doi.org/10.22498/pages.32.1.32

Comparing recent cyclone and tsunami deposits from southeast India

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We examined multi-proxy evidence preserved within the 2004 Indian Ocean tsunami and overlying 2011 Cyclone Thane deposits on the southeast coast of India. We found no distinguishing features between the deposits.

Over 35% of the Earth's population lives in coastal zones and is vulnerable to a suite of acute (e.g. storms, cyclones and tsunamis) and chronic (e.g. sea-level rise) coastal hazards (UNEP). Many coastlines and communities are at risk of one or more of these coastal hazards. To properly prepare coastlines that are at risk of these acute coastal hazards, coastal communities and decision makers require detailed knowledge of the occurrence, frequency and magnitude of these events on their coastlines. Fortunately, large storms infrequently impact coastlines, and tsunamis are rare events, but when either event strikes, the outcome can be devastating. Unfortunately, the infrequency of large events makes it challenging for decision makers and communities to prepare.

To overcome this challenge, coastal geological records of both depositional and erosional characteristics have been examined to identify signatures of past coastal hazards (e.g. Switzer et al. 2014). These studies typically focus on areas where a coastal hazard has been encountered (e.g. Jankaew et al. 2008). However, to appropriately identify which coastal hazard has affected a region, modern analogues must be examined to identify characteristics that are unique to each hazard (e.g. Morton et al. 2007). Although much effort has focused on distinguishing between storm and tsunami characteristics in the geological record, these studies have examined deposits of tsunami and storms from different coastlines (e.g. Kortekaas and Dawson 2007; Morton et al. 2007), or have examined deposits that have occurred decades apart and may have undergone alteration (e.g. Nanayama et al. 2000). To date, very few studies have examined the geological signatures of a known tsunami and known storm deposit from the same location (e.g. Pham et al. 2017; Yap et al. 2021). We contribute to this growing body of knowledge by examining the beautifully preserved sedimentary deposits formed by the 26 December 2004 Indian Ocean tsunami (IOT), and the 2011 Cyclone Thane from Devanampattinam on the northern outskirts of Cuddalore, southeast India (Fig. 1a).

The 2004 tsunami and the 2011 cyclone

The 2004 IOT was triggered by a magnitude moment 9.2 earthquake centered off northeastern Sumatra and propagated northwards along 1500 km of the Sumatran-Andaman subduction zone, killing 230,000 people (Fig. 1). The IOT propagated across the Bay of Bengal and struck southeast India at 8:30 a.m. local time, causing approximately 16,000 deaths and US$2 billion (International Recovery Platform 2004). At Devannampatinam, the tsunami had a maximum run-up height of 7 m and 700 m of inundation; and deposited a 38 cm thick sediment deposit.

Cyclone Thane made landfall near Cuddalore between 6:30 and 7:30 a.m. on 30 December 2011, causing over US$1 billion in damage and killing 48 people (Fig. 1; IMD 2012). At Devannampatinam, the storm surge run up was approximately 2 m, inundated approximately 300 m and deposited 27 cm of sediment.

Comparison of Cyclone Thane and 2004 IOT sedimentary deposits

Using satellite imagery of the region and discussions with local survivors, we identified a site approximately 300 m north of the village of Devannampatinam that preserves the 2004 IOT and 2011 Cyclone Thane deposits (Fig. 1a). The site was a partially vegetated; sandy beach dunes and backshore lagoonal environments formed from the closure of the Pennai River. At this site we excavated the 95 cm deep pit DPM3a and conducted multi-proxy analysis at centimetre-scale resolution that included stratigraphy, sediment grain-size, grain shape, and heavy mineral counts (Fig. 2a). Multivariate statistical analysis of the sedimentary variables demonstrates distinct differences between storm and tsunami deposits (Fig. 2b). We analyzed the microbial communities of 26 samples from the pit (Yap et al. 2021), but present the results of 13 representative samples here (Fig. 2c).

From deepest to shallowest, the sedimentary units observed in Pit DPM3a are an intertidal sand, 38 cm thick 2004 IOT deposit, a 12 cm thick layer of eolian (wind blown) sand, and the 27 cm thick Cyclone Thane deposit (Fig. 2a). All of the units consist of medium sands (average size from 0.25–0.5 mm). The intertidal unit consists of northward dipping beds and thin horizontal beds, both with distinct heavy mineral layers (10–30%; Fig. 2a). The tsunami deposit consists of two beds separated by thin heavy-mineral laminations. From the bottom to the middle of the beds, the grain size becomes larger, and from the middle of the beds the grain size becomes smaller (Fig. 2a). These two beds represent deposition from two sequential waves, and much of the sediment came from the pre-existing nearshore or onshore environments. The eolian deposit consists of sands that have been partially reworked upper-2004-IOT sediments, some leaves and plastic waste (Fig. 2a). The storm deposit is composed of horizontal layers that consist of different proportions of heavy minerals (15–60%). The layers are thicker at the bottom of the deposit and become thinner towards the top. It is likely that the sediments came from the shoreface or onshore environments (Fig. 2a).

Discriminant function analysis (DFA) of all four deposits indicates that sedimentologically, only the heavy mineral distribution in the storm deposit can distinguish the four units (Fig. 2b). However, at Silver Beach, less than 2 km south of Devannampattinam, Srinivasalu et al. (2007) and Switzer et al. (2012) described 2004 IOT deposits with abundant heavy minerals and dense laminations, in contrast with Pit DPM3a.

Comparison of Cyclone Thane and 2004 IOT microbial communities

Analysis of microbial communities followed standard procedures of extracting deoxyribonucleic acid (DNA) sequences from the sediment (Yap et al. 2021). Microbial

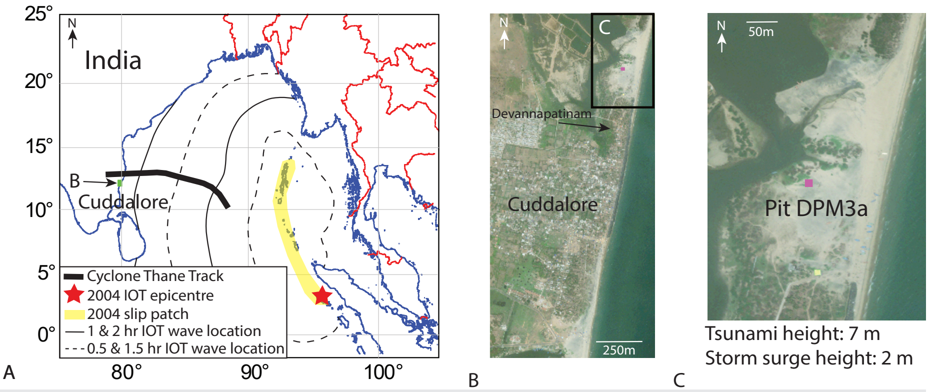

Figure 1: (A) Map of the Bay of Bengal showing the location and travel times of the 2004 IOT and Cyclone Thane storm track. **(B)** Satellite image of the Cuddalore coast showing the location of Devannampatinam and the pit site. **(C)** Satellite image of the beach near Devanampattinam where pit DPM3a was excavated.

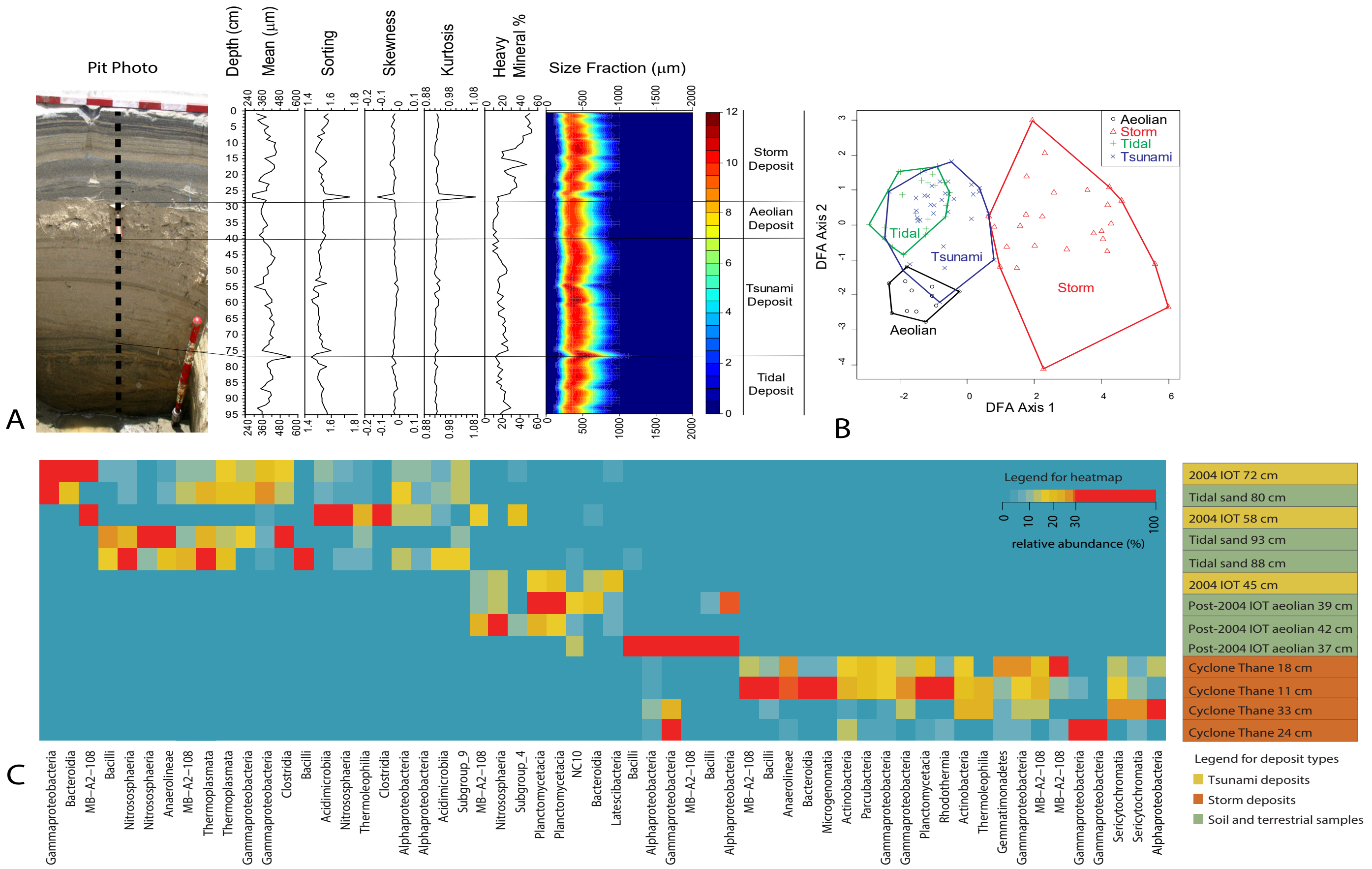

Figure 2: (A) Sedimentological parameters of Pit DPM3a. **(B)** DFA of sediment grain-size characteristics and heavy-mineral content of DPM3a units. **(C)** Microbes heatmap showing the relative abundances of different microbial groups in DPM3a communities. Figure modified from Yap et al. 2021.

metabarcoding analysis performed in this study targets the 16S ribosomal ribonucleic acid (rRNA) gene that identifies archaea, bacteria and eukaryotic taxa, as well as the 18S rRNA gene that is primarily used for identifying eukaryotic taxa. These rRNA markers are functionally similar over evolutionary time within a species, but exhibit variation across different species. The amplified DNA (called an amplicon) is then sequenced through a next-generation sequencer that generates a vast amount of DNA-sequence data. The distinct structure of the DNA sequences are determined (called amplicon sequencing variants – ASVs), and these ASVs are taxonomically distinct, thereby representing different species. Grouping of the average 42,406 DNA sequences resulted in a total of 4971 unique ASVs.

The microbial communities in the Cyclone Thane deposit significantly differed from the microbial communities in the 2004 IOT deposit, whereas the microbial communities within the 2004 IOT deposit were not significantly different from the underlying intertidal and overlying eolian deposits (Yap et al. 2021). The unique taxa preserved in the Cyclone Thane deposit included taxa from the families *Chromobacteriaceae*, *Rubinisphaeraceae*, *Burkholderiaceae*, *Micromonosporaceae*, *Bacillaceae*, *Nocardioidaceae*, *Sporichthyaceae*, *Caulobacteraceae*, and *Chitinophagaceae*, classes Sericytochromatia and Thermoplasmata, and the phylum Parcubacteria (Fig. 2b). No eukaryotic taxa could distinguish between the Cyclone Thane and 2004 IOT deposits.

Although it seems promising that storm and tsunami deposits can be distinguished by their microbial communities, further examination of another modern storm deposits on Phra Thong Island, Thailand, revealed that only taxa from the family *Chitinophagaceae* and class Thermoplasmata were present in both deposits (Yap et al. 2021). Further analysis of modern storm deposits may confirm the global signature of these taxa as unique to storm deposits. As no unique tsunami microbial signatures were present in the 2004 IOT deposits in India or Thailand, it is apparent that no global microbial signature exists for tsunami deposits (Yap et al. 2021).

This analysis focused on developing modern microbial signature analogues from storm and tsunami deposits. However, the microbial communities identified from the stacked 2004 and paleotsunami deposits from Thailand clearly show that the microbial communities become homogenized with non-tsunami sediments with age (Yap et al. 2023). It is likely the same would occur with older storm deposits under similar environmental conditions.

From our analysis of the 2011 Cyclone Thane and 2004 IOT deposits on the southeast coast of India, the sedimentological, stratigraphic and environmental DNA can discriminate recent coastal overwash events. However, modern analogues of both storm and tsunami deposits from the same geographical area are required to accurately discriminate between storm and tsunami deposits preserved in the geological record.

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