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Stratigraphic evidence for an early Holocene earthquake in Aceh, Indonesia

Candace A. Grand Pre [a,b], Benjamin P. Horton [a,*], Harvey M. Kelsey [c], Charles M. Rubin [d], Andrea D. Hawkes [e], Mudrik R. Daryono [f], Gary Rosenberg [g], Stephen J. Culver [h]

[a] Sea Level Research, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA 19104, USA
[b] Earth and Environment, Franklin and Marshall College, Lancaster, PA 17603, USA
[c] Department of Geology, Humboldt State University, Arcata, CA 95521, USA
[d] Earth Observatory of Singapore (EOS), Nanyang Technological University, Singapore
[e] Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[f] Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung, Indonesia
[g] Department of Malacology, The Academy of Natural Sciences, Philadelphia, PA, USA
[h] Department of Geological Sciences, East Carolina University, Greenville, NC 27858, USA

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ABSTRACT

The Holocene stratigraphy of the coastal plain of the Aceh Province of Sumatra contains 6 m of sediment with three regionally consistent buried soils above pre-Quaternary bedrock or pre-Holocene unconsolidated sediment. Litho-, bio-, and chronostratigraphic analyses of the lower buried soil reveals a rapid change in relative sea-level caused by coseismic subsidence during an early Holocene megathrust earthquake. Evidence for paleoseismic subsidence is preserved as a buried mangrove soil, dominated by a pollen assemblage of *Rhizophora* and/or *Bruguiera/Ceriops* taxa. The soil is abruptly overlain by a thin tsunami sand. The sand contains mixed pollen and abraded foraminiferal assemblages of both offshore and onshore environments. The tsunami sand grades upward into mud that contains both well-preserved foraminifera of intertidal origin and individuals of the gastropod *Cerithidea cingulata*. Radiocarbon ages from the pre- and post-seismic sedimentary sequences constrain the paleoearthquake to 6500–7000 cal. yrs. BP. We use micro-and macrofossil data to determine the local paleoenvironment before and after the earthquake. We estimate coseismic subsidence to be 0.45 ± 0.30 m, which is comparable to the 0.6 m of subsidence observed during the 2004 Aceh–Andaman earthquake on Aceh's west coast.

1. Introduction

On December 26th, 2004 a 1600 km segment of the Sunda megathrust ruptured, producing the 9.2 Mw Aceh–Andaman earthquake. This was one of the largest earthquakes in recorded history, generating a tsunami that devastated south and southeast Asia (Subarya et al., 2006; Chlieh et al., 2007). Before the Aceh–Andaman earthquake, Sieh et al. (1999) provided proxy data from corals concluding that active interseismic strain accumulation is occurring on the southern reach of the Sunda megathrust. Further, using coral records of sea-level change, Zachariasen et al. (1999, 2000) and Natawidjaja et al. (2006) demonstrated that great megathrust earthquakes have occurred across the southern portion of the Sunda subduction zone over the past thousand years. However, there was no historical precedent for great earthquakes along the northern portion of the Sunda Trench, where the 2004 earthquake ruptured (Briggs et al., 2006).

Despite this lack of historical documentation, the coastal lowlands in the vicinity of the Sunda megathrust contain geologic evidence for prehistoric earthquakes. For example, late Holocene paleotsunami have been inferred as the depositional agents of sand sheets within the beach ridge plains of Thailand (Jankaew et al., 2008) and northern Sumatra (Monecke et al., 2008). Here, we provide geological evidence of early Holocene coseismic subsidence across the coastal lowland of the Aceh Province, an area located off the northern portion of the Sunda trench (Fig. 1).

Geologic evidence of coseismic subsidence and interseismic uplift can be recognized in stratigraphic sequences preserved in some coastal environments on the upper plate of a convergent margin (Atwater and Hemphill-Haley, 1997). In such locations interseismic uplift is identified as a gradual fall in relative sea level (RSL). Coseismic subsidence, caused by a rupture on the subduction zone, is recognized in the stratigraphic record as a rapid rise in RSL (Nelson et al., 1995). Coseismic subsidence is commonly identified in coastal environments at the contact between a buried soil, which accumulates during the interseismic period, and an overlying mud sequence, which is deposited after rapid coseismic subsidence

* Corresponding author. Tel.: +1 215 573 5388; fax: +1 215 898 5724.
E-mail address: bphorton@sas.upenn.edu (B.P. Horton).

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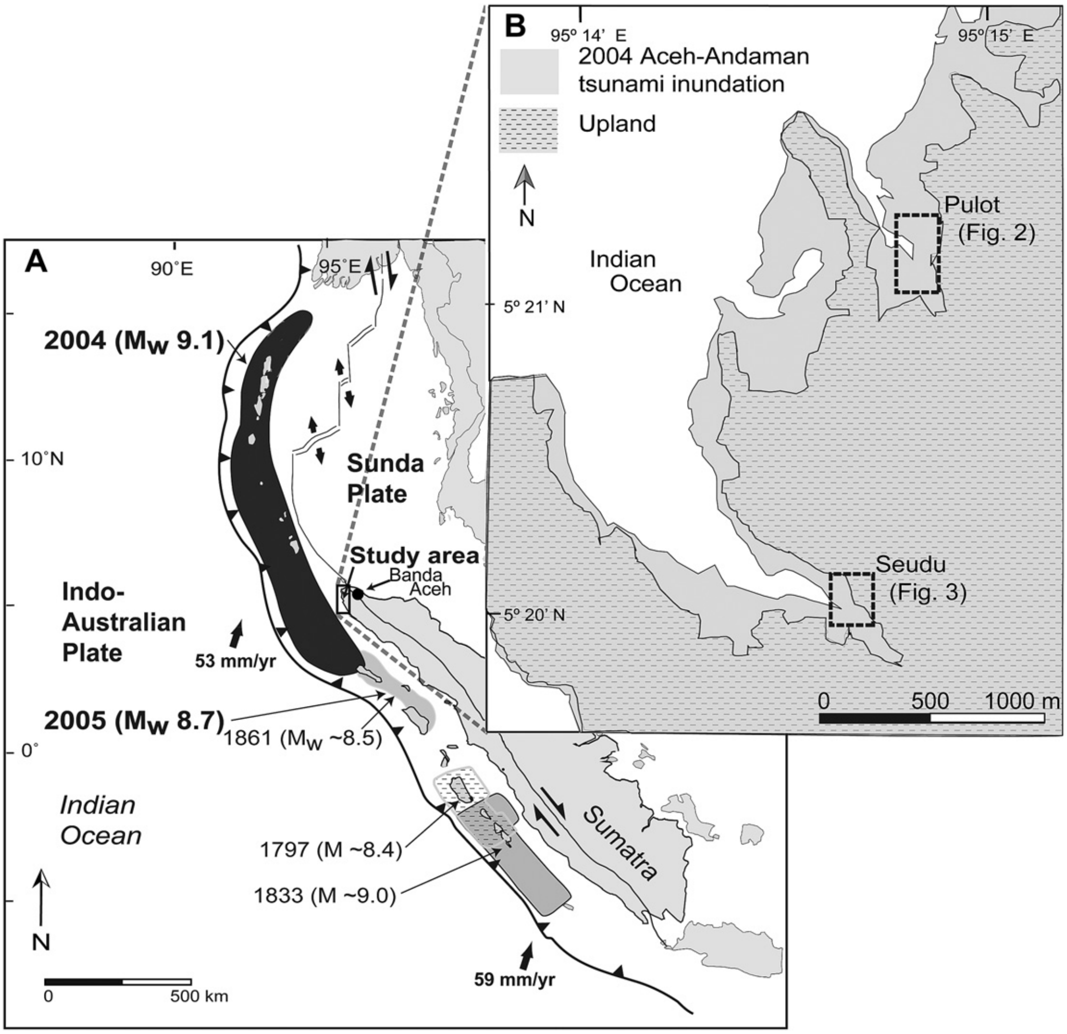

Fig. 1. (A) Regional map of the 26 December 2004 rupture and other large ruptures along the Sunda megathrust (Curray, 2005; Lay et al., 2005; Briggs et al., 2006; Chlieh et al., 2007). The Indo-Australian and Sunda relative plate motions are from Prawirodirdjo and Bock (2004). The fault map is generalized from Curray (2005) and the 2004 Aceh–Andaman slip patch extent (black shading) is from Chlieh et al. (2007). The slip patches for the 1833 (light gray shading) and 1797 (stippled pattern) earthquakes are from Natawidjaja et al. (2006) and Briggs et al. (2006). The slip patch for the 2005 and 1861 (lightest gray shading) are from Briggs et al. (2006). (B) Study region 20 km southwest of Banda Aceh, the provincial capital of Aceh Province.

(Nelson et al., 1996). Subsidence in these coastal environments creates accommodation space, which allows for the deposition of transgressive lithologic sequences. A megathrust earthquake can also produce a tsunami, and tsunamigenic sediment may be deposited between the interseismic buried soil and the post-seismic muds (Nelson et al., 1996; Shennan and Hamilton, 2006).

Although lithostratigraphic transitions in cores may suggest an environmental change induced by a RSL change (for instance, flooding will change a freshwater marsh to an intertidal environment), it is through the use of biostratigraphy that transitions between different environments can be documented and the amount of subsidence or uplift can be quantified (Shennan and Hamilton, 2006; Hawkes et al., 2011). In the temperate environments of Cascadia, Chile, Alaska and Japan, microfossils (diatoms, foraminifera and pollen) have been extensively used to identify soil-mud couplet sequences and infer the amount of coseismic subsidence (Sawai et al., 2004; Cisternas et al., 2005). In this study, we investigate the coastal evolution of the Aceh Province using litho- and chronostratigraphic techniques. We also introduce a multi-proxy biostratigraphical methodology using pollen, gastropods, and foraminifera to confirm that in tropical coastal environments, despite relatively higher levels of bioturbation and diagenesis (Berkeley et al., 2007), we can identify geologic evidence of prehistoric great earthquakes, which are similar to the 2004 Aceh–Andaman earthquake. Further, using these techniques, we are able to quantify the amount of coseismic subsidence that occurred with these prehistoric earthquakes.

2. Study area

We selected two field sites in coastal northern Sumatra to identify stratigraphic evidence of prehistoric earthquakes. Sumatra, located on the southeast Asian plate, is 150–200 km west of the Sunda Trench (Fig. 1A). Recent continuous-GPS geodesy shows that oblique convergence in the northern reach of the Sunda trench, from northern Sumatra to Burma/Myanmar, is 53 mm/yr (Prawirodirdjo and Bock, 2004). This portion of the subduction zone ruptured in the 2004 Aceh–Andaman Earthquake (Meltzner et al., 2006). Historical evidence suggests several smaller earthquakes (7.9 > Mw < 9.0) occurred north of the 2004 Aceh–Andaman epicenter including earthquakes in 1847, 1881, and 1941 along the Nicobar–Andaman plate boundary (Bilham et al., 2005; Subarya et al., 2006). To the south the convergence is nearly perpendicular to the trench and faster at 59 mm/yr (Prawirodirdjo and Bock, 2004). Here, the most recent great earthquake occurred in 1833 along the southern portion of the Sunda megathrust and produced a ca M 9.0 earthquake (Fig. 1) (Sieh et al., 1999; Zachariasen et al., 2000; Natawidjaja et al., 2004; Bilham et al., 2005; Briggs et al., 2006).

Sumatra is defined as a far-field region in studies of Holocene sea-level change because it is distant from Northern Hemisphere ice sheets (Clark et al., 1978). In such regions-RSL rose rapidly during the early Holocene to a highstand that varies in timing and magnitude (Mitrovica and Milne, 2002; Milne et al., 2005). In southeast Asia, RSL rose at ca 5.5 mm/yr to the highstand that occurred between 7000 and 3000 cal. yrs. BP with a magnitude of 2–6 m (Horton et al., 2005a). RSL then fell from the highstand during the late Holocene at a rate of ca 1.1 mm/yr (Mitrovica and Milne, 2002; Milne et al., 2005).

Our study focused on coastal freshwater lowlands 20 km south-southwest of Aceh (Fig. 1B). We investigated satellite imagery, air photographs, geological and topographical maps to determine the key areas for field examination. We conducted a 25 km reconnaissance survey along the west coast of Aceh Province that revealed a stratigraphically consistent sequence of buried soils. For detailed analysis, we focused on two field sites within the study area, Pulot and Seudu, which are protected from open-ocean wave attack and have minimal fluvial input from local streams (Fig. 1B). The Pulot study area is 500 m inland from the coastal village and is located on an emergent floodplain between 1 and 2 m above modern mean tidal level (MTL). Seudu provides supporting stratigraphical data and is located 2.5 km south of Pulot (Fig. 1B) and at the landward edge of an embayment (Fig. 1B). The Seudu coring locations were in former shrimp ponds, abandoned after the 2004 earthquake. Farmers had modified this land to be suitable for shrimp aquaculture, disrupting and reworking the sediment to a depth of ca 1 m. The surface elevations are between ca −0.5 and 0.5 m MTL. Along the Pulot and Seudu section of the Sumatran coast tides are mixed (*i.e.,* the daily tides consist of two high and two low waters that are not of equal amplitude) with a mean tidal range of 0.6 m.

3. Methods

3.1. Core selection

At both Pulot and Seudu, we examined the stratigraphy in cores taken along intersecting transects (Fig. 2). Cores were collected with a 25 mm diameter, half-cylinder gouge corer. The cores were logged to depths of 1–6 m along the transects in order to test for lateral continuity of lithologic units. Soils were described in the field using the Troels-Smith (1955) method for the description of organic-rich sediment. We use the term “soil” for dark horizons where visible woody and herbaceous fragments and humified organic matter made up at least 10–20% of the lithologic unit. The overlying mud and sand was distinguished by its lack of organic matter, a change in color to gray or brown-gray and clay to sand mineral content. Using methods adapted from Kelsey et al. (2002), the soils were correlated on the basis of depth below ground surface, lithostratigraphy, stratigraphic separation and the thickness of sediment from the top of one buried soil to the next.

We used a digital auto-level to establish core elevations. Survey closure error for the survey of core elevations and coastal profile

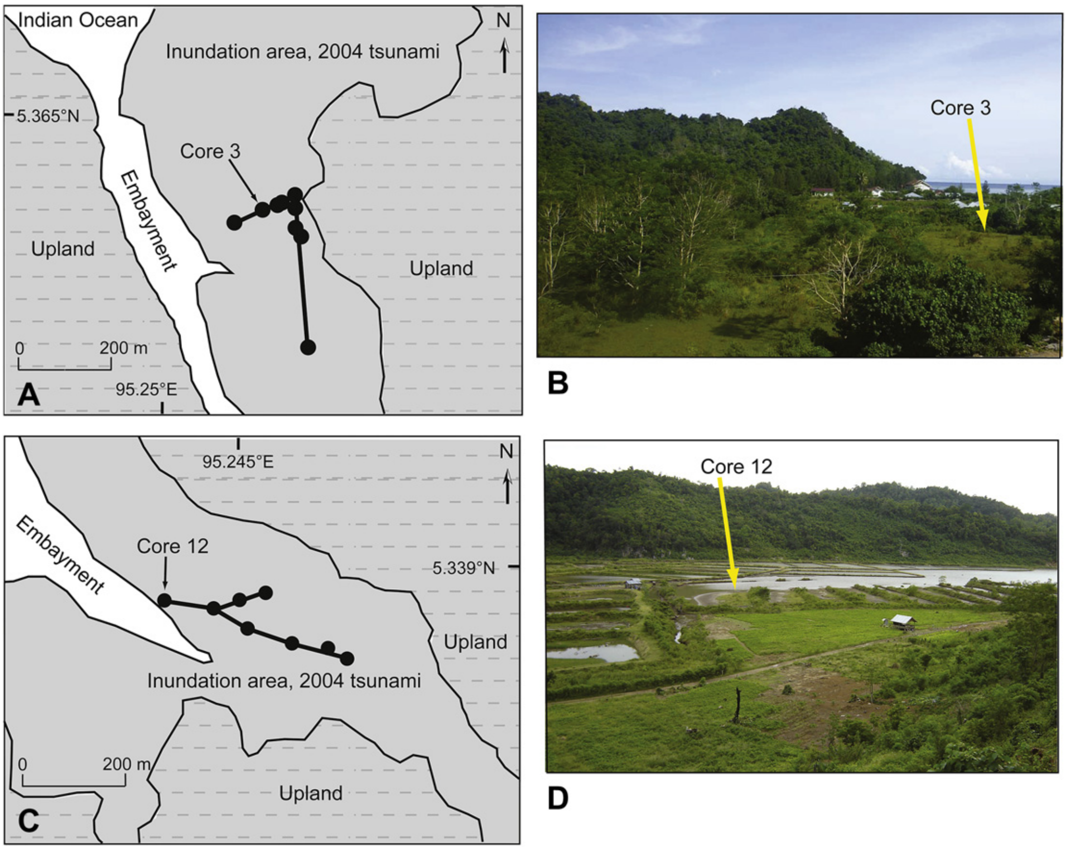

Fig. 2. (A) Map of the field site at Pulot. The Pulot cores (black filled circles, Fig. 3) were taken from a 200 × 400 m area along two transects within the inundation area of the 2004 Aceh–Andaman tsunami. (B) Photograph of the Pulot field site in the river lowlands taken from the road, looking northwest over the study area. (C) Map of the field site at Seudu. The Seudu cores (black filled circles, Fig. 4) were taken from a ca 200 × 400 m field area along two transects within the inundation area of the 2004 Aceh–Andaman tsunami. (D) Photograph of the Seudu field site taken from the road looking southwest over the study area.

elevations was less than or equal to 0.05 m. We related these elevations to local MTL, determined by hourly surveys of local tidal levels.

We selected the lower buried soil from two cores (core 3 from Pulot and core 12 from Seudu) for further stratigraphical analysis. We used micro- and macrofossil data, specifically pollen, foraminifera and gastropods, to reconstruct former paleoenvironments and RSL changes associated with coseismic subsidence during great earthquakes.

3.2. Pollen

Pollen is a widely used paleoenvironmental proxy on passive (e.g., Godwin, 1940; Tooley, 1978) and active (e.g.,Long and Shennan, 1994; Hughes et al., 2002; Zong et al., 2003) coastlines. Pollen assemblages are indicative of coastal vegetation, which varies with changes to the inundation period, salinity and pH of the environment (Erdtman, 1952; Brush and DeFries, 1981). Hughes et al. (2002) and Engelhart et al. (2007) suggested that modern distributions of salt marsh and mangrove pollen are zoned relative to the tidal frame, thereby implying they are a suitable sea-level indicator. Furthermore, pollen is a robust microfossil due to its thick exine surface, which is made from sporopollenin (Zetzsche, 1932). This attribute is vital for paleoenvironmental reconstructions in tropical environments, where preservation of microfossils such as diatoms and foraminifera can be compromised (Berkeley et al., 2007). For example, we found no foraminiferal tests or diatom frustules in the mangrove soils of Aceh province (Grand Pre, 2011).

Pollen slides were prepared for taxonomic identification following standard methods (Traverse, 1988; Willard et al., 2003). A *Lycopodium* tablet was added to each sample as an aliquot to calculate concentrations. Each sample was treated with hydrochloric acid to remove the carbonate fraction then neutralized and acetolyzed in a hot water bath for 10 min. Samples were washed to a neutral pH and treated with potassium hydroxide and sieved with 10 and 150 μm sieves to remove the clay and coarse fractions. The remaining material was stained with Bismark Brown, mounted with glycerin jelly, and counted under light microscopy. Identifications were compared to plates and descriptions in Grindrod (1985), Thanikaimoni (1987), Yulianto et al. (2005), and Engelhart et al. (2007). The genera *Bruguiera* and *Ceriops* could not be separated and were grouped together (e.g., Grindrod, 1985). The environmental interpretations of the pollen were based on the studies of Horton et al. (2005a), Yulianto et al. (2005) and Engelhart et al. (2007).

3.3. Foraminifera

Calcareous foraminifera are present in mud and sand units and are used to reconstruct the tidal flat to inner shelf depositional environments. The distribution of foraminiferal species in these environments will vary from site to site (e.g., Culver and Buzas, 1980), nevertheless, relatable patterns are well developed and relatively easily recognized (Hayward et al., 1999). Furthermore, quantitative approaches have been employed to delineate finer zonation schemes from benthic foraminifers (e.g., Culver, 1988; Horton et al., 2007; Rossi and Horton, 2009; Woodroffe, 2009).

To prepare the foraminifera we concentrated samples using a polytungstate flotation technique (Munsterman and Kerstholt, 1996) and picked 300 individuals when possible (Buzas, 1990). Individuals were identified to the genus or species level. We confirmed identifications by comparison with primary type and figured specimens at the Natural History Museum, London and in the Cushman Collection at the Smithsonian Institution, Washington, D.C. Environmental interpretations of the foraminifera were based on the studies of Loeblich and Tappan (1994), Wang and Chappell (2001), Horton et al. (2003, 2005b, 2007), Berkeley et al. (2007) and Woodroffe (2009).

We used a stratigraphically constrained CONISS (Grimm, 1987) cluster analysis on the combined foraminifera and pollen taxa to produce a nested series of clusters represented as a hierarchy or dendrogram (Prentice, 1986). Constrained analysis specifies that clusters consist of contiguous samples. Only taxa that comprised 5% or more in any sample were included in the analysis. The data were transformed to normalized chord distances and the dendrogram was scaled as total sum of squares. The analysis was performed in TGView (ver. 2.0.2) (Grimm, 2004).

3.4. Gastropods

Macrofossils of intertidal and marine invertebrates can also be used to reconstruct changes in paleoenvironment (e.g., Laborel et al., 1994; Pirazzoli et al., 1996; Lambeck et al., 2004). Gastropod shells and shell hash of *Cerithidea cingulata* was found in the Pulot and Seudu cores. Identification of *C. cingulata* was confirmed by comparison with materials from the Academy of Natural Sciences, Philadelphia, Pennsylvania. Environmental interpretations of *C. cingulata* were based on the studies from Vohra (1970), Rao and Sukumar (1981, 1982), Houbrick (1984) and Reid et al. (2008).

3.5. Radiocarbon dating

Plant macrofossils were collected where possible from the upper centimeters of the lower soil to provide maximum limiting radiocarbon age of soil burial. If two or more calibrated radiocarbon ages are available, we report the youngest age range as the closest approximation to the time of soil burial. The timing of soil burial was calculated from calibrated radiocarbon ages using CALIB (ver. 6.0) (Stuiver and Reimer, 1993) software with the IntCal09 data set of Reimer et al. (2009). The samples were analyzed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) in Woods Hole, MA (Table 1).

C. cingulata gastropods were collected from the sandy mud unit, overlying the lower buried soil, to provide minimum limiting radiocarbon ages on soil burial. We calculated ΔR, a regional correction to the globally averaged marine reservoir effect Reimer et al. (2009) by measuring the ^{14}C age of ten individual *C. cingulata*

Table 1
Radiocarbon ages for the middle and lower buried soils of Pulot and Seudu.

Core ID	Sample ID	Lab code	Core depth (m)	$\delta^{13}C$	^{14}C BP (1σ)	Cal. yrs BP (2σ)[a]	Material
Pulot[b] (C4)	PU07C04265	Beta-236194	2.65–2.66	−28.3	5090 (±) 40	5740–5920	Wood
Pulot (C3)	PU07C03410	OS-79207	4.10–4.12	−7.15	5770 (±) 30	5890–6410	Gastropod, *Cerithidea cingulata*[c]
Pulot (C3)	PU07C03426	Beta-236192	4.26–4.27	−25.8	6060 (±) 40	6790–7140	One black wood fragment
Pulot (C3)	PU07C03437	Beta-236193	4.37–4.38	−26.5	6160 (±) 40	6950–7170	One black wood fragment
Seudu (C12)	PF07C12467	Beta-236191	4.67–4.68	−28.2	6690 (±) 50	7470–7660	12 black wood fragments

[a] Dates are calibrated using the IntCal09 and Marine09 data sets of Reimer et al. (2009) to a 2-sigma confidence range.
[b] Date for the middle soil.
[c] The age of the gastropod shell was corrected for the marine reservoir effect using a ΔR value of 15 ± 119.

shells collected before 1950 from the Aceh province and southeast Asia (Grand Pre, 2011). The specimens were prepared using the standard procedures of Southon et al. (2002) and analyzed at the Keck Carbon Cycle AMS Facility at the University of California at Irvine. The ^{14}C age measured for each shell was compared to the expected ^{14}C from the Marine09 calibration curve Reimer et al. (2009). The values for the 10 shells varied from −164 to +221 years, which yield a ΔR of 15 ± 119 years. The ages of plants in the soils and the gastropod age are calibrated to two standard deviations where years 'before present' (BP) is years before AD 1950.

4. Identification of buried soils

4.1. Lithostratigraphy of Pulot and Seudu

The stratigraphy at Pulot and Seudu revealed up to 6 m of sediment with three buried soils above pre-Quaternary bedrock or pre-Holocene unconsolidated material. On the basis of 12 cores in two approximately perpendicular transects (N67°E; N04°W) at Pulot, the approximate depths of the lower, middle and upper buried soils were 4.6 m, 3.1 m and 2.2 m (Fig. 3). At Seudu, 10 cores from two transects (N90°E; N60°W) revealed the depths of the lower, middle and upper buried soils to be 4.5 m, 2.7 m, and 1.5 m, respectively (Fig. 4).

At both sites, the lower buried soil is overlain, with a sharp (<1 mm) contact, by a 0.05–0.20 m thick sand that thinned landward (Figs. 3 and 4). Overlying the sand is 1–3 m of sand to muddy sand or mud to sandy mud. The bottom contact of this deposit often contains whole gastropods or a shell hash. Where present, the muddy sand deposit grades vertically into a middle buried soil. An upper soil is also identified, which overlies ca 0.5–1 m of sand and muddy sands. Overlying the entire sequence is a 0.08–0.35 m thick sand unit deposited by the 2004 Aceh-Andaman tsunami.

4.2. Paleoenvironmental reconstructions of the lower buried soil

We performed litho-, bio-, and chronostratigraphic analysis on the lower buried soil at Pulot (core 3) and Seudu (core 12). At Pulot an organic-rich lower buried soil is found between 4.40 and 4.24 m core depth. The soil is indicative of a mature mangrove environment, because the high concentration, low diversity pollen assemblages (Fig. 5A) are dominated by *Rhizophora* and *Bruguiera/Ceriops* taxa, with secondary influences of *Avicennia* and *Excoecaria* (Yulianto et al., 2005; Horton et al., 2005b; Engelhart et al., 2007). A detrital wood fragment, 0.01 m below the upper contact of the buried soil, produced an age of 6790–7140 cal. yrs. BP. A detrital wood fragment 0.12 m below the upper contact of the buried soil yielded an age of 6950–7170 cal. yrs. BP.

At Pulot, the lower soil is sharply overlain (contact < 1 mm) by a 0.12 m thick medium-fine sand, which is indicative of a tsunami deposit because of its position above the buried soil (Atwater and Hemphill-Haley, 1997) and the contained mixed offshore and

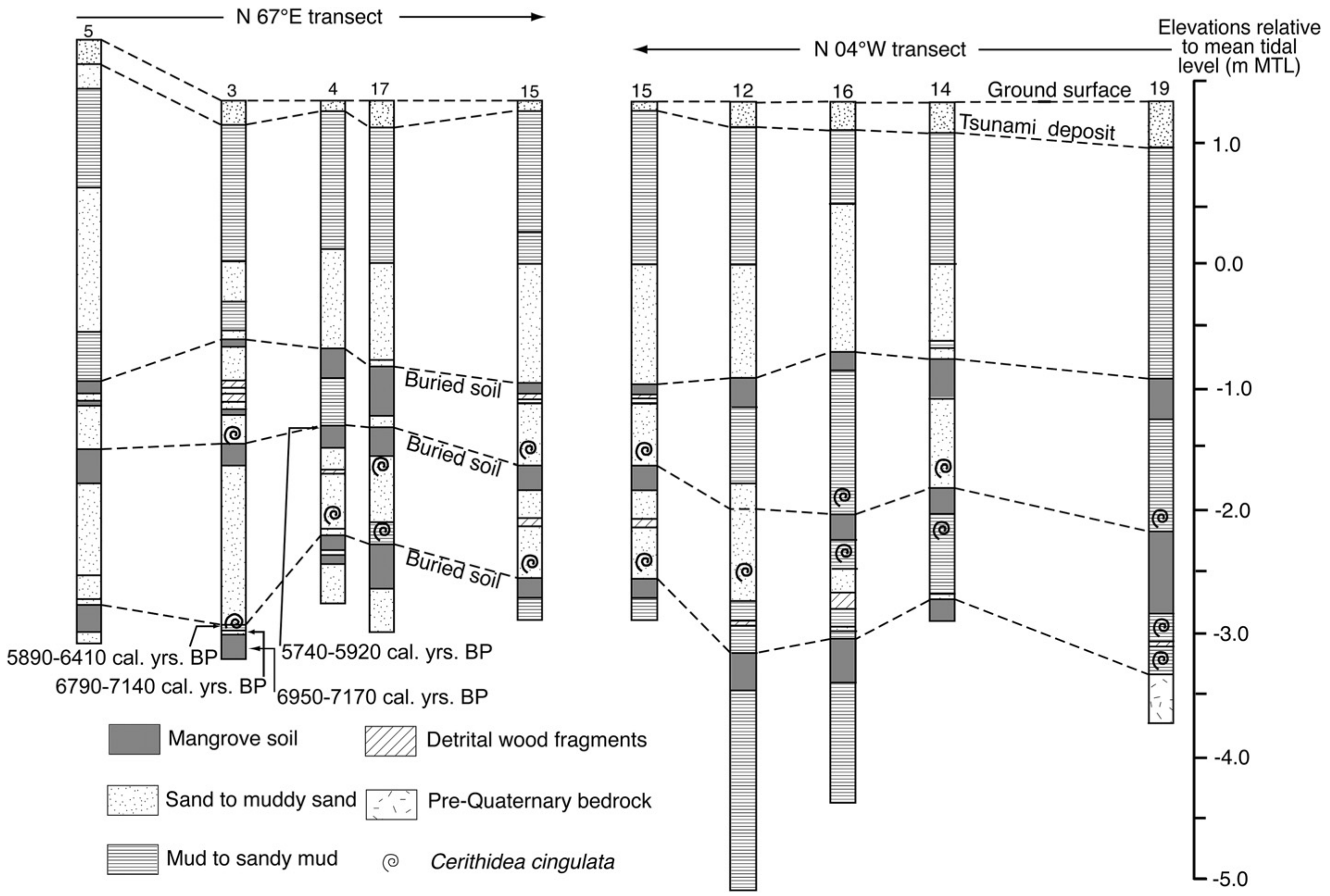

Fig. 3. Litho- and chronostratigraphy of the cores from the two transects at Pulot (see Fig. 2A, B for core locations). The location of core 15 is where the two transects intersect (Fig. 2A). The dashed line shows correlations between tops of soils. Lithostratigraphic units were described using the Troels-Smith (1955) methodology and simplified into five units (see key on figure). Shells of the gastropod *Cerithidea cingulata* are marked with a black spiral symbol. Radiocarbon ages (Table 1) are shown in stratigraphic position (2-sigma age range). Core 3 was used for lithological and microfossil analysis.

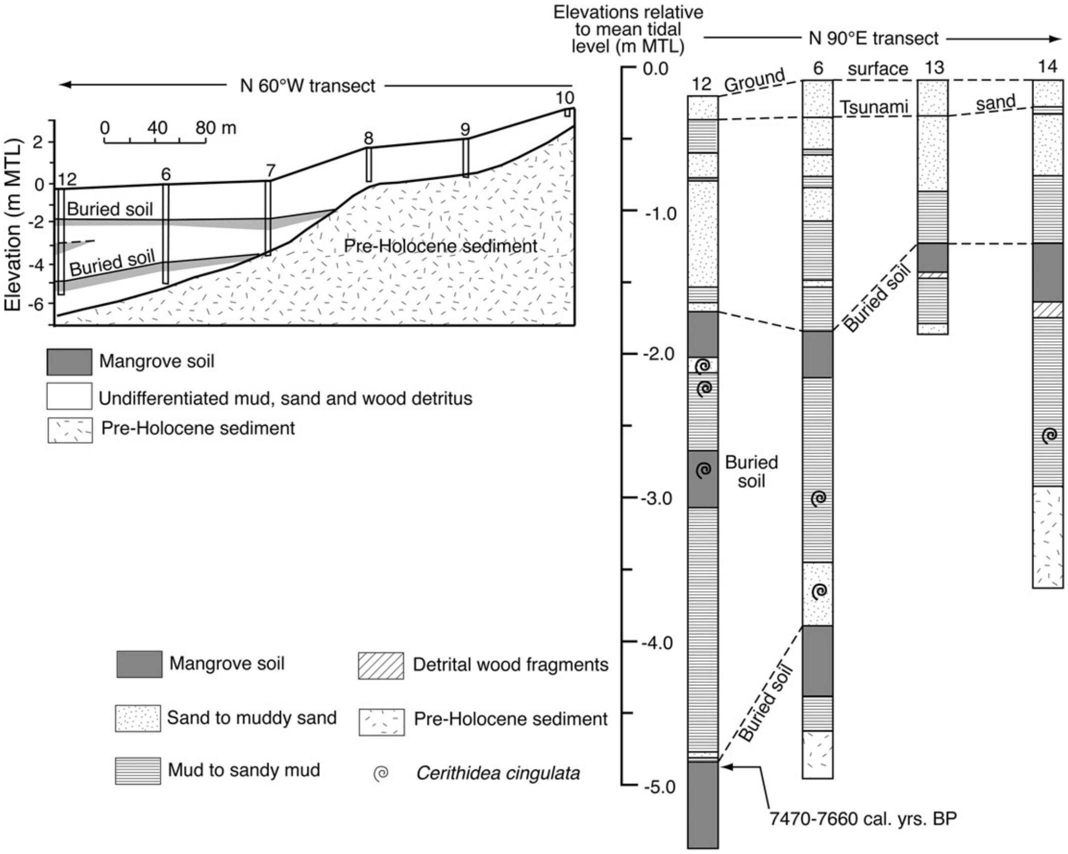

Fig. 4. Litho- and chronostratigraphy of the cores from the two transects at Seudu (see Fig. 2C, D for core locations). The location of core 6 is where the two transects intersect (Fig. 2C). The dashed line shows correlations between tops of soils. Lithostratigraphic units were described using the Troels-Smith (1955) methodology and simplified into five units (see key on figure). Shells of the gastropod *Cerithidea cingulata* are marked with a black spiral symbol. One radiocarbon age (Table 1) is shown in stratigraphic position (2-sigma age range). Core 12 was used for lithological and microfossil (pollen and foraminifera) analysis.

onshore microfossils (Dawson et al., 1996). The sand deposit includes low concentration, mixed tropical forest and mangrove pollen and calcareous foraminifera (Fig. 5A). In many cases the foraminifera have undergone digenesis, dissolution or are broken. The high diversity assemblage includes intertidal (*Quinqueloculina* sp., *Ammonia aoteana*, and *Ammonia tepida*) and inner shelf (*Asterorotalia gaimardi*, *A. milletti*, *Pararotalia venusta*, *Pararotalia nipponica*, and *Nonionella* sp.) taxa (Loeblich and Tappan, 1994; Horton et al., 2005b, 2007; Woodroffe, 2009).

The inferred tsunami deposit grades upward into a mud with very fine sand (4.12–4.08 m core depth). Mixed tropical forest taxa are absent in the low concentration pollen assemblage. Well-preserved foraminifera show an increase in *Ammonia*, *Elphidium* and *Quinqueloculina*, which inhabit modern tidal flats of Indonesia (Horton et al., 2005b) and other tropical environments (e.g., Wang and Chappell, 2001; Horton et al., 2003; Berkeley et al., 2007). The inference of a tidal flat depositional environment is supported by the identification of numerous whole specimens of the intertidal gastropod *C. cingulata* (Vohra, 1971; Rao and Sukumar, 1981, 1982; Houbrick, 1984). A *C. cingulata* shell from the mud unit immediately above the tsunami sand (Figs. 3 and 5A) yielded an age of 5890–6410 cal. yrs BP. CONISS cluster analysis on the combined foraminiferal and pollen data (Fig. 5A) confirm that the soil, sand, and mud assemblages were distinct, with the primary break in the dendrogram occurring at the upper contact of the buried soil.

A similar stratigraphy to that at Pulot, supported by cluster analysis, was found at Seudu (Fig. 5B). At the base of the core (4.73–4.59 m depth) is a soil that yielded a high concentration of mangrove pollen dominated by *Bruguiera/Ceriops* with *Excoecaria*, rather than *Rhizophora* (Fig. 5B). These mangrove taxa are also typical of mature mangroves, but such assemblages are found at the landward edge of the intertidal zone (Yulianto et al., 2005; Engelhart et al., 2007). The maximum age of soil burial, based on a wood sample 0.08 m below the upper contact, is 7470–7660 cal. yrs BP. A sharp contact (<1 mm) separates the mangrove soil from a 0.14 m thick very fine sand unit. This sand contains similar mixed microfossil assemblages of tropical forest pollen and abraded, inner shelf and intertidal foraminifera. The sand grades vertically to a sandy mud. Mangrove pollen in the mud is sparse and mixed tropical forest taxa are absent. A well-preserved foraminiferal assemblage is dominated by intertidal species such as *Ammonia* sp. and *Triloculina tricarinata* (Loeblich and Tappan, 1994; Woodroffe, 2009). In contrast to Pulot, we do not find any whole specimens of *C. cingulata,* but rather their fragments as a shell hash.

5. Archives of great subduction-zone earthquakes in Aceh Province

Core stratigraphy at two sites on the coastal plain of the west coast of Aceh Province harbors stratigraphic evidence of three buried soils. Radiocarbon dating of the lower buried soil and a single date from the middle soil (Table 1) suggest they formed between 5000–7000 cal. yrs BP, during a period of rapid RSL rise in southeast Asia (Horton et al., 2005a). Dura et al. (2011) identified buried soils in southwestern Sumatra, which also formed before the mid-Holocene highstand. Dura et al. (2011) suggests that buried soils are only found

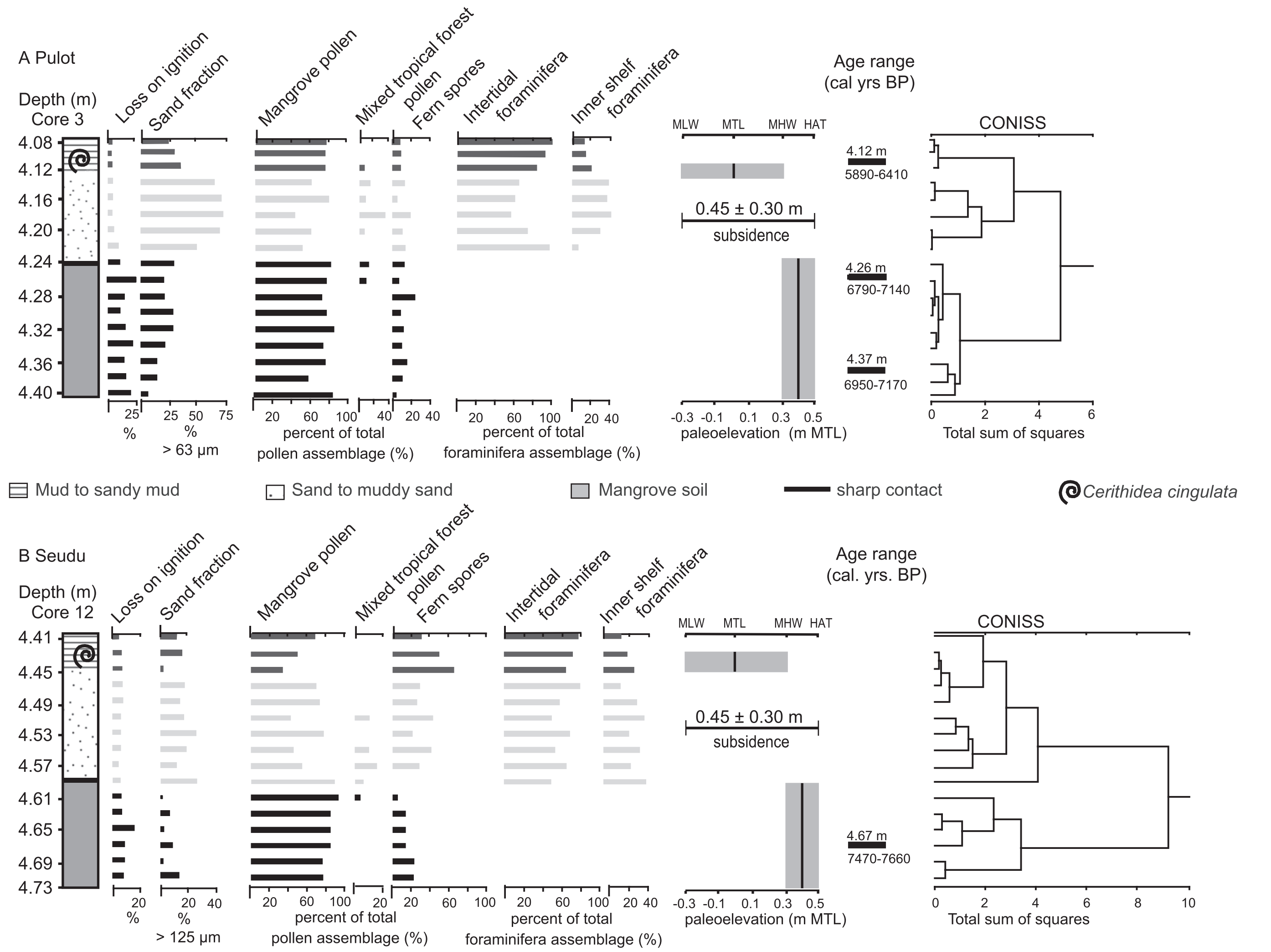

Fig. 5. Summary of stratigraphic data of the lower buried soil sequence at (A) Pulot, core 3 and (B) Seudu, core 12. Paleoelevation estimates for the preseismic environment are calculated from the pollen data and estimates for the post-seismic environment are calculated from the foraminiferal and gastropod data. HAT = highest astronomical tide, MHW = mean high water, MTL = mean tide level, and MLW = mean low water. The lithostratigraphy for both cores is described using the Troels-Smith (1955) methodology and simplified for this figure into three units (see key on figure). Sharp contacts are shown between the mangrove soil and sand to muddy sand deposits as a thick, black line. The contact between the sand to muddy sand, and mud to sandy mud deposits in both cores are gradational. Shells of the gastropod *Cerithidea cingulata* are marked with a black spiral symbol. Calibrated radiocarbon ages are expressed as a calibrated age range (2-sigma age range). Constrained Incremental Sums of Squares cluster analysis (CONISS) of the combined microfossil data (foraminifera and pollen) are shown.

during periods of RSL rise, which create the accommodation space needed for preservation. Neither our research, nor Dura et al. (2011), found evidence of preserved buried soils during the late Holocene, when RSL was falling at far-field locations (Mitrovica and Milne, 2002; Milne et al., 2005).

The stratigraphy of the lower buried soil satisfies the five criteria of Nelson et al. (1996) to distinguish coseismic subsidence from evidence for other coastal processes (e.g., Horton et al., 2005a; Cochran et al., 2007): 1) the lower buried mangrove soil is laterally consistent along at least 25 km of coastline; 2) sand beds indicate a tsunami contemporaneous with the submergence of the buried soil; 3) radiocarbon ages on the buried soil are broadly synchronous for similar stratigraphies at Pulot and Seudu; 4) abrupt contacts and microfossil assemblages at both study sites suggest sudden submergence; and 5) the submergence is sufficiently lasting to convert the depositional setting from higher to lower intertidal environments.

We used pollen, foraminifera and gastropod data to quantify coseismic subsidence and inquire whether earthquakes of comparable magnitude to the 2004 earthquake have occurred in the past. However, analogous modern intertidal environments to the lower buried soil-mud couplets are absent along the west coast of Aceh Province, because of extensive land reclamation during European colonization and more recently by clearance for aquaculture (Whitten et al., 1997), compounded by destruction from the 2004 earthquake (Medrilzam et al., 2005; Kanagaratnam et al., 2006). Fortunately, studies on the modern mangrove environments of Sulawesi, Indonesia (Horton et al., 2005a, 2007; Engelhart et al., 2007) and elsewhere in southeast Asia (e.g., Anderson, 1963, 1983; Anderson and Muller, 1975; Morley, 1999; Kamaludin, 2001; Yulianto et al., 2005) have shown mangrove environments extending hundreds of meters inland from the coast.

Mangroves can grow from mean tide level (MTL) to highest astronomical tide (HAT) (e.g., Grindrod, 1985; Kamaludin, 1993; Ellison, 2005; Yulianto et al., 2005; Horton et al., 2005a), although they do not produce enough organic matter at their seaward fringe for a soil to accumulate (Matthijs et al., 1999; Engelhart et al., 2007). In modern intertidal environments of Sulawesi, the mangrove soil is found between mean higher high water (MHW) and HAT dominated by the species *Rhizophora*, *Bruguiera/Ceriops*, *Avicennia* and *Excoecaria* (Horton et al., 2005a, 2007; Engelhart et al., 2007). Thus, we interpret the preseismic elevation of the mature mangrove buried soil to be between MHW and HAT. A regional tide model (Egbert and Erofeeva, 2002) estimates the elevation to be 0.45 ± 0.30 m MTL (MHW and HAT are 0.3 m and 0.6 m MTL, respectively).

We used foraminifera and the gastropod, *C. cingulata*, to estimate the post-seismic elevation of the mud. The foraminiferal assemblage is dominated by well-preserved *Ammonia*, *Elphidium* and *Quinqueloculina* taxa that inhabit modern tidal flats of Indonesia (Horton et al., 2005b) and other tropical environments (e.g., Wang and Chappell, 2001; Horton et al., 2003; Berkeley et al., 2008; Woodroffe, 2009). Rao and Sukumar (1982) and Houbrick (1984) suggest that *C. cingulata* lives in a similar tidal flat environment. This species prefer muddy substrate and standing crops decrease drastically in substrates that are greater than 75% sand (Rao and Sukumar, 1981). Reid et al. (2008) demonstrated *C. cingulata* to be a complex of species. All members of this multi-taxon complex, however, live within the intertidal environment. Vohra (1971) found that *C. cingulata* lives in high abundance between mean high water (MHW) and mean low water (MLW). Similarly, Rao and Sukumar (1982) found the highest standing crop around MTL in their study in South India. Thus, we estimate the paleoelevation of the mud to be from MHW (0.3 m MTL) to mean low water (MLW, −0.3 m MTL).

To calculate coseismic subsidence (CS) we used the following equation (Hawkes et al., 2010):

$$CS = E_{pre} - E_{post} \qquad (1)$$

where E_{pre} is the elevation of the preseismic buried soil and (E_{post}) is the elevation of the post-seismic overlying mud. We calculated the uncertainty of coseismic subsidence (CS_{error}) using:

$$CS_{error} = \sqrt{\left[(E_{pre}\ error)^2 + (E_{post}\ error)^2\right]} \qquad (2)$$

where E_{pre} error and E_{post} error are the elevational ranges of the buried soil and intertidal mud, respectively. Taking the upper and lower limits of tidal elevation for mangroves and intertidal environments respectively, the amount of coseismic subsidence is 0.45 ± 0.30 m, which is comparable to observations (ca 0.6 m in northwestern Sumatra) of subsidence along the same coast impacted by the 2004 Aceh–Andaman earthquake (Subarya et al., 2006; Chlieh et al., 2007).

Radiocarbon ages (Table 1) constrain the time of the megathrust earthquake marked by the upper contact of the lower soil to the early Holocene. At Pulot, we constrained the age of the earthquake by dating a detrital wood fragment 0.02 m below the preseismic buried soil upper contact and a *C. cingulata* shell found at the lower contact of the post-seismic mud. We calibrated the maximum age of the preseismic soil to be 6790–7140 cal. yr BP. We applied the regional ΔR correction (15 ± 119 years) to the marine calibration curve (Reimer et al., 2009), which produced a minimum age for the post-seismic surface (the contact between tsunamigenic sand and intertidal mud) of 5890–6410 cal. yr BP. The ages are stratigraphically consistent and suggest that a paleoearthquake occurred at 6500–7000 cal. yrs BP.

6. Conclusions

The Holocene stratigraphic record described herein demonstrates that multi-proxy investigations of coseismic subsidence hold considerable promise for unraveling and extending the record of prehistoric great earthquakes in tropical environments. The lithostratigraphy of the coastal plain west of Aceh Province revealed ca 6 m of sediment with three buried soils above pre-Quaternary bedrock or pre-Holocene unconsolidated sediment. The lower buried mangrove soil is regionally consistent along at least 25 km of coastline and there is evidence of a tsunami contemporaneous with the submergence of this soil. The abrupt contacts and micro (foraminifera and pollen) and macrofossil (gastropod) assemblages from two study sites (Pulot and Seudu) suggested sudden coseismic subsidence that was sufficiently lasting to convert the depositional setting from higher to lower intertidal environments. Radiocarbon ages on the lower buried soil are broadly synchronous for similar stratigraphies at Pulot and Seudu infering that the coastal plain west of Aceh Province coseismically subsided ca 6500–7000 cal. yrs BP. The amount of subsidence, 0.45 ± 0.30 m, is constrained by the abrupt change from a mangrove to a tidal flat environment.

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