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ABSTRACT

Sediment cores from Karagan Lagoon in southeastern Sri Lanka retrieved deposits from the A.D. 2004 Indian Ocean tsunami and older similar deposits that provide evidence for a tsunami 2417 ± 152 cal. (calendar) yr B.P. to 2925 ± 98 cal. yr B.P., and for six tsunamis between 4064 ± 128 cal. yr B.P. and 6665 ± 110 cal. yr B.P., a period for which the sediment record appears continuous. Radiocarbon dating indicates that the recurrence interval is variable, ranging from 181–517 yr to 1045 ± 334 yr, with a mean recurrence interval of 434 ± 40 yr during the ca. 4000–7000 cal. yr B.P. continuous interval. Assuming that these tsunamis were generated by giant earthquakes along the Sumatra-Andaman subduction zone, a reasonable assumption for this far-field transoceanic location, this record extends the giant-earthquake history for the Indian Ocean region. The longest recurrence interval of more than 1000 yr implies that earthquakes along the subduction zone may reach twice the size of the 2004 earthquake.

INTRODUCTION

The 26 December 2004, magnitude (M) 9.2, Sumatra-Andaman earthquake and resulting transoceanic tsunami caught the world off guard, killing more than 230,000 people. More than 3000 people were killed in the town of Hambantota located in southeastern Sri Lanka (6.2500°N, 81.1667°E) (Anputhas et al., 2005). The tsunami arrived from the east, destroyed the low-lying parts of the town, and inundated Karagan Lagoon (6.132456°N, 81.121834° E) (Fig. 1A), depositing sand over the town and into the lagoon (Figs. DR1–DR3 in the GSA Data Repository[1]). Tsunami inundation in Hambantota extended up to 3 km inland, the maximum wave height was 6.1 m, and runup was 11 m (Wijetunge, 2006; Goff et al., 2006). Anecdotal evidence from the *Mahāvaṃsa*, Sri Lanka's national chronicle, suggests that a previous tsunami occurred in 200 B.C. (Geiger and Bode, 1964).

The 2004 tsunami deposited a layer of sediment in the eastern part of Karagan Lagoon. To search for paleotsunamis, we collected 22 sediment cores, 0.5–4.0 m in length (Fig. 1; Fig. DR4; Table DR1). The evolution of the lagoon is related to Holocene sea-level rise and the variability in aridity due to changes in the Indian monsoon system during the past 7000 yr (Jackson, 2008; Ranasinghe et al., 2013a, 2013b). A relatively fast rate of mid-Holocene sea-level rise started at ca. 7300 cal. (calendar) yr B.P., submerged the Sri Lankan coastline, and established Karagan Lagoon (Ranasinghe et al., 2013a). In 2004, Karagan Lagoon was separated from the sea by a stretch of sand dunes 15 m high and 100–200 m wide along the lagoon's southern coastline with one artificial cut (ca. A.D. 1998), while the eastern portion was separated from the sea by the town of Hambantota (Figs. DR5 and DR6). Because Karagan Lagoon remained a low-lying area throughout the past 7000 yr, it is an ideal repository for paleotsunami events.

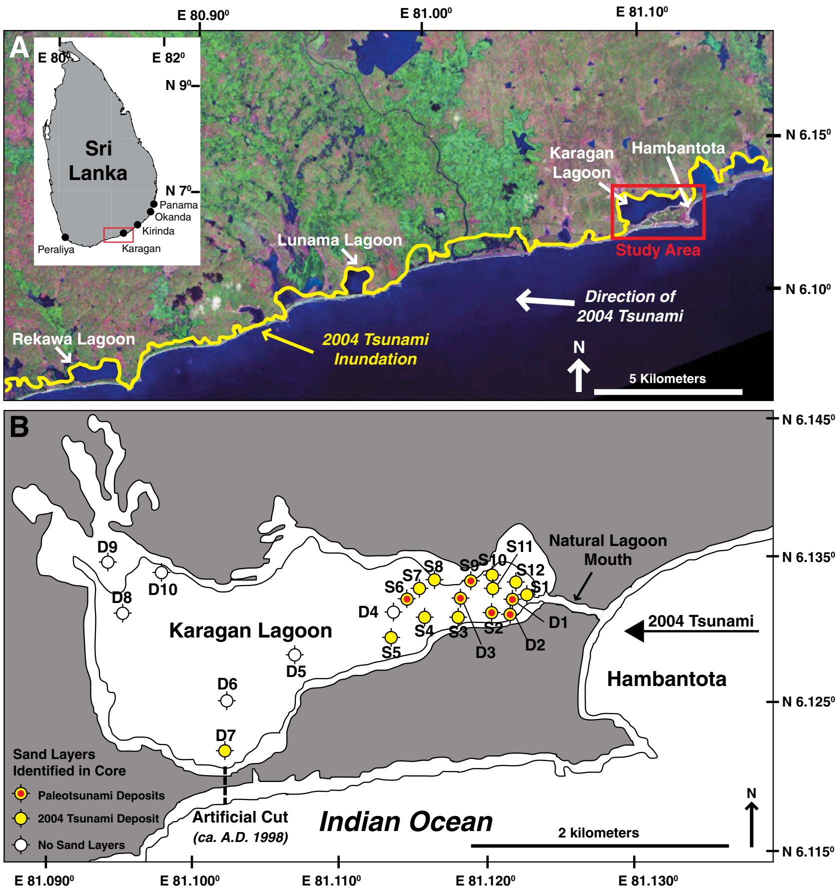

Figure 1. A: Inundation by the 26 December 2004 tsunami (yellow line) along Sri Lanka's southeastern coastline showing that most coastal lagoons were inundated. Satellite image predates the 2004 tsunami. B: Core locations in Karagan Lagoon, color-coded according to sand deposits. D1–D10 are deep cores, 1.0–4.0 m in total depth; S1–S12 are shallow cores, <1.0 m in depth. Both the 2004 tsunami and paleotsunami deposits are confined to the eastern portion of Karagan Lagoon, except in core D7 where the 2004 tsunami entered via an artificial cut (ca. A.D. 1998). Map depicts Karagan Lagoon at the time of the 2004 tsunami and core collection from 2005–2006, prior to the construction of the Port of Hambantota.

[1]GSA Data Repository item 2014305, Figures DR1–DR15 and Tables DR1–DR5, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TSUNAMI DEPOSITS

Karagan Lagoon sediments consist of siliciclastic clays and silt with traces of fine-grained quartz sand. The in-situ fauna consists mainly of molluscs, benthic foraminifera (e.g., *Ammonia beccarii*), and ostracodes. The 2004 tsunami deposit was present near the top of 16 of the 22 cores (Fig. 1B; Fig. DR7). The deposit consists of very fine to very coarse sand composed of dominantly quartz grains with lesser amounts of other minerals, marine benthic and planktonic foraminifera (including *Globigerina* sp.), some molluscs (whole and/or fragments), and carbonate grains. It varies in thickness from 1 to 22 cm influenced by localized microtopography, in some places displays multiple cycles of grading, and typically has a sharp erosional basal boundary (Fig. 2; Figs. DR7–DR9). Cores from the western part of the lagoon do not contain sand, except core D7 that contains a 2004 tsunami deposit due to inundation through the artificial cut (ca. 1998) (Fig. 1B; Fig. DR6).

Seven layers of sand deposits were found deeper in six cores; however, no core contains all eight deposits (Fig. 1B; Table 1). These deeper sand deposits feature similar provenance, grain size, and thickness to the 2004 tsunami deposit (Figs. DR10 and DR11) (Jackson, 2008). These deeper deposits also contain marine foraminifera (dominantly *Globigerina* sp., *Quinqueloculina* sp., and *Elphidium advenum*) that document that the sediment was transported from the offshore marine environment. Just like the 2004 tsunami deposits, the deeper sand deposits are confined to the eastern portion of the lagoon, which is the direction from which tsunamis from the Sumatra-Andaman subduction zone arrive (Fig. 1). Based on their sedimentological similarity to the 2004 tsunami deposit, clear marine influence, and spatial distribution, we interpret the deeper sand deposits to be seven paleotsunami deposits.

Deposition by tropical cyclones can be ruled out for three reasons. First, Karagan Lagoon is located near the equator (~6°N) and is rarely affected by tropical cyclones. Second, the sand layers extend significantly beyond typical storm inundation limits (300 m) (Morton et al., 2007). Third, the deposits lack common storm-related sedimentary structures. Deposition by riverine input or monsoonal flooding can also be eliminated because the lagoon is not fed by rivers, the sand layers are marine in origin, and the deposits are confined to the eastern portion of the lagoon. Therefore, tsunamis are the only likely depositional mechanism for the sand layers.

TSUNAMI CHRONOLOGY

To decipher the timing of the paleotsunami deposits, we used accelerator mass spectroscopy (AMS) radiocarbon methods to date the bulk organic content of the sediment immediately above and below the deposits (Table 1; Fig. DR12; Tables DR2 and DR3). Material from within the

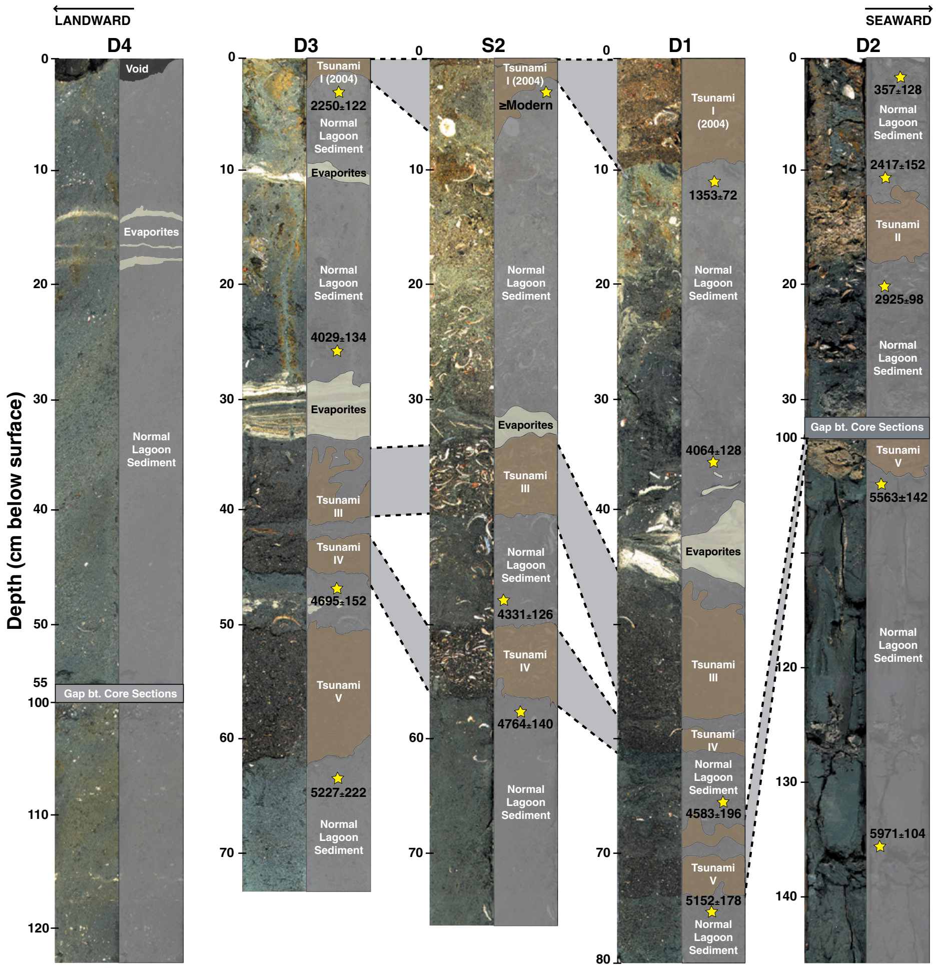

Figure 2. Paleotsunami deposits I–V in core (Karagan Lagoon, Sri Lanka), showing top sections of cores D1, D2, D3, D4, and S2. Shown are core photographs, interpretations, and radiocarbon dates reported as μ ± 2σ cal. (calendar) yr B.P., where present is defined as A.D. 1950. Cores D1, D2, D3, and S2 collectively contain the A.D. 2004 tsunami deposit (tsunami I) and four sand layers interpreted as paleotsunami deposits (tsunamis II–V) deposited prior to 5500 cal. yr B.P. Tsunamis III–V correlate stratigraphically, as shown by the presence of evaporites above tsunami III and by the dates. Core D4 does not contain any tsunami deposits, though it features the same evaporite horizon that is present in cores D3, S2, and D1.

TABLE 1. TSUNAMI DEPOSITS RECORDED IN KARAGAN LAGOON, SRI LANKA

Tsunami deposit	Minimum top depth in cores* (m)	Maximum bottom depth in cores* (m)	Age above tsunami deposit† (μ ± 2σ calendar yr B.P.)	Age below tsunami deposit† (μ ± 2σ calendar yr B.P.)	Midpoint age of tsunami deposit§ (calendar yr B.P.)	Cores containing deposits
I#	0.00	0.22	–	–	26 December 2004	S1–S12; D1–D3, D7
II	0.14	0.19	2417 ± 152	2925 ± 98	2700	D2
III	0.33	0.58	4064 ± 128	4331 ± 126	4200	S2, D1, D3, (S6††)
IV	0.45	0.62	4331 ± 126	4583 ± 196	4500	S2, D1, D3
V	0.51	1.06	4764 ± 140	5152 ± 178	5000	D1, D2, D3, (S9††)
VI#	1.00	2.09	6197 ± 156	6249 ± 68	6200	D1, D2, D3
VII#	2.77	2.81	6249 ± 68	6455 ± 118	6400	D1, (D2**)
VIII#	3.24	3.73	6455 ± 118	6665 ± 110	6600	D1, D3, (D2**)

Note: Raw data and calibrations are described in Tables DR2 and DR3 and in Figure DR12 (see text footnote 1).
*For top depths (m), the shallowest occurrence in the suite of cores is recorded. For bottom depths (m), the deepest occurrence in the suite of cores is recorded.
†For ages above the tsunami deposit, the oldest radiocarbon age date (μ) was selected. For ages below the tsunami deposit, the youngest radiocarbon age date (μ) was selected. This produces the most constrained time range for each tsunami event.
§The midpoint ages of tsunamis II–VIII were calculated as the midpoint between the oldest μ and youngest μ calibrated ages, rounded to the nearest hundredth year (Fig. DR12).
#Shown in Figures DR7 and DR13–DR15.
**Possible correlation, but below 2.0 m, core D2 is bioturbated or was possibly disturbed during coring.
††Possible correlation to cores S6 and S9, respectively, based on stratigraphy.

deposits was not dated because tsunamis entrain and transport sediments and microfauna from a variety of sources. AMS radiocarbon ages were calibrated using OxCal version 4.1 (https://c14.arch.ox.ac.uk/embed.php?File=oxcal.html; Bronk Ramsey, 2009) using calibration curve IntCal09 (Reimer et al., 2009) and are reported as μ ± 2σ cal. yr B.P., where present is defined as A.D. 1950. The resultant ages produce a time range for each tsunami event, with the minimum age above and the maximum age below the deposit (Table 1; Fig. DR12).

The youngest paleotsunami deposit is only found in core D2 and has an estimated age of 2417 ± 152 to 2925 ± 98 cal. yr B.P., which may correlate to the tsunami mentioned in the *Mahāvaṃsa* (tsunami II, Table 1; Fig. 2). Below a distinct evaporite horizon, there are three paleotsunamis deposits with ages of: 4064 ± 128 to 4331 ± 126 cal. yr B.P. (tsunami III), 4331 ± 126 to 4583 ± 196 cal. yr B.P. (tsunami IV), and 4764 ± 140 to 5152 ± 178 cal. yr B.P. (tsunami V) (Table 1; Fig. 2). These tsunami deposits are well constrained stratigraphically because the ages above, between, and below the deposits from the different cores fall within the same range. Three deeper paleotsunami deposits have estimated ages of: 6197 ± 156 to 6249 ± 68 cal. yr B.P. (tsunami VI), 6249 ± 68 to 6455 ± 118 cal. yr B.P. (tsunami VII), and 6455 ± 118 to 6665 ± 110 cal. yr B.P. (tsunami VIII) (Table 1; Figs. DR13–DR15). For tsunamis VII and VIII, the age above the deposits equals the age below the subsequently younger deposit because there is only one age date between the two deposits, therefore the ages are not as well constrained as for tsunamis III–V.

From 7000 to 4000 cal. yr B.P., 3.5 m of sediment was deposited, whereas only 0.5 m of sediment accumulated in Karagan Lagoon from 4000 cal. yr B.P. to present (Fig. 3). The sedimentation rates are related to the rate of sea-level change. Sea level rose to ~1.5 m higher than today until ca. 4900 cal. yr B.P. and then started to lower at ca. 3000 cal. yr B.P. to its present position (Ranasinghe et al., 2013a). The stabilization and slight fall of sea level after this time resulted in a reduced sedimentation rate in the lagoon. This, combined with the fact that tsunamis can erode and rework deposits from previous events, makes preservation of deposits less likely. Consequently, the preservation of the tsunami events is higher in the older strata of the cores (ca. 7000–4000 cal. yr B.P.), and additional tsunamis may have affected Karagan Lagoon over the past 4000 yr but only one tsunami deposit, in addition to the 2004 tsunami deposit, is preserved.

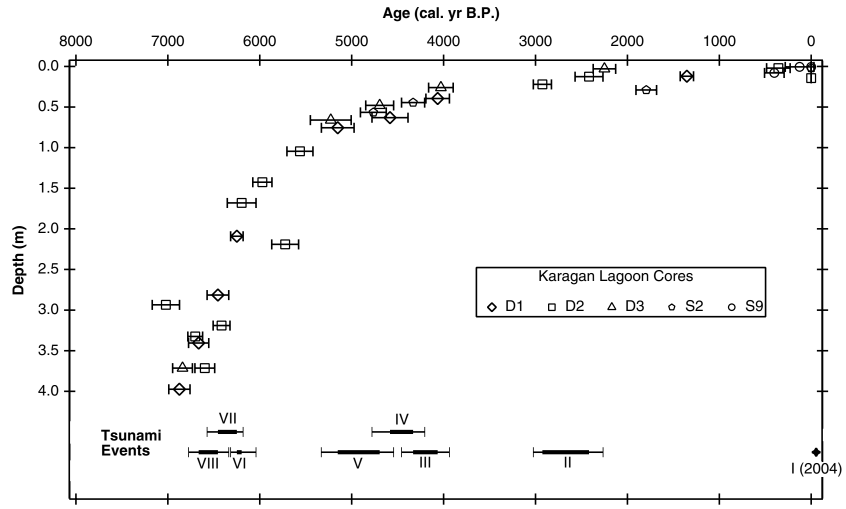

Figure 3. Sediment accumulation rates in Karagan Lagoon, Sri Lanka. Radiocarbon dates are for bulk organic background sediment (μ ± 2σ cal. [calendar] yr B.P., where present is defined as A.D. 1950) from five cores. Black horizontal bars indicate age ranges of tsunamis I–VIII (minimum μ ± 2σ to maximum μ ± 2σ); black star is the 26 December 2004 tsunami.

INDIAN OCEAN TSUNAMI HISTORY

Karagan Lagoon appears to contain an uninterrupted record of Indian Ocean tsunami history from ca. 7000–4000 cal. yr B.P. during which six tsunamis occurred (tsunamis III–VIII, Table 1). From 4000 cal. yr B.P. to present, only one paleotsunami (tsunami II) and the 2004 tsunami are recorded.

Paleotsunami deposits from Karagan Lagoon correlate with other sand deposits found along the southern coast of Sri Lanka. Three tsunami deposits with ages of 4200, 4500, and 5000 cal. yr B.P. found in Kirinda and Okanda Lagoons 30 km and 80 km to the east were likely deposited by tsunamis III, IV, and V, respectively (Ranasinghage, 2010; Fig. 1; Table 1; Table DR4). Abeyratne et al. (2007) dated a sand layer at 4829 ± 362 cal. yr B.P. in Kirinda Lagoon that is coeval with tsunami V (Table DR4). Two deposits found 130 km to the west in Peraliya Lagoon could have been deposited by tsunamis II and III, but their radiocarbon ages are inconclusive (Dahanayake et al., 2012). One deposit from Panama Lagoon has an age of 6817 ± 132 cal. yr B.P. and could correlate to tsunami VIII (within the ± 2σ range) (Ranasinghage, 2010).

Only one core in Karagan Lagoon contains a paleotsunami deposit younger than 4000 cal. yr B.P., but regional evidence provides information about tsunamis during this period. Two paleotsunami deposits are reported in southeast India (ca. 1000 and 1500 cal. yr B.P.) (Rajendran et al., 2006, 2011), three in northern Sumatra (A.D. 780–990, 1290–1400, and 1907) (Monecke et al., 2008), and up to five in the Andaman and Nicobar Islands (all within the past 2000 yr) (Rajendran et al., 2007; Rajendran, 2013) (Table DR4). Several studies have identified paleotsunami deposits in Thailand including two in Phra Thong (550–700, <2200–2400 sidereal yr B.P.) (Jankaew et al., 2008), three in Ban Bang Sak (500–700, 1180–1350, and <2000 cal. yr B.P.) (Brill et al., 2011), and one on the Andaman Coast (2720–4290 cal. yr B.P.) (Rhodes et al., 2011) (Table DR4). In addition, six sedimentary deposits are identified in the Rasdhoo Atoll Lagoon, Maldives (420–890, 890–1560, 2040–2340, 2420–3380, 3890–4330, and 5480–5760 cal. yr B.P.) (Klostermann et al., 2014). It is unclear whether all deposits represent tsunamis comparable in size to the 2004 event, but previous megathrust ruptures similar to that of 2004 have been inferred from uplifted corals off northern Sumatra (Meltzner et al., 2010).

The oldest deposit reported by Jankaew et al. (2008) in Thailand (<2200–2400 sidereal yr B.P.) may correlate to tsunami II and to the tsunami reported in the *Mahāvaṃsa*. Two of the older deposits from the Maldives (2420–3380 and 3890–4330 cal. yr B.P.) may correlate to tsunamis II and III, respectively (Klostermann et al., 2014). The Thailand deposit 2720–4290 cal. yr B.P. reported by Rhodes et al. (2011) could also correlate to tsunami II or III. A paleoearthquake at 6500–7000 cal. yr B.P. recorded in Aceh, Indonesia, may correlate with tsunami VIII (Grand Pre et al., 2012).

IMPLICATIONS

The Karagan Lagoon record extends the history of giant earthquakes along the Sumatra-Andaman subduction zone, assuming that earthquakes from this plate boundary caused the tsunamis. We find a mean recurrence interval of 363 ± 102 yr for the well-constrained tsunamis III–V, and 434 ± 40 yr for tsunamis III–VIII (Table DR5). The shortest time between two consecutive tsunamis during the time period of 7000–4000 cal. yr B.P. is 181–517 yr (between tsunamis IV and V). The longest time is 1045 ± 334 yr and is documented in three cores (D1, D2, D3) (between tsunamis V and VI; Table DR5). This wide range of times between major tsunami-generating earthquakes adds Sumatra-Andaman to the list of subduction zones that exhibit a great variability in rupture mode, which has been observed in Cascadia and Chile (Satake and Atwater, 2007) and is under investigation for Japan.

The long hiatus period between two consecutive tsunamis of 1045 ± 334 yr is approximately twice the interevent period prior to the 2004 earthquake (Rajendran, 2013). This length of time between major earthquakes shows that the plate boundary fault is capable of accumulating a slip deficit of 40–50 m between earthquakes in the southern half of the rupture zone with a relative plate convergence rate of 40–50 mm/yr (McCaffrey, 2008). Such large accumulation of stress, if released in a complete stress-drop rupture similar to that off of Japan in A.D. 2011 (Lin et al., 2013; Hasegawa et al., 2011), would produce an earthquake up to twice the size of the 2004 event.

The results of this study confirm that Sri Lanka and much of the Indian Ocean basin is affected by large tsunamis at non-uniform intervals, from a few hundred years to over a thousand years, and which could be as large or even larger than the 2004 tsunami.

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