

Factors guiding tsunami surge at the Nagapattinam–Cuddalore shelf, Tamil Nadu, east coast of India

K. S. R. Murthy*, A. S. Subrahmanyam, G. P. S. Murty, K. V. L. N. S. Sarma, V. Subrahmanyam, K. Mohana Rao, P. Suneetha Rani, A. Anuradha, B. Adilakshmi and T. Sri Devi

National Institute of Oceanography, Regional Centre, 176, Lawsons Bay, Visakhapatnam 530 017, India

The Tamil Nadu margin, in particular the Nagapattinam–Cuddalore shelf was the worst affected by the tsunami surge and inundation caused by the great Sumatra earthquake of 26 December 2004 (M_w 9.3). Surge heights in this part were of the order of 2 to 5 m, with inundation of the order of few hundred metres into the interior coast, thus causing huge loss of human life and property. Several reasons were attributed to the unusual surge in this part of the Tamil Nadu margin, the main reason being its relative proximity to the origin of the event, apart from the concave nature of the shelf with a gentle gradient. A detailed analysis of geophysical data of the Nagapattinam–Cuddalore shelf is presented. The results indicate that the structure of the underlying basement, the morphology and the land–ocean tectonics are the main guiding factors for the run-up heights in case of the Nagapattinam–Cuddalore shelf. The fault-controlled basement structure, and a straight coastline with narrow and gentle shelf have helped in rapid transgression of the surge inundating the coastal area.

Keywords: Basement structure, Cuddalore–Nagapattinam shelf, run-up height, shelf morphology, tsunami surge.

THE Sumatra earthquake (M_w 9.3) of 26 December 2004, with its epicentre located SW of Sumatra island (3.29N, 95.98E) occurred at the interface of the Indian and Burmese plates, where the former subducts beneath the Burmese plate all along the Andaman–Sunda Arc^{1–4}. It is the fifth largest earthquake since 1900 and the largest since the 1964 Alaska earthquake. At this region the Indian plate moves towards NE at the rate of 6 cm/yr relative to the Burmese plate, which results in an oblique convergence at the Sunda trench. The oblique motion is partitioned into thrust-faulting and strike-slip faulting, which occur at the plate interface. The Sumatra earthquake was a result of such thrust-faulting^{1,4,5}.

The earthquake with a focal depth of 30 km has affected a length of nearly 1200 km along the interface⁶, with the rupture mainly propagating towards the north of the epicentre within an average width of 200 km. The average displace-

ment of the fault plane⁶ is 15 m. The rupture appears to have occurred in two stages; in the first stage it propagated rapidly to about 400 km followed by a slow rupture for about 500 km. The total duration of the rupture is around 800 s (13 min). Subsequent observations indicate that this catastrophic event made the earth wobble on its axis. An anticlockwise rotation of the islands of the Andaman and Nicobar region by about 2–3 m has been reported. The southern parts of these islands have undergone submergence of about 2 m, whereas the northern Andaman area has experienced an uplift of about 1 m^{7,8}. As many as 2000 aftershocks have been reported in this area even after seven months of the main event, with some of them having magnitudes greater than 7.0 (e.g. within 2 h of the event, M_w 7.3; 28 March 2005, M_w 8.4; 24 July 2005, M_w 7.3).

The earthquake appears to have disturbed a water column of nearly $100 \times 70 \times 1.5$ km volume, resulting in a unique Indian Ocean tsunami that has engulfed the coastal area of the Indian Ocean rim countries, including Indonesia, Thailand, India, Sri Lanka and as far west as Somalia in East Africa^{1,5}. Inundation on the coastal stretches is as much as 2 km in some cases, the worst affected being the Andaman and Nicobar Islands and southern parts of the east coast of India. Tidal measurements at Port Blair, Chennai and Visakhapatnam indicate surge heights of the order of 1.5–5.5 m amsl, with maximum height near Nagapattinam and Karaikal⁹. Tsunami waves reached the Nicobar Islands within a few minutes, the Andaman Islands within half an hour and the Indian coast in about 2–2.5 h^{8,9}. Sea-level transgression was of the order of 1100–1200 m in case of the Andaman coast, 350–1100 m in case of Nicobar and nearly 200–800 m in case of Tamil Nadu margin of the east coast of India.

The east coast of India is more prone to natural hazards like cyclones, storm surges and now the new hazard in the form of tsunamis, in comparison to the west coast. The Eastern Continental Margin of India (ECMI) is a passive margin evolved during the process of break-up of Eastern Gondwanaland during late Cretaceous¹⁰. In the pre-break-up scenario, the present Krishna–Godavari basin was conjugate with the Enderbyland of east Antarctica¹¹. Most rivers in the peninsular part of India flowing over southeastern and eastern slope discharge into the Bay of Bengal, which results in a mosaic of basinal and non-basinal morphology. Shallow bays associated with the basinal areas are more affected by the crossing of cyclones and storm surges, due to the wider shelf with gentle slope.

One of the important parameters to be considered in the context of cyclones/storm surges/tsunamis is the seabed morphology, including the shelf/slope characteristics of the margin. In this connection, the Regional Centre, National Institute of Oceanography, Visakhapatnam, India has collected bathymetry, magnetic and gravity data over the ECMI from Karaikal in the south to Paradip in the north. Morphology, stratigraphy, structure and tectonics of ECMI, including offshore river basins like the Cauvery, Krishna–

*For correspondence. (e-mail: ksr@nio.org)

Godavari and Mahanadi were analysed from the data¹⁰⁻¹⁴. Here, we make use of the data to analyse the factors that helped the high tsunami surge in case of the Nagapattinam–Cuddalore shelf of the Tamil Nadu margin.

It is evident from the bathymetric sections of the ECMI that the shelf is in general steep and narrow in the south (except off Chennai), whereas it is relatively wider and gentle in the north¹². However, some of the offshore river basins are associated with shallow bays with a concave coastline (Cauvery and Krishna–Godavari, for example). There is significant change in the direction of the coastline at 14°N, south of which the coastline is oriented in a N–S direction, whereas north of it is NE–SW in orientation. The average width of the shelf in the Nagapattinam–Cuddalore part is of the order of 79 km with a gentle gradient of 1 : 300. The gradient¹² of the continental slope in this part is approx. 1 : 18.

The southern part of the eastern continental shelf of India from Karaikal in the south (11°N) to Visakhapatnam in the north (approx. 18°N) was affected by the tsunami surge caused by the Sumatra earthquake (Figure 1). However, the Tamil Nadu shelf, in particular the Nagapattinam–Cuddalore part (shown as shaded zone in Figures 1–3), was the worst affected by the tsunami surge of 26 December 2004. The observed run-up heights in this part are as much as 5.2 m (Nagapattinam, for example) with inundation to a distance of nearly 800 m into the interior⁹. This part of the shelf represents the offshore Cauvery basin. Qualitative inferences^{15,16} suggest that some of the main reasons for the high tsunami surge in case of the Nagapattinam–Cuddalore shelf of Tamil Nadu margin are: (i) its close proximity to the source of the tsunami, (ii) configuration of the coastline and bathymetry of the shelf and (iii) tectonics associated with the offshore Cauvery basin.

Earlier analysis from magnetic data of the Cauvery basin¹³ suggests that the basin is fault-controlled, with two major E–W faults (shown as F1 and F2 in Figure 1a) extending from the land into the offshore. The northern fault is located north off Pondicherry, whereas the southern fault is located north off Vedaranyam. Magnetic and gravity data indicate shallow basement on either side of the main basin, with a down-throw underlying major part of the basin (schematic cross-section shown in Figure 1b). Dyke intrusions, with N–S trends were inferred north and south of these two E–W fault trends. In the central part of the basin, a minor basement rise representing probable offshore extension of the Kumbakonam Ridge was also delineated (shown as KR in Figure 1a). Thus the Nagapattinam–Cuddalore part of the Tamil Nadu margin is a structurally controlled basin flanked by two major fault lineations.

The free-air gravity anomaly map (Figure 2) is characterized by a significant north-south trending linear gravity low with major discontinuities, FZ1 and FZ2 along 12°15'N and 11°45'N respectively, indicating major fault zones¹⁴. The discontinuity observed in the gravity data (FZ1) correlates well with the major discontinuity observed in

the magnetic data (F1). Similar trend has also been evidenced from the bathymetry, which may indicate a major structural trend. The E–W trending lineation F2 (Figure 1a), which correlates well with the landward Palghat–Cauvery Lineament (PCL), can be considered as its offshore extension. The PCL has been termed as a shear zone. These studies have also revealed a good correlation between land–ocean tectonics and coastal seismicity and the epicentre of a moderate earthquake of magnitude 5.6 that occurred on 26 September 2001 was located over the fault trend FZ1, which was inferred as the offshore extension of the MBA lineament¹⁴.

Detailed bathymetry map and sections of the Nagapattinam–Cuddalore shelf (from 10.5 to about 12°N; Figure 3a, b) indicate that one of the main reasons for the higher run-up heights and inundation in the Nagapattinam–Cuddalore coast could be the concave shape of the shelf

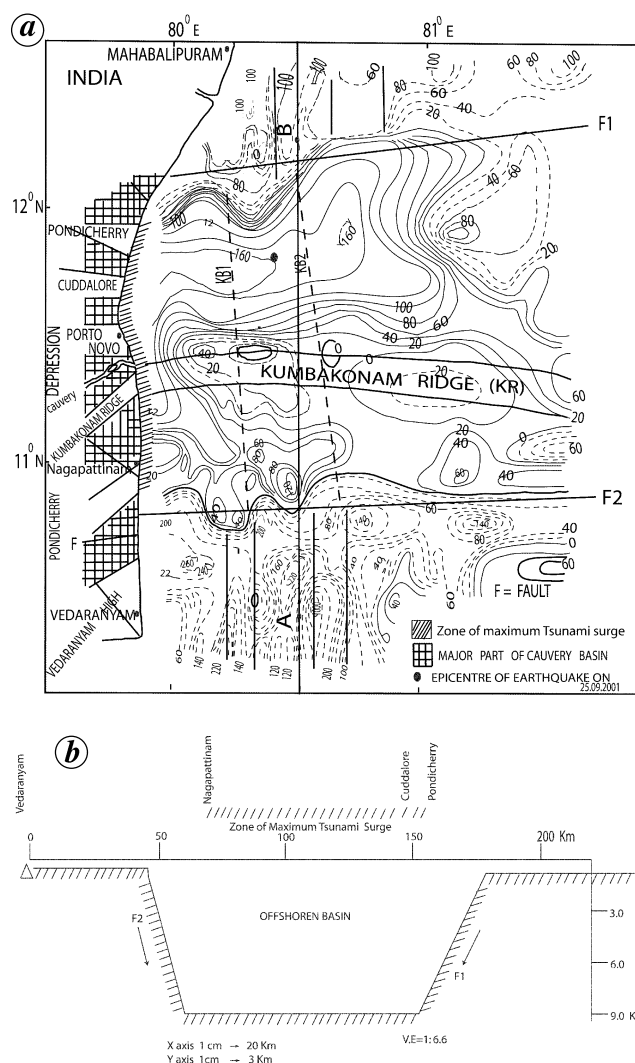


Figure 1. a, Magnetic anomaly map of Cauvery basin with structural interpretation (contour interval: 20 nT). b, Schematic cross-section of basement along profile A–B of Cauvery basin. Horizontal scale: 1 cm → 20 km; vertical axis: 1 cm → 3 km; VE = 6.6.

with a gentle slope, which might have accelerated the tsunami surge to flush through at a rapid force. Bathymetry sections off Pondicherry (CB3) and Cuddalore (CB4) indicate a narrow continental shelf and slope, with a gentle gradient up to about 3000 m water depth, representing the concave nature of the shelf. The sections off Vedaranyam (CB9) in the south and those north of Pondicherry (CB1 and CB2) indicate a wider shelf with steeper slope (Figure 3 b), representing the southern and northern boundaries of the concave shelf. The area within these boundaries is more affected by the tsunami surge.

The earliest bathymetry observations over the offshore Cauvery basin revealed the presence of submarine canyons off Cuddalore and Pondicherry¹⁷. Subsequent geophysical studies also suggested that major valleys off Pondicherry are formed due to the existence of mega lineaments¹⁸. The lineament pattern played a major role in shaping the continental slope morphology, besides erosional and depositional processes.

The high run-up heights and inundation in case of the Nagapattinam and Cuddalore shelf are therefore due to favourable seabed morphology, which in turn is the result of the faulted basement structure.

The Tamil Nadu part of the ECMI was relatively more affected by the tsunami surge caused due to the 26 December 2004 Sumatra earthquake (M_w 9.3), in comparison to the northern part of the ECMI, though the tsunami waves reached as far north as Visakhapatnam. The tsunami waves reached Tamil Nadu shelf approximately 2 h after the earthquake that occurred around 06.29 h (IST) at Sumatra Islands on 26 December 2004. Run-up heights near the

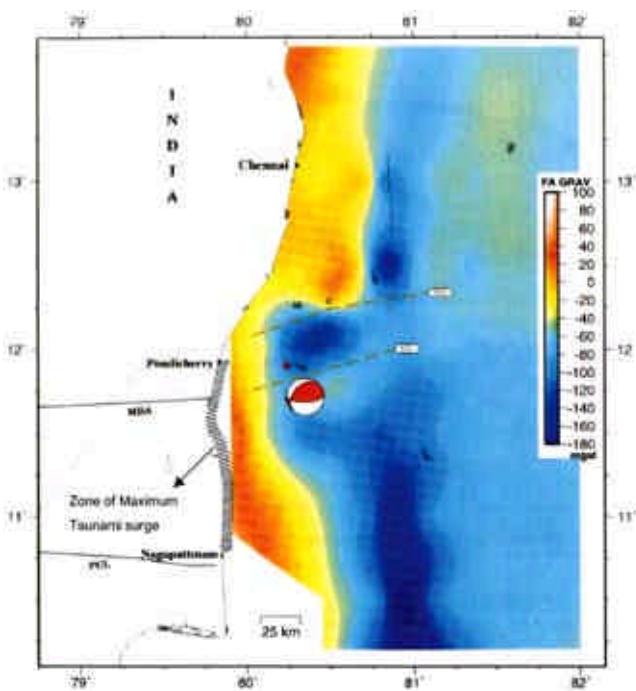


Figure 2. Free-air gravity map of Cauvery offshore basin.

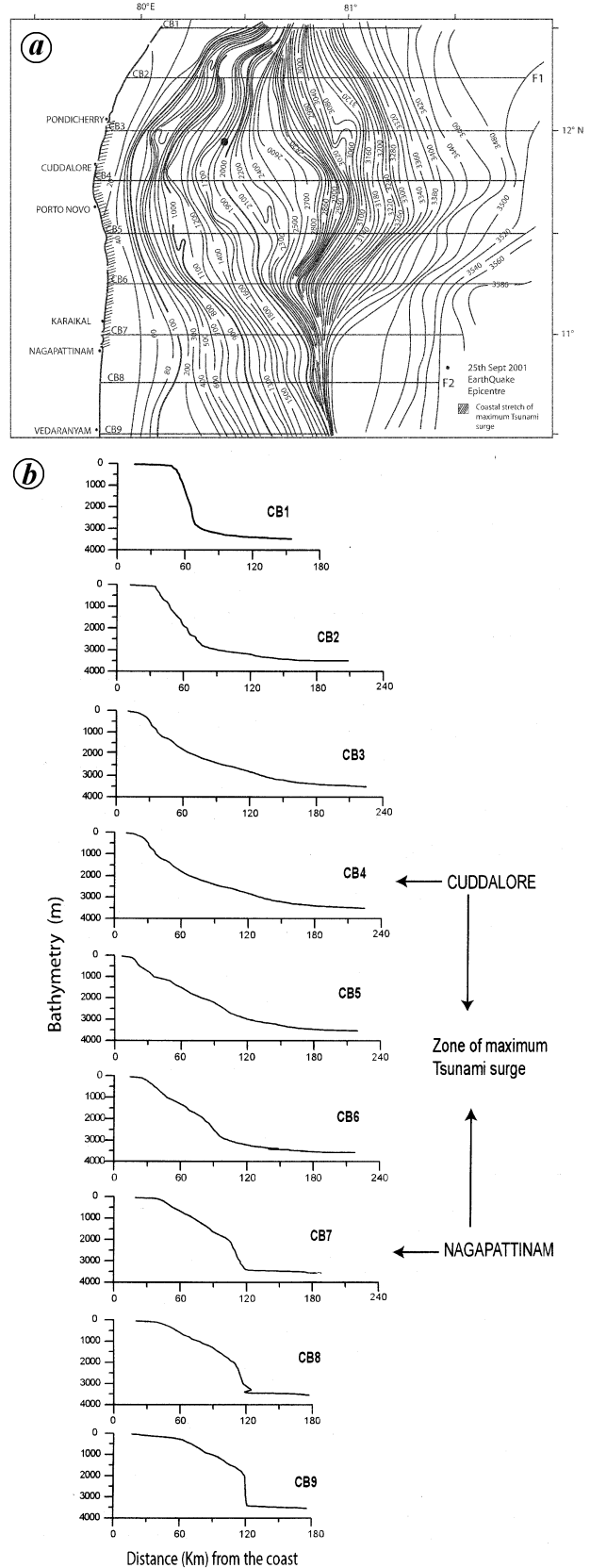


Figure 3. a, Bathymetry map of Cauvery offshore basin. Numbers indicate depth in metres. Contour interval variable (F1 and F2 are fault trends inferred from Figure 1 a). b, Bathymetry sections of Cauvery offshore basin.

Tamil Nadu shelf ranged from 2.6 to 5.6 m with run-up distances of the order of 150–800 m. Inundation caused due to the surge was higher over the Nagapattinam–Cuddalore part of the Tamil Nadu shelf, resulting in loss of human life of the order of a few thousands, in addition to heavy loss of property. Analysis of geophysical data of Tamil Nadu margin indicates that the higher amplitudes of tsunami surge and inundation are mainly due to the concave morphology of the shelf, apart from the fact that this part of the east coast of India is relatively at close proximity to the source of the tsunami. The straight nature of the coast with a gentle shelf/slope gradient, and the fault controlled structure of the basin resulting in concave shelf morphology, are some of the major factors that might have helped the rapid surge into this part of the shelf.

Similar analysis of bathymetry, magnetic and gravity data of the entire ECMI might help to demarcate risk-prone zones for tsunami surge and also in identifying zones of coastal seismicity which may be potential sources for local tsunamis. The fact that even ten months after the Sumatra event, aftershocks (>5.0 M) still continue in the Andaman and Nicobar segment of the Sunda trench, stresses the importance of these studies over the ECMI, which is now faced with a new type of natural hazard in the form of tsunamis, unusual to this part of the Indian Ocean.

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Acheulian cave at Susroni, Konkan, Maharashtra

Ashok Marathe

Deccan College Postgraduate and Research Institute,
Pune 411 006, India

The discovery of a Late Acheulian cave occupation at Susroni in Palshet near Guhagar, on the banks of a small perennial stream, near a waterfall, at a height of 85 m amsl and 2 km inland is the first of its kind on the more than 7500 km long coastline or on the Deccan plateau. On the basis of observations made on tool typology, geomorphology and lithostratigraphy, it is shown that early man occupied the cave during early Late Pleistocene.

Keywords: Acheulian, Maharashtra, Palaeolithic, Susroni.

THE Acheulian tradition forms a distinctive facies of the Lower Palaeolithic. The tradition derives its name from

e-mail: pranav@pn2.vsnl.net.in