Large storms originating in the Indian Ocean move northwest away from Thailand's west coast,

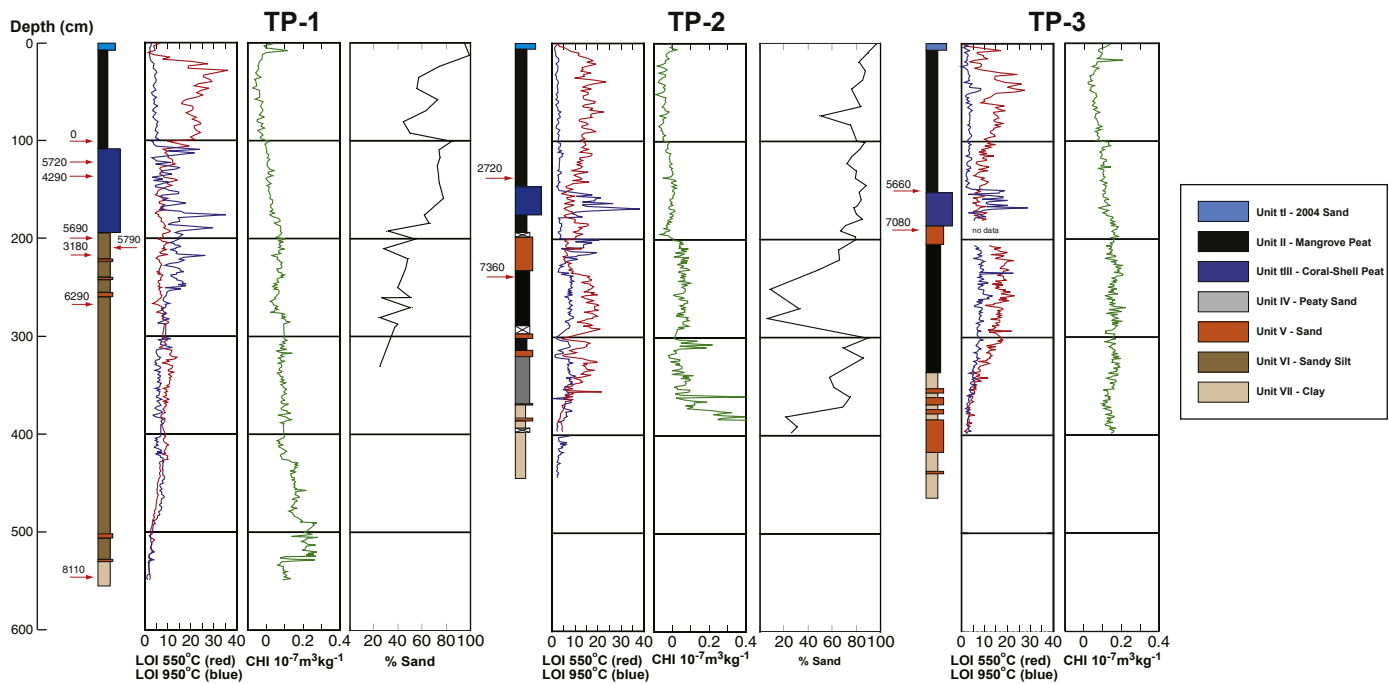


Fig. 8. Graphs showing loss-on-ignition (LOI) and magnetic susceptibility data. Left graphs show LOI at 550 °C (red) and 950 °C (blue) in percent. Magnetic susceptibility is shown on the right graphs in green. Also see Table 3.

while Pacific storms lose substantial strength crossing Thailand's peninsula. Similar to Jankaew et al. (2008), it is concluded, therefore, that a large storm is not a viable mechanism to explain Unit tIII.

If Unit tIII is not a storm deposit, is it a tsunami deposit? Again, the diffuse sedimentology of Unit tIII makes the application of recommended sedimentological criteria for demonstrating tsunamigenic origin ineffective (Morton et al., 2007). As a result, two different criteria are used to interpret Unit tIII: 1) stratigraphy, and 2) a modern analog approach.

Stratigraphically, it is important to demonstrate that Unit tIII is an event horizon and not a facies boundary associated with the regional early-to-late Holocene sea level regression (Tanabe et al., 2003). A key to interpreting Unit tIII lies in its relationship to Unit II, IV, and VI. In the most shoreward cores of both transects, the transition from Unit II to Unit IV or VI occurs either gradationally within, or at the base of Unit tIII. However, landward the Unit II/Unit IV & VI boundary underlies Unit tIII at an increasing depth (Fig. 9). Thus, Unit tIII cuts across the Unit II/Unit IV & VI boundary, which supports the statement that Unit tIII represents a time line or event horizon rather than an environmental facies boundary. We cannot completely discount the possibility that Unit tIII represents two or more "events", but if so, the time interval encompassing the multiple events must be much shorter than the time interval for the transgression of the mangrove environment (unit II) across the study area.

Having interpreted Unit tIII as an event horizon, it is necessary to determine the "event" responsible for its deposition. Here, the modern analog approach is used. There are several distinct similarities between Unit tl and Unit tIII. First, both units are characterized by angular, poorly sorted, coral clasts and various sized shell fragments (Figs. 6 and 7). Although the diffuse nature of Unit tIII makes it difficult to visually compare the sandiness of Unit tIII to Unit tl, quantitative grain size data proves that both Unit tl and tIII are sand rich and sandier than the units above and/or below (Fig. 8). Due to the dilution of sand by bioturbation, Unit tl is characterized by higher sand content than Unit tIII. The absence of angular, poorly sorted, coral clasts in any of the other units, excepting Unit tl, suggests a special mechanism for transporting off shore coral material into the

mangrove environment. As previously stated, the 2004 tsunami impacted the coral reefs along Thailand's west coast with various magnitudes (Phongsuwan and Brown, 2007; Chavanich et al., 2008). Therefore, it is reasonable to assume that older tsunami events would likewise impact the coral reef systems along Thailand's west coast. Like the proposed 2004 tsunami origin for the coral in Unit tl (Fig. 6), it is inferred by the modern analog approach that the coral in Unit tIII was similarly transported inland by a tsunami wave – the same line of reasoning is assumed for the shell material in Unit tIII. There is, however, one obvious difference between Unit tl and Unit tIII that requires an explanation – Unit tIII is much thicker than Unit tl. The most plausible explanation is the reworking of sediment through bioturbation over time. Like Unit tl, it is thought that Unit tIII was deposited as a much thinner layer of angular, poorly sorted, coral clasts, various sized shell fragments, and sand across the floor of a Holocene mangrove forest. Subsequent burial, decay of the destroyed mangroves, bioturbation by crabs and roots in the subsequently recovered mangroves, and tidal currents should mix the coral clasts, shell material and sand thoroughly with the enclosing mangrove peat. The result is diffuse peat-matrix-supported layer much thicker than the original deposit with dispersed angular coral fragments, shell material, and diffuse sand. The coral fragments are reduced in size due to weathering that is facilitated by mangrove roots (rootlets occur within many of the Unit tIII coral fragments suggesting they facilitated the weathering of the coral). Second, both Unit tl and Unit tIII are spatially congruent. The spatial congruence of Unit tl and Unit tIII within the same wide zone of destroyed mangrove forest is a potential evidence for a similar origin, possibly representing earthquakes of similar magnitude. Third, because Unit tIII is an event horizon and a storm origin is unlikely, the deposition of Unit tIII requires an alternative explanation – an explanation characterized by low recurrence intervals and high energy. It is concluded that in the absence of a storm explanation, a tsunamigenic origin is the best alternative explanation, particularly in the context of the similarities between Unit tl and Unit tIII (see reason #2 above). Fourth, the "best-age" for Unit tIII is similar to (i.e. brackets) a tsunami event age identified along the southeastern tip of India dated at 3710 years

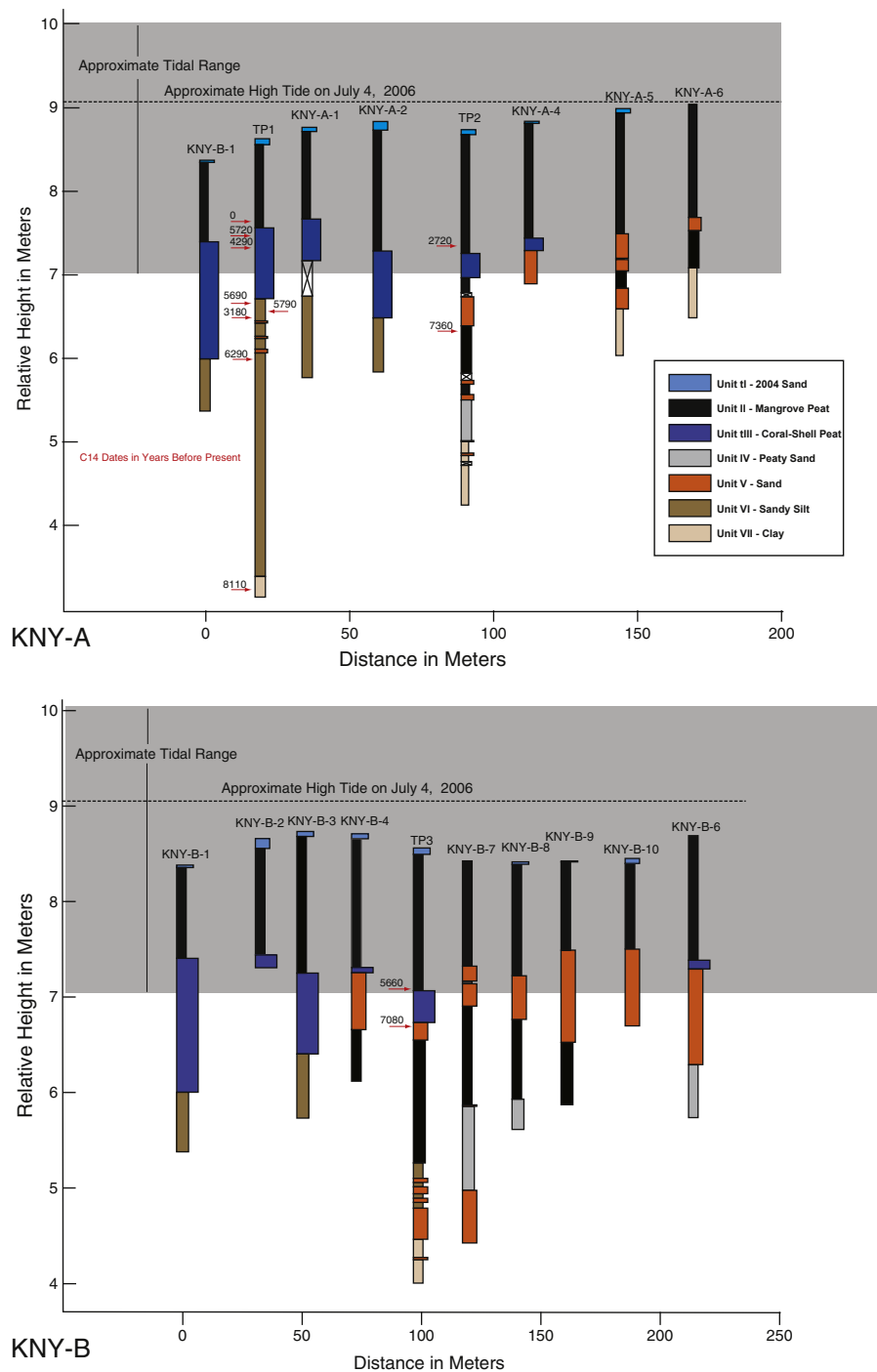


Fig. 9. Correlation of cores along two transects at Klong Thap Lamu, see Fig. 3C for locations. TP1–3 are piston cores, other cores were described in the field. The two transects intersect at the first core. Both transects trend inland away from the tidal channel to the right. Cores are positioned vertically relative to the high-tide line marked on the diagram. Relative vertical elevations of the top of each core were surveyed using the relative water level as the tide rose. Red arrows mark locations of 14 C dates in years before present (see Table 4).

before present using OSL (Nair et al., 2010). Although chronological similarity is perhaps the least convincing evidence, the similar ages across the Indian Ocean support a tsunami origin rather than a storm origin for this mid-Holocene event horizon.

4.3. Chronology

In an attempt to bracket the age of Unit tIII, we collected 12 samples from our 3 piston cores for AMS ^{14}C dating (Table 4). Samples were selected from various depths including from above and below

Unit tIII (Fig. 8). The materials dated include a variety of bark, wood, and twig fragments. From within Unit tIII, a shell and piece of coral were dated. All ages are calibrated to calendar years before present using the radiocarbon calibration program CALIB 5.0.2, except for the two reservoir-corrected ages below, which we acquired later and subsequently calibrated using CALIB 6.0 (Stuiver et al., 2005). The shell and coral fragment were corrected for a marine reservoir effect using the local reservoir correction for the eastern Indian Ocean (Nicobar Islands) (<http://calib.qub.ac.uk/marine/> [Calib 6.0]); (Southon et al., 2002).

Table 3
Lithostratigraphic unit sedimentology and interpretation.

Lithostratigraphic unit	Description	Magnetic susceptibility	LOI 550 °C	LOI 950 °C	Interpretation
Unit tI – 2004 Sand	greenish gray fine to very fine quartz sand, few grains of medium sand, sub-angular to sub-rounded, broken shells, trace mica flakes	0.00 ± 0.02	6.62 ± 4.03	1.77 ± 0.87	2004 tsunami deposit
Unit II – Mangrove peat	abundant coarse fibers of peat, many modern roots, high organic content, matrix is fine sand and silt	0.01 ± 0.05	15.25 ± 4.65	4.16 ± 3.90	mangrove swamp
Unit tIII – Coral-shell peat	gravel clasts mostly matrix supported – maybe clast supported at top – coral decreases downward and fines downward, matrix maybe peat, sandy peat, peaty sand, or sand, strongly bioturbated, large macerated shell fragments	0.02 ± 0.02	7.82 ± 2.08	10.75 ± 6.72	paleotsunami deposit
Unit IV – Peaty sand	sandy matrix, grayish brown to dusky brown, small pieces of bark and wood fragments common, small to moderate amounts of peaty fibers, locally contains small pebbles of quartz	0.07 ± 0.07	10.92 ± 4.61	2.93 ± 1.60	successional pre-mangrove environment
Unit V – Sand	medium to fine sand, contains sand to pebble sized shell fragments, no coral fragments, clast supported, may or may not contain small amounts of peaty fibers	0.07 ± 0.11	5.70 ± 2.38	4.69 ± 4.74	tidal channel deposit ± paleotsunami deposit(?)
Unit VI – Sandy silt	silt with medium to fine sand, contains sand to pebble sized shell fragments, no coral fragments, clast supported, may or may not contain small amounts of peaty fibers	0.11 ± 0.05	7.30 ± 2.52	7.72 ± 3.39	lagoonal environment
Unit VII – Clay	grayish orange light brown to moderate reddish brown mottled, contains pieces of angular rock fragments, black organic fragments	0.67 ± 0.87	4.53 ± 4.34	2.29 ± 1.34	inter-tidal? pre-Holocene highstand?

The base of TP-1 is dated at 8110 cy BP. This date reflects sedimentation either at the onset of, or just before, the early Holocene sea level maximum along the Andaman coast (Sinsakul, 1992). All ages exceed 3180 cy BP at depths below Unit tIII (Fig. 8). Three dates from just above Unit tIII range from 0 to 5660 cy BP. The modern date (from the 104–105 cm level of core TP-1) demonstrates the impact of bioturbation by the mangrove root system and its ability to confound dating efforts. From within Unit tIII in TP-1, a coral fragment at 115–118 cm dated 5720 cy BP; a shell at 130 cm depth yielded an age of 4290 cy BP (Fig. 8).

Despite the obvious impact of bioturbation on the overall age-depth stratigraphy, there is meaningful information to extract from these dates. First, the buried coral-shell peat unit (Unit tIII) is clearly not the same age as the 2004 AD tsunami. Dates significantly older than 2004 AD as well as a thick sedimentary unit (Unit II) separate Unit tIII from Unit tI (Figs. 5 and 6). Second, Unit tIII is likely not younger than 2720 cy BP and not older than 7080 cy BP based on upper and lower bracketing ages (Fig. 6). The modern age in TP-1 above Unit tIII is assumed too young and the result of dating a modern root. Third, based on reasoning discussed below, the maximum age for

Unit tIII can be further narrowed to likely no older than 4290 cy BP (Fig. 6). Fourth, combining the upper minimum bracketing age and the shell age from within Unit tIII provides a “best-estimate” age range for the event of ≥ 2720 and ≤ 4290 cy BP.

How did we reason this “best-estimate” conclusion? Normally, events, for example storm layers in lake basins, are dated by obtaining a date above and below the event unit (Bird and Kirby, 2006). The extensive root system, however, of the mangrove environment make this bracketing method less reliable because dateable organic material (e.g. roots, leaves, sticks) are easily displaced from stratigraphic order by root action. The range of dates from above Unit tIII and below Unit tIII clearly demonstrate the difficulty with using bracketing ages as the sole source for determining an event's age in mangrove environments (Fig. 9). An alternative method for dating events is to obtain ages from the event unit itself. Several researchers have proposed that under the right depositional circumstances, age data using organic material found within a tsunami layer is considered the most reliable estimate of the tsunami's age (Benson et al., 1997; Nanayama et al., 2007; Scheffers et al., 2008). Considering the latter method, a shell and coral fragment from within Unit tIII were dated. The rationale for dating

Table 4
Radiocarbon data.

Number	Core ID	Depth interval (cm)	Material dated	¹ UCIAMS#	¹⁴ C Age (BP)	Calendar years BP	2-Sigma range
1	TAP-1*	104–105	bark fragment	26246	– 35 ± 20	0	NA
2	TAP-1^	115–118	coral fragment	45295	5360 ± 20	5720	5567–5875
3	TAP-1^	130	shell	45296	4235 ± 20	4290	4083–4491
4	TAP-1*	155–156	bark fragment	26247	4965 ± 20	5690	5644–5740
5	TAP-1*	201–202	twig fragment	26248	5065 ± 20	5790	5747–5834
6	TAP-1*	212–213	bark fragment	26249	2985 ± 20	3180	3101–3250
7	TAP-1*	258–259	twig fragments	26250	5465 ± 20	6290	6268–6302
8	TAP-1*	527–528	bark fragment	26251	7310 ± 20	8110	8039–8176
9	TAP-2*	127–128	bark fragment	26252	2550 ± 20	2720	2698–2747
10	TAP-2*	238–239	bark fragment	26253	6460 ± 20	7360	7323–7403
11	TAP-3*	137–139	wood fragment	26254	4940 ± 20	5660	5607–5716
12	TAP-3*	164–165	bark fragment	26255	6165 ± 20	7080	6999–7160

*Calib Rev 5.0.2 (Stuiver et al., 1995).

^Calib Rev 6.0 marine reservoir corrected (Stuiver et al., 1995).

¹University of California, Irvine Accelerator Mass Spectrometry Laboratory ID Number.

shell and coral material is that both were previously alive and subsequently washed ashore during the tsunami event. Obviously, the 1500 year difference between the coral and shell ages suggests that one of the two was not alive prior to transportation. Because it is not possible for an older event (i.e. coral age of 5720 cy BP) to entrain younger material (i.e. a shell that did not yet exist [4290 cy BP]), it is concluded that the event is no older than 4290 cy BP and that the coral represents previously dead coral material entrained during the Unit tIII event. As a result, we use the shell age of 4290 cy BP as the maximum age for Unit tIII. It is important to note that coral reefs are subject to regular disturbance from wave action (Perry, 2001; Fabricius et al., 2008). Consequently, it is not unreasonable to assume that the older coral age represents previously destroyed/dead coral that was mobilized inland during the Unit tIII tsunami event. The upper bracketing age (i.e. minimum age) is admittedly less well constrained. Three dates were obtained from directly above Unit tIII: modern, 2720, and 5660 cy BP. The modern age is considered too young and the product of dating a modern root, which is reasonable based on the observation of live roots at ≥ 1 m depth, during the excavation of a trench. The older age of 5660 contradicts the shell age obtained within Unit tIII and is therefore considered too old and potentially representative of pre-Unit tIII mangrove material transported ashore during the Unit tIII event, and subsequently reworked. By default, an age of 2720 cy BP remains and is therefore considered a possible minimum bracketing age. It is clear from our age data that dating events in a mangrove environment is challenging. Nonetheless, we conclude that the best-estimate age range for Unit tIII is ≥ 2720 and ≤ 4290 cy BP. We stress, however, that an absolute date is not required to test our hypothesis that a paleotsunami record is preserved in the sediments of a mangrove environment.

4.4. Summary

A detailed analysis of sediment cores from a modern mangrove environment along the northern Andaman Coast of Thailand in Klong Thap Lamu resulted in several conclusions.

- 1) In response to the regional early-to-late Holocene sea level regression sediments from the Klong Thap Lamu site change from a pre-highstand inter-tidal environment upwards into the modern mangrove environment.
- 2) Superimposed on this regressional sedimentary sequence is Unit tIII – a diffuse sandy peat matrix supported layer much thicker than the original deposit with dispersed angular coral fragments (smaller than original due to weathering), shell material, and diffuse sand. Similarities to Unit tI (the 2004 tsunami deposit) as well as the absence of a viable alternative for its origin (e.g. storm surge) make a tsunami origin the most likely mechanism to explain Unit tIII.
- 3) Radiocarbon dates on shell and coral material from within Unit tIII combined with an upper bracketing age suggest that the tsunami event occurred sometime between ≥ 2720 and ≤ 4290 cy BP. If we are correct, this tsunami predates the 3–4 tsunami events recognized to the north at Koh Phra Thong (Jankaew et al., 2008; Fujino et al., 2009).
- 4) Unit tIII is a potential far-field equivalent of a recently recognized tsunami event deposit on the southwestern Indian coast ca. 3710 years before present (Nair et al., 2010).
- 5) Addressing the original hypothesis, mangrove environments are potential sites for preserving paleotsunami sediment and should be considered as viable archives elsewhere as scientists seek to reconstruct the history of past tsunami events.

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