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Evidence of ancient sea surges at the Mamallapuram coast of India and implications for previous Indian Ocean tsunami events

C. P. Rajendran[1,*], Kusala Rajendran[1], Terry Machado[1], T. Satyamurthy[2], P. Aravazhi[2] and Manoj Jaiswal[3]

[1]Centre for Earth Science Studies, Akkulam, Thiruvananthapuram 695 031, India
[2]Archaeological Survey of India, Chennai Circle, Chennai 600 009, India
[3]Wadia Institute of Himalayan Geology, Dehra Dun 248 001, India

The Indian Ocean may have a geologic history of tsunami events similar in size and source area comparable to that of the 26 December 2004 event. Searching for geological evidence for previous tsunamis in the near-source region is one way to constrain previous occurrence of such events. Since the 2004 tsunami proved devastating even far from its source, evidence for predecessors can be sought in remote locations, including the east and southwest coasts of India. Here we report observations from two trenches in the Mamallapuram (Mahabalipuram) beach, 55 km south of Chennai (Madras) on the east coast of India, an area also affected by the 2004 tsunami. We discuss the possibility that the sections in question may contain evidence to suggest two pre-2004 tsunami events occurring ~ 1000 years and ~ 1500 years ago respectively.

Keywords: Geological evidence, Indian Ocean, Mamallapuram, tsunami.

*For correspondence. (e-mail: rajendran_cp@yahoo.com)

THE great tsunami of 26 December 2004 affected most parts of the east coast of India (Figure 1). Thousands of people living in the coastal regions of the Indian Ocean fell victims to this unprecedented event. Although smaller tsunami events have been registered in the past, events comparable to that of 2004 have not been documented. Telltale evidence for such occurrences provides constraints on the regional tsunami history, an important input for future hazard evaluation. We believe that with a rich cultural heritage, some of the ancient settlements along the east coast of India may prove to be potential sites for preservation of such evidence of destruction. We made a preliminary search at Mamallapuram, an important port built under the Pallava kings about 1000–1300 years ago (see Keay[1]) for historical details on the AD 4–9 century Pallava dynasty, which ruled parts of the present-day State of Tamil Nadu and its neighbouring areas). There are two important reasons that motivated us to begin investigations here. One, the 2004 tsunami, surging as much as 3–6 m above datum, stripped beaches and created circular depressions along the Mamallapuram coast, now filled with tidal water (see also Chadha *et al.*[2]). We suspect that the events in the past could have affected the coast in a similar fashion. Two, scouring along the beach exposed buried rock sculptures and temple basements that prompted the Archeological Survey of India (ASI) to excavate these sites, exposing multiple occupational levels. This gave an opportunity to examine the deep trenches (~ 4 m) that were also expected to provide reliable chronological constraints of the event horizons.

Early navigators refer to Mamallapuram as a town of the seven pagodas (turrets of the Hindu temples). Many scholars believe that the sea had encroached on these temples in the past; the only surviving structure is the Shore Temple (a world heritage site) that escaped the 2004 tsunami because it stands behind a shore protection wall. Further, this temple built on hard rock, would have resisted the scouring action by the tsunami at the foundation level, which probably explains its long-term stability. The other temples are completely submerged today, but their top parts were visible until a few centuries ago[3]. If this is caused by rise in sea level relative to land, coastal retreat may explain the references in the ancient South Indian texts about episodes of great flooding[4]. Chambers[3], an early British explorer, attributed the submergence to 'overflowing sea', which he suspected was caused by an earthquake.

Positive evidence for coastal retreat was recently found through underwater exploration on the northeastern side of the Shore Temple, about 600 m from the present coast. The exploration revealed remains of huge stone constructions, dating to 8th century AD, at 6–15 m below the present sea level[5]. Considering an average erosion of 55 cm/yr, the shoreline 1500 years ago must have been about 800 m seaward of the present coast[6]. It is therefore reasonable to believe that structures now offshore must have been onshore ~ 1000 years ago[5].

Subsequent to the 2004 tsunami, ASI conducted excavations at two sites in Mamallapuram. At one of these sites, about 300 m south of the Shore Temple, basement of a stone temple from the late Pallava period (8th century AD) was uncovered. The other scoured site is at Saluvankuppam, about 1.5 km north of the Shore Temple and about 150 m from the sea (Figure 2, bottom panel). Excavations at this site revealed multiple cultural settlements with clear-cut working levels and associated sedimentary horizons (Figure 3 *a* and *b*); some of which are discussed here.

The ASI site at Saluvankuppam (referred here as trench 1 or T1) exposed a brick basement, overlain by remains of stonewalls and fallen granite pillars (Figure 2). From the varying styles, type of materials and the nature of artifacts, three phases of construction are evident. The youngest structure (Phase III), built in granite belongs to the late Pallava period (8th–9th century AD) and its base is about 2 m below the present ground surface. Phase II (6–8 century AD) is represented by an underlying brick basement. A much older level of construction using an earlier genre of bricks exists at a depth of about 3.2 m below the present ground level. Only a part of this structure (early 4th century AD; Phase I) has been exposed at present on the eastern side of the trench (Figures 2, 3 *a* and *c*).

Stratigraphy of the eastern and southern walls consists of several layers of sand, mixed with brick debris, shells and pottery shards. Human modification and levelling of the ground is evident at various levels on the eastern (seaward) side (Figure 3 *a* and *b*). We noted three layers of highly compacted sand, consisting of brick debris, plaster, shell remains and calcretes at various depths (L1, L2 and L3 in Figure 3 *a* and *b*). Corresponding to various phases of construction, they probably represent working levels for each settlement. These layers may have been compacted to level and stabilize the ground. Since such layers are seen only on the eastern side of the trench, protection from the sea appears to be a major motivation. It appears that each of these three settlements was destroyed and that the succeeding generations used the ruins as new basements.

We noted two anomalous layers of sand, the younger one marked as S1, occurring within the latest settlement layer, and the older one marked as S2, occurring above the oldest phase of construction. Both these layers occur as discontinuous patches of varying thickness and their laminated structure, with embedded pieces of bricks, suggests deposition under turbulent conditions. The younger layer, S1 shows a maximum thickness of 10–14 cm on the southern wall of the trench, tapering gradually on the eastern wall. A thinner version of this layer (1–2 cm) was also seen on the northern wall, with a faint extension to the eastern wall. We observed fine flow structures with laminations and grading within this layer. Restricted spatial extent of the sand and its prominence on the seaward side suggest possible wave action. The maximum thickness, 14 cm, was observed close to a 4 m-tall granite outcrop that marks the southern limit of the trench (Figure 2). Perhaps, this tall rock must have caused deflection of the waves, leading to more scouring and also providing a sheltered depositional niche for the retreating water.

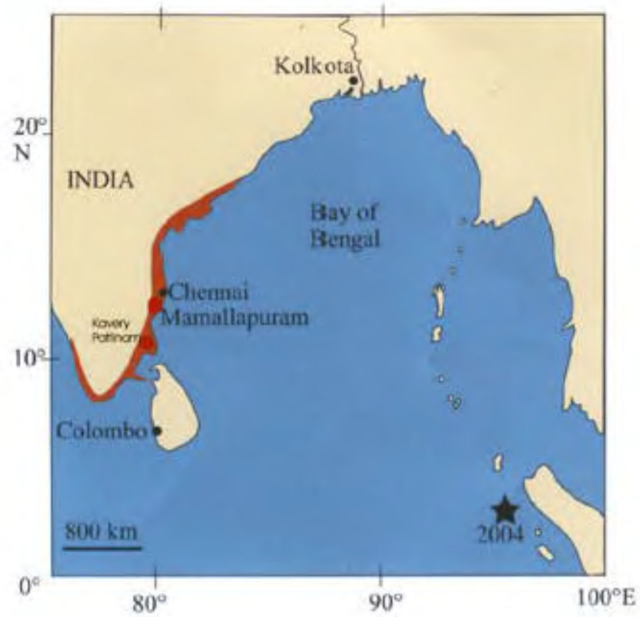

Figure 1. Map showing areas along the east and southwest coast of India affected by the 26 December 2004 tsunami. Star shows location of the 2004 megathrust earthquake (after Stein and Okal[18]).

Figure 2. (Top panel) Excavation site (trench 1, T1) at Saluvankuppam. The top of the structure is ~ 2 m below the present ground level of sand dune. (Bottom panel) Elevation profile of the area showing location of the site.

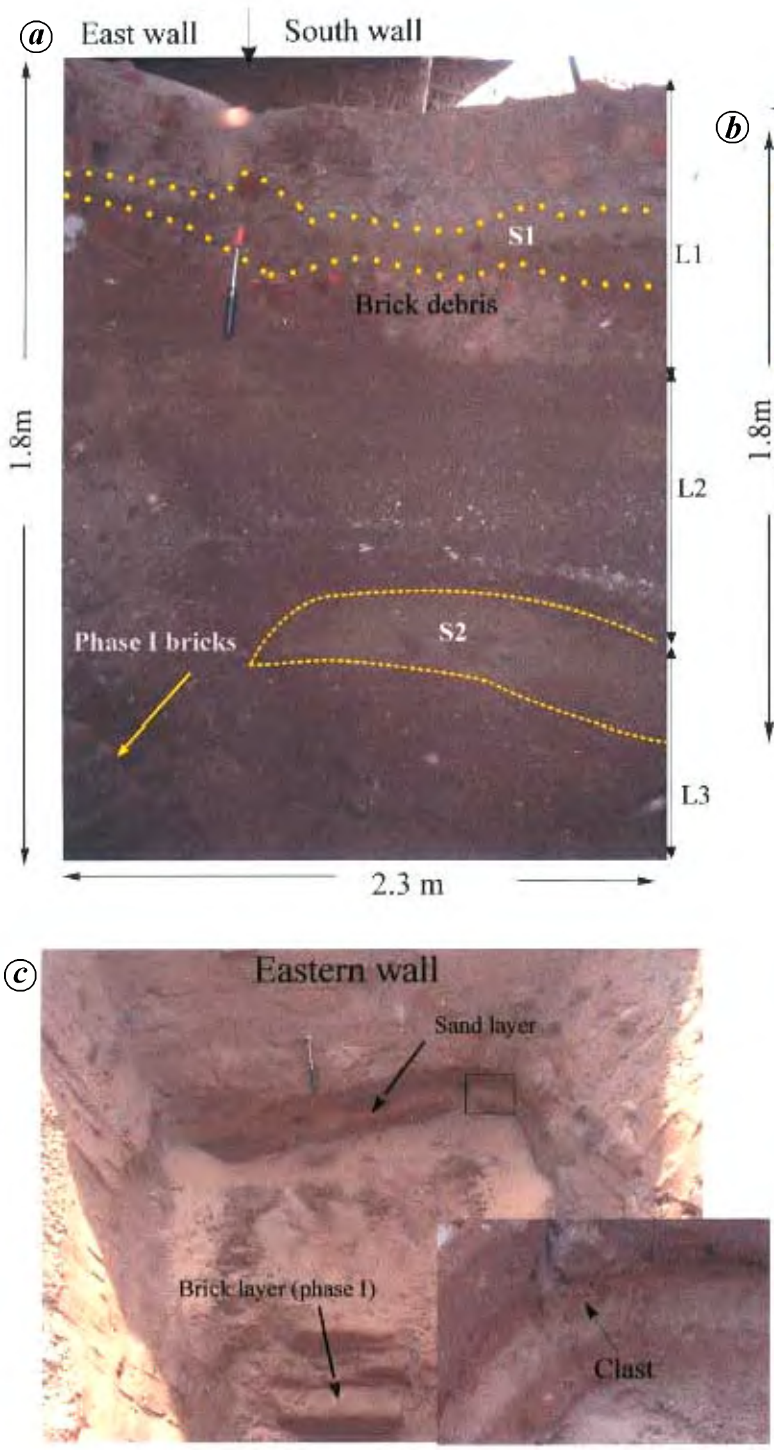

Figure 3. ***a***, View of the eastern and southern walls of the ASI trench (T1) showing working levels of settlements – L1, L2 and L3 and suspected tsunami layers (S1 and S2). ***b***, Details of structures observed on the southern wall; S1 occurs within the brick debris and S2, above a compacted layer of sand. Flow structures are observed within S1 and S2. Patches of fine granite chips are noted only in the top layer of debris, presumably a fill made subsequent to flooding. Bricks belonging to Phase 1 are noted on the bottom of the eastern wall. ***c***, View of the eastern wall of the trench (trench 2, T2) that bottomed on the phase I brick construction, exposing the anomalous sand layer. (Inset) close-up of the layer showing flow structures and clasts.

Could an unusual sea surge account for repeated destruction of the ancient structures here and also explain the unusual layers of fine sand described above? Destruction of the granite temple probably post-dates AD 851 – the approximate age of the inscriptions (an earlier form of Tamil) on the fallen stone pillars (according to ASI sources). Since all the granite pillars lie to the west side of the temple complex, it is possible that they may have been destroyed by sea surges from the eastern side. The 2004 tsunami inundation data[2] imply that a previous tsunami of similar size could have reached 800 m inland and damaged many of the man-made, near-sea structures of weak foundations located on a previously extended coast. That the 2004 tsunami exposed the older temple sites along the Mamallapuram beach implies that a similar size tsunami in the past could have scoured the temple foundations. Like the one at Saluvankuppam, temples built on the sand are more vulnerable to the souring action of the tsunami than those built on rock outcrops.

After the inferred sea surge and selective scouring, more brick debris was probably dumped as a means of protection. Some portions of the topmost layer of debris consist of granite chips, which are totally absent from the lower levels. This change in the content of debris is noteworthy because, as mentioned earlier, granite became a choice of construction (by the Pallavas) only after the 6th century and Pallava temples made of granite at Mamallapuram are dated[1] to 8th century AD. Thus, it appears that the original brick fill was reinforced after the sea surge and only these portions, notably those above the suspected tsunami deposit, contain granite fragments. Charcoal pieces obtained from the sand layer (S1) provided an age of 955 ± 30 BP (AD 1019–1161), and probably postdate the construction of the Stone Temple. The flooding event may have occurred between the inscriptional age of AD 851 (minimum age) and the calibrated charcoal date of AD 1161 (Table 1). It is interesting that the suspected tsunami deposit from this trench yielded fragments of oceanic diatom species like *Navicula* and *Coscinodiscus* (Prema Paul, University of Madras, pers. commun.).

At deeper levels, we logged another layer of fine-grained sand (10 cm), possibly of marine origin at a depth of 3.0 m from the surface (S2 in Figure 3 *a* and *b*). This discontinuous layer of sand occurs above the ruins of the oldest brick structure (Phase I) and as in the case of S1, this is also prominent on the southern wall, with a slimmer eastward extension. We presume that the presence of granite outcrop may have provided favourable conditions for the selective deposition of this layer as well.

Ten metres south of T1, a separate trench revealed another discordant layer of sand, presumably of marine origin and a possible extension of S2. This 2.5 m-deep trench (referred as trench 2 or T2) bottomed on the extension of the oldest brick structure observed in the ASI site (Figure 3 *c*). A layer of sand, with maximum thickness of 10 cm was exposed in the southeastern corner of the trench. This layer marked by fining upward sequence contains clasts from the underlying layer; it also shows laminations suggesting deposition controlled by the flow of water[7–9]. Its occurrence at a cultural level suggests that it was deposited by an unusual sea surge in an area that is otherwise protected from wave action. However, in this trench (T2) we did not observe the extension of the younger sand layer (S1) present in T1. Perhaps, this deposit was preserved selectively and is specific to that site as it was trapped within the debris. It is also possible that this layer was eroded subsequently. As shown in Table 1, we obtained two sets of radiocarbon ages to constrain the time of deposition of the lower layer of sand from T1 and T2 (Figure 3 *a* and *c* and Table 1). Charcoal samples yielded ages of 1674 ± 30 yrs BP (AD 321–427) and 1581 ± 35 yrs BP (AD 405–564).

However, it should be mentioned here that our experiments to obtain infrared stimulated luminescence ages of the tsunami sand did not yield ages commensurable with the radiocarbon ages. The infrared stimulated luminescence SAR analyses of the feldspar grains from the suspected younger and older tsunami sand layers yielded only 361 ± 75 years and 566 ± 120 yrs, respectively. The analysis were carried out on a Riscoe TL/OSL-12 system using infra red LED emitting 800 ± 80 nm wavelength light on the feldspar grains due to very low sensitivity of the quartz separates. One of the reasons for this discrepancy between the radiocarbon and optical-stimulated luminescence ages could be the anomalous fading generally associated with the feldspar grains. We prefer the radiocarbon dates because they are supported by archaeological constraints.

The deposits inferred to have been associated with past sea surges from both the trenches contained significant quantity of foraminifera such as *Ammonia dantata* (S. Sreenivasalu, Anna University, pers. commun.). This particular species habituates only at depths varying between 40 and 50 m in moderately quiet environment and is also present in the recent (24 December 2004) tsunami deposit from the Nagappattinam coast[10]. Probability for storm waves to churn the sea floor at such depth is much less because the maximum storm-related wave height (*Hm*) for the east coast is 6 m (NIO, 1998). Waves of this height can cause only sediment traction at sea-bottom depths shallower than 20 m. Therefore, *A. dantata* found in the samples are unlikely to have been brought by storm waves.

Although the long-term sea-level rise has been viewed as the main cause of submergence and destruction of temples along the Mamallapuram coast about 1000 years ago[5], the 2004 event provokes us to explore alternate explanations. It is tempting to consider if an event similar to that of December 2004 could have contributed to the destruction of these structures. Did massive, short-lived coastal inun-

Table 1. Radiocarbon ages from Saluvankuppam, Mamallapuram

Sample ID*	Radiocarbon age (yrs BP)	Calendric years (2σ interval)
MB/AR/UL	955 ± 30	AD 1019–1161
MB/AR/BL	1674 ± 30	AD 321–427
MB/T1/BL	1581 ± 35	AD 405–564

*Charcoal.

dations in the historical past strike a body blow to the coastal community that existed those days? The Mamallapuram coast has generally been sheltered from the region's large cyclones[11], although occasional storm surges had indeed occurred in the area (e.g. 2 m storm surge was registered in October 1994). Thus could a storm-related episode be considered as an equally possible cause to explain the destruction of these structures? This is an important question that needs to be resolved.

The deposits exposed at Saluvankuppam occur in an area that is far from the tsunami sources in the Indian Ocean. The far-source tsunami deposits offer many classificatory challenges unlike the near-source deposits. In the near-source locales, overprinting of tectonic deformation and association with peat beds (submerged vegetation) facilitate distinguishing a tsunami deposition[12,13]. Far from the influences of near-source tectonism, distinguishing suspected tsunami deposits is not easy; an outstanding issue being how to distinguish tsunami deposits from storm or flood deposits.

Storm deposits are most often interbedded and expected to be laminated (coarse-grained to fine-grained sand), exhibiting delta foreset stratification and sub-horizontal planar stratification[14]. In contrast, the tsunami inundation, characterized by pulses of surges (turbulent phases), still stands (slow deposition) and backwash (reworking) is ideally represented by indications or a mixture of initial massive deposits with flow structures, superceded by quieter deposition (finer materials, mud drapes, etc.) that show up as interbedded finer material and silty layers either with or without lamination. There may be more than one to three subunits of massive to fining upward sequences (for a discussion on 2004 tsunami deposits on the east coast of India, see Rajamanickam, 2006 and the papers therein)[15]. The completeness of such sequences is more evident closer to the source; characteristics of tsunami deposits far away from source are not well documented and the 2004 tsunami may offer an opportunity to study the same. However, absence of any or all of the characteristics should not constitute an argument to disregard a deposit as not being tsunamigenic if there is other overwhelming evidence. As described earlier, the Saluvankuppam sections do not exhibit the entire sequential development of tsunami deposition, and they could represent a part of such a sedimentation process.

To summarize, at Saluvankuppam trenches, we observed two fining upward marker sequences (with definitive ages) with flow structures, embedded clasts and brickbats concentrated at the lower levels, which suggest flow dynamics that may be comparable to tsunami-induced sedimentation (mostly backwash). The spatially restrictive nature of these deposits (other trenches in the region did not reveal these sequences) indicates that they are not a normal part of near-shore sedimentation. Preservation of these deposits at Saluvankuppam is itself a surprise considering the erosive nature of the environment. As shown by the 2004 tsunami, the waves instead of depositing the sand actually scoured the area, leaving circular depressions along the berm, now filled with tidal water (in some cases this activity revealed the temple foundations). The reason for sediment preservation at Saluvankuppam we think, is the presence of a rock outcrop in the vicinity, which provided a trap at its seaward side; the onward rushing eddying currents may have scoured the seaward side of the rock outcrop producing a general depression for the backwash to settle. Evidence of graded settling supports our assumption that the tsunami-related sediments were deposited possibly during the retreat of water (backwash deposits). Preliminary observations on the foraminiferal and diatom assemblages within the anomalous deposits (S1 and S2 layers) from these trenches indicate contributions from the deeper levels of the ocean. As mentioned earlier, this is an important point that tentatively points out that these layers are related to deeply churning long-period tsunami waves.

It is important to understand the spatial and temporal context of the deposits in question and whether there are correlative deposits elsewhere (the Indian Ocean tsunami affected a number of littoral countries). Mamallapuram sections are sited along the beach and such an environment generally is not conducive to preserving all the stratigraphic markers with their purity. Our preliminary data imply the possibility of at least two events of large coastal flooding at this site: one event around AD 950 and the other between AD 320 and 560. The present communicatin is only a preliminary attempt at a local scale, where the suspected tsunami deposits are preserved fortuitously, and more detailed regional studies at other sites in the east coast are to follow. Our ongoing work in the Andaman–Nicocbar region (near-source) indicates a tsunami occurrence along submergence of vegetation around 1000 years ago[16], which agrees with the date of the suspected penultimate tsunami event inferred at Mamallapuram. Further, analyses of the pre- and post-seismic GPS data from the Andaman–Nicobar region indicate 700–1000 years of recurrence for the giant tsunamigenic earthquakes at the 2004 source[17].

Expanding the search for anomalous sand layers to other areas along the east coast, particularly closer to ancient cultural settlements should be a major component of future work. Such work would help to constrain ages of suspected tsunami sand sheets and also to characterize them in terms of flow hydraulics, sedimentology, mineralogy and lithology, so as to discriminate them from other types of coastal sedimentation, including storms or flood deposits. The December 26 event provides a unique template for future studies. Companion studies are also needed to identify palaeoseismic evidence in Aceh (Sumatra) and the Andaman–Nicobar Islands to constrain the causative earthquakes.

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Characterization of clay minerals in the Brahmaputra river sediments, Assam, India

P. Kotoky[1,*], D. Bezbaruah[1], J. Baruah[1], G. C. Borah[1] and J. N. Sarma[2]

[1]Geoscience Division, Regional Research Laboratory, Jorhat 785 006, India
[2]Department of Applied Geology, Dibrugarh University, Dibrugarh 786 004, India

Characterization of clay minerals of the Brahmaputra river sediments within a selected stretch by X-Ray diffraction, differential thermal analysis and Fourier transform infrared spectra has revealed the association of dominant kaolinite with subordinate amount of illite and chlorite. The mineral assemblage, as evidenced from the study, may find its use towards effective understanding of related engineering properties and utilization in flood-management approaches, intimately connected with the lives and properties of the people of Assam.

Keywords: Brahmaputra river, clay minerals, flood management, sediments.

THE braided mighty Brahmaputra river that, occupies one-tenth of the Brahmaputra Valley represents a high-energy fluvial environment, characterized by steep valley gradients, non-cohesive banks and, consequently, high rate of bank erosion and bed load transport[1–3]. Despite gigantic efforts and colossal expenditure (>Rs 15,000 million)[4], the Brahmaputra continues to wreck havoc due to uncontrollable floods since time immemorial, putting in peril the lives and properties of the millions of people[5].

The recent study on its erosion activity[2,3] has established that the activity is not uniform throughout the stretch, with the bank, where Older Alluvium sediments and banks composed of higher clay contents are exposed, offering significant resistance to the erosive power of the river. It is therefore essential to understand the clay mineral component of the associated sediments of the river basin, as it has an intimate relationship with the engineering properties of the bank sediments in question, which, in turn, are related with the extent and nature of erosion mechanisms involved. It is expected that the present study will open up an avenue to understand and establish measures to be adopted towards flood-management approaches.

Forty-five bed sediment samples each about 2 kg were collected along a stretch (within 93°30′–94°30′E long. and 26°30′–27°15′N lat.) of the Brahmaputra river channel (Figure 1), which covers the world's largest river island 'Majuli' under extreme threat of erosion[1,6,7] and the world

*For correspondence. (e-mail: probhatk@yahoo.com)