6. Burkill, P. H., Mantoura, F. C. and Owens, N. J. P., Biogeochemical cycling in the northwestern Indian Ocean: A brief overview. *Deep-Sea Res. II*, 1993, **40**, 643–649.
7. Madhupratap, M. *et al.*, Mechanism of the biological response to winter cooling in the Northeastern Arabian Sea. *Nature*, 1996, **386**, 549–552.
8. Morrison, J. M. *et al.*, The oxygen minimum zone in the Arabian Sea during 1995. *Deep-Sea Res. II*, 1999, **46**, 1903–1931.
9. Naqvi, S. W. A. *et al.*, Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature*, 2000, **408**, 346–349.
10. Smith, S. L., Understanding the Arabian Sea: Reflections on the 1994–1996 Arabian Sea expedition. *Deep-Sea Res. II*, 2001, **48**, 1385–1402.
11. Platt, T. and Sathyendranath, S., Oceanic primary production: Estimation by remote sensing at local and regional scales. *Science*, 1988, **241**, 1613–1620.
12. Sarangi, R. K., Chauhan, P. and Nayak, S. R., Inter-annual variability of phytoplankton blooms in the northern Arabian Sea during winter monsoon period (February–March) using IRS-P4 OCM data. *Indian J. Mar. Sci.*, 2005, **34**, 163–173.
13. Gregg, W. W. *et al.*, Ocean primary production and climate: Global decadal changes, *Geophys. Res. Lett.*, 2002, **30**, 15, doi: 10.1029/2003GLO16889.
14. Dupelssy, J. C., Glacial to interglacial contrasts in the northern Indian Ocean. *Nature*, 1982, **295**, 319–321.
15. Sarkar, A., Ramesh, R., Bhattacharya, S. K. and Rajagopalan, G. S., Oxygen isotope evidence for a stronger winter monsoon current during the last glaciation. *Nature*, 1990, **343**, 548–551.
16. O'Reilly, J. E. *et al.*, Ocean colour chlorophyll algorithms for SeaWiFS. *J. Geophys. Res.*, 1998, **103**, 24,937–24,953.
17. Prasanna Kumar, S. and Prasad, T. G., Winter cooling in the northern Arabian Sea. *Curr. Sci.*, 1996, **71**, 834–841.
18. Barber, R. T. *et al.*, Primary productivity and its regulation in the Arabian Sea during 1995. *Deep-Sea Res. II*, 2001, **48**, 1127–1172.
19. Muraleedharan, P. M. and Prasanna Kumar, S., Arabian Sea upwelling – A comparison between coastal and open ocean regions. *Curr. Sci.*, 1996, **71**, 842–846.
20. Prasanna Kumar, S. *et al.*, High biological productivity in the central Arabian Sea during the summer monsoon driven by Ekman pumping and lateral advection. *Curr. Sci.*, 2001, **81**, 1633–1638.
21. Bange, H. W. *et al.*, A revised nitrogen budget for the Arabian Sea. *Global Biogeochem. Cycle*, 2000, **14**, 1283–1297.

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Subsidence of southern part of erstwhile Dhanushkodi township, Tamil Nadu – evidences from bathymetry, side scan and underwater videography

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The southern part of erstwhile Dhanushkodi township, Tamil Nadu, experienced subsidence and submergence during AD 1948–49. Shallow bathymetric and side-scan surveys together with sampling and underwater videography confirm the extent and quantum of subsidence. The studies reveal that a vertical tectonic movement (fault) parallel to the coastline with a displacement of ~ 5 m led to the subsidence of the southern part of the township. This fault movement has occurred 57 years ago and hence could be the latest neo-tectonic movement ever recorded along the east coast of India.

Keywords: Dhanushkodi, neo-tectonic activity, subsidence, submergence, vertical displacement.

THE coastal zone, the link between ocean and land margins, constantly experiences several dynamic processes, which at times result in various hazards to human beings. Such processes include erosion, accretion, upliftment, subsidence, submergence and their combined influence.

The extreme southeastern part of Rameswaram Island (Figure 1), known as Dhanushkodi Foreland, is well-known in Hindu mythology and is of religious importance. High-intensity storms and cyclones have frequently attacked this area and led to vast material and human losses in the past, particularly the cyclone of AD 1964. The erstwhile Dhanushkodi township (presently in ruins) underwent subsidence during the mid-twentieth century. This communication documents the marine geo-scientific investigations at Dhanushkodi area and provides evidences for coastal subsidence in the southern part of the erstwhile Dhanushkodi township in the Gulf of Mannar (Figure 1) and geological reasons for subsidence during AD 1948–49. Bathymetry, side scan and sampling surveys provide an insight into subsidence through underwater videography.

The southeastern tip of peninsular India assumes much importance from a geological point of view. However, till date, geological studies around Dhanushkodi are meagre, except for limited geomorphological observations by

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Geographical Information System (GIS)-based animation[1] and IRS-ID LISS III data around Adam's Bridge Islands[2]. Due to the shallow nature of the sea, no research vessel could attempt to negotiate the area around Dhanushkodi for marine geo-scientific studies. Geomorphologically, the onshore area is known for its extensive stretch of longitudinal sand dunes and sandy beach. The Geological Survey of India made systematic geomorphological studies of Rameswaram Island and drilling operations from Dhanushkodi to Adam's Bridge Islands, and also obtained information through enquiries from the local elderly people who were eyewitnesses to the subsidence. The studies reveal that the southern side of erstwhile Dhanushkodi township facing the Gulf of Mannar underwent severe erosion and subsidence between AD February 1948 and January 1949. Consequently, the southern part of the township comprising places of worship, residential areas, roads, etc. over a width of ~ 500 m along the N–S direction and a stretch of 7 km along WNW–ESE direction (Figure 1) was destroyed by wave attack and submerged to the depth of 5 m. Following this destructive event, then the District Administration has dumped granite blocks and made a series of wooden piles down to ~ 10 m all along the coastline, in order to arrest further wave attack and eventual loss of land. The granite blocks and wooden piles were subsequently covered by littoral sand.

Field studies and local enquiries confirm that the whole Dhanushkodi township prior to subsidence (i.e. AD 1948–49) was at an elevation of > 3 m above the present sea level. The unaffected northern part of the township even now remains at ~3 m above sea level. The sequence of events suggests that submergence of the township might have taken place due to the fast rate of subsidence of the southern part (presently under the sea). Additional observations, subsequent to local enquiries, aroused a keen interest to evaluate the geological reasons, if any, for such rapid rate of subsidence. Hence, detailed surveys were conducted in the offshore area of about 12×2 km between Kothandaramar temple and Dhanushkodi tip (Figure 1), by engaging a locally available mechanized wooden boat of 8 m length, fitted with portable echosounder.

Bathymetric observations were made continuously along shore-perpendicular and parallel tracks at 250 m interval, whereas between Mukundarayarchatram (locally known as Mundramchatram) and Dhanushkodi tip, the tracks were maintained at 125 m interval. This network enabled collection of closely spaced bathymetric data from the reported area of subsidence. The shot points at every two-minute intervals were recorded using hand-held (Micrologic) Global Positioning System (GPS).

The tide-corrected depths by harmonic interpolation were plotted on the base chart. The bathymetric contour map (Figure 2) and a 3D computer model of the seafloor (Figure 3) indicate a scarp face aligned parallel to the coast from Mukundarayarchatram to Dhanushkodi tip, indicating the actual extent and magnitude of subsidence (Figures 2 and 3). It is evident that a fracture (fault) in the offshore has occurred along WNW–ESE direction parallel to the coastline at ~ 2.5 m of the present water depth. The vertical displacement of the inferred fracture (fault) is estimated to

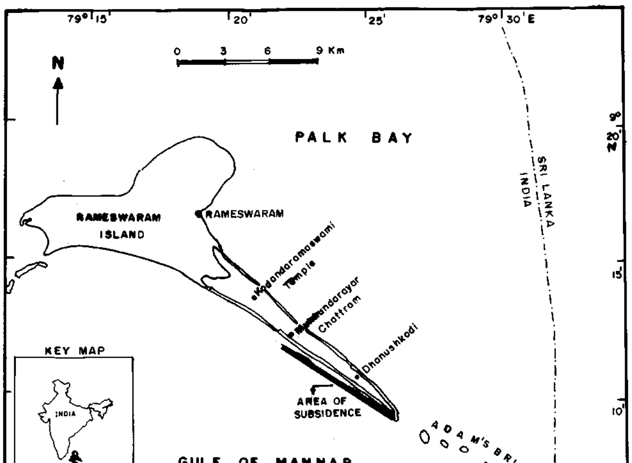

Figure 1. Map showing area of study and subsidence.

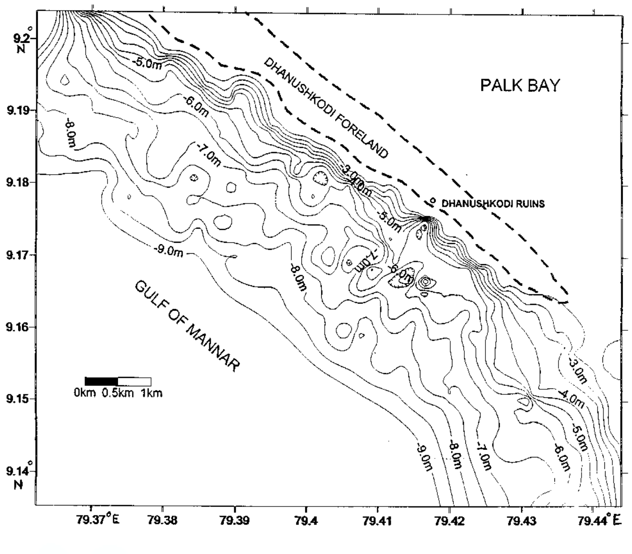

Figure 2. Bathymetry map.

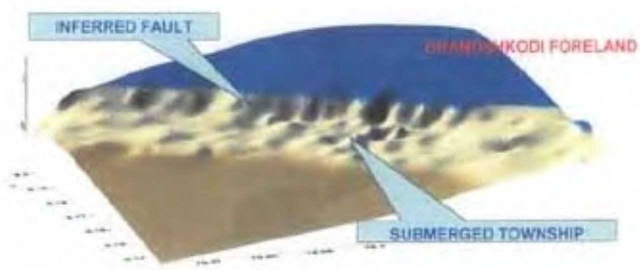

Figure 3. 3D computer model of bathymetry.

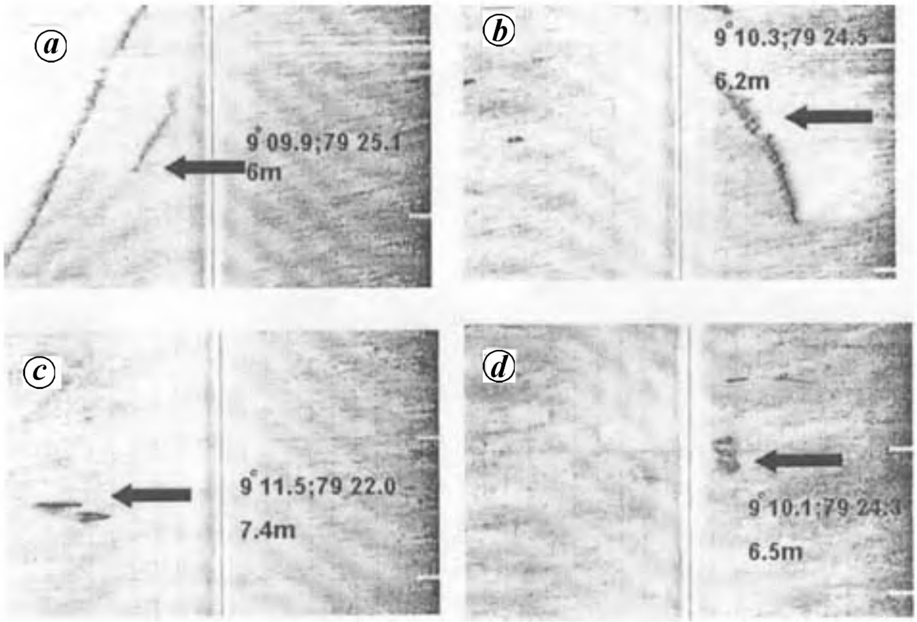

Figure 4. Side-scan records of Dhanushkodi depicting subsidence. ***a*** and ***b***, Shore linear road; ***c*** and ***d***, Collapsed residential buildings.

be ~ 5 m (Figures 2 and 3). This fracture (fault) detected at the offshore zone appears to be sympathetic to the regional lineament known as Vaigai lineament (WNW–ESE) along Vaigai river course in the adjoining mainland. The area of subsidence is characterized by pinnacled surface (Figure 3), probably projections of civil structures such as residential blocks, places of worship, etc. According to the local divers, the scarp face is of 3–5 m relief and observations on samples picked up by divers from the scarp face confirm the occurrence of coarse-grained beach rock.

Seabed samples collected by van Veen grab between 1 and 10 m water depths at 100 m grid revealed that the area is generally covered by a veneer of coarse to medium shelly sand and silty sand with a few small pockets of clayey sand and clay beyond 6 or 7 m depths. There is paucity of sediment input into the offshore domain. Further, due to submergence of coastal zone by faulting, the shoreline migrated landward, the pre-existing coastal plain deposits were reworked by near-shore waves and current activity to form a widespread deposit of shelly sand and silty sand over the submerged township and facilitated filling-up of depressions between features or structures. Hence, only the relatively elevated structures are practically devoid of sediment cover.

Due to depth and draft constraints, side-scan survey was carried out along three shore-parallel tracks between 5 and 10 m depths by deploying GSI Research Vessel *R.V. Samudra Shaudhikama*. The records exhibit linear features and elevated hard objects that could possibly be roads and collapsed residential buildings, respectively (Figure 4 *a–d*).

On the basis of bathymetric records, potential locations were selected and skilled divers from local fishermen community were deployed to retrieve materials from the zone of subsidence. Construction materials like bricks, chiselled coral blocks, clay tiles, asbestos roof sheets, etc. were recovered. Subsequently, locally available wooden boats (8 m length) and professional underwater divers (Diving Consultancy, Tuticorin, Tamil Nadu) with underwater still and movie cameras attached with on-board monitor, were engaged for systematic and detailed underwater videography. For every diving operation, a marker buoy was tied on the location of objects or structures for detailed video recording and retrieval of materials. Locations of every buoy were recorded on-board using hand-held GPS. On reaching the important spots, the divers manually cleaned the objects, videographed and retrieved materials of significance.

Underwater video observations confirmed one main road with collapsed houses of the erstwhile Dhanushkodi township at 5 to 7 m depth. The above observation matches well with the area of subsidence picked up from the bathymetric map prepared exclusively for this purpose. A number of objects located and retrieved during the underwater videography could be further classified into (i) E–W-aligned road, rectangular brick-wall structures suggesting collapsed houses/buildings, (ii) circular and semi-circular brick walls considered as the full or a portion of ring wells, (iii) walls constructed by chiselled coral blocks (Figure 5 *a*), (iv) well-chiselled and faceted pillars made from shelly sandstone, possibly parts of temple structure and (v) a variety of household articles such as metal tumbler, broken frying pan, sanitary iron pipes, etc. (Figure 5 *a* and *c*). The granite blocks and wooden piles laid along the coastline to arrest further erosion have now been exposed due to recent seasonal coastal erosion (Figure 5 *d*).

After collection of all scientific data, local Tamil Nadu State Land Records were consulted for old survey records pertaining to this area, to gather additional information

Figure 5. Materials retrieved from submerged township. ***a***, Well-chiselled coral block; ***b***, Broken frying pan and brick; ***c***, Piece of sanitary pipe; ***d***, Granite blocks and wooden piles laid along the coastline during 1948–49, now exposed.

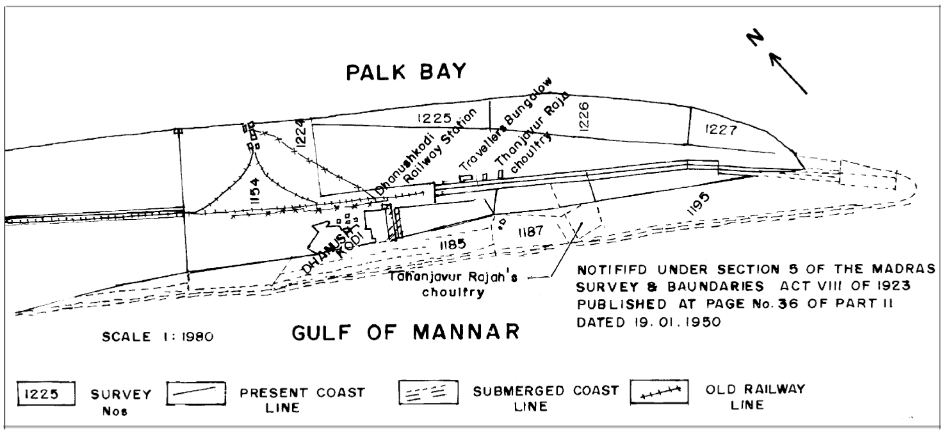

Figure 6. Land record showing area of subsidence.

about the past habitation. Comparison of the maps of Dhanushkodi village prepared by State Revenue authorities prior to (AD 1948–49) and after the (AD 1950) subsidence has facilitated demarcation of the actual area of subsidence by survey numbers, names of the important buildings, etc. (Figure 6). Land records prepared after 1950 provide yet another proof of subsidence of the southern part of erstwhile Dhanushkodi township.

The observations mentioned above substantially prove the subsidence and submergence of erstwhile Dhanushkodi township. Reportedly, when sea retreated to about 500 m from the present coastline prior to the arrival of recent tsunami wave in December 2004, the subsided and submerged part of the township got exposed for a while. This rare sight has been witnessed by the local fishermen community. The local inhabitants believed that coastal erosion was the main causative factor for the destruction and subsidence of the township in mid-twentieth century. The present marine geo-scientific observations, however, confirm a vertical movement parallel to the coastline with a displacement of ~5 m in the offshore segment (Figures 2 and 3), which actually led to the subsidence of the southern part of the township.

Such neo-tectonic movements at various places along the east coast of India have been reported[3–6]. Normally, neotectonic movements in the coastal zone may be discerned by the study of palaeo-strandlines. However, the area of study does not show any indication of such strandline positions, except a wide Aeolian belt along the coast. Under this scenario, other critical sets of data pertaining to nearshore bathymetry, side scan, sampling and underwater videography have provided valuable clues in support of the subsidence phenomenon through neo-tectonic activity. Usually it is not an easy task to confirm the evidence of Holocene faulting within the unconsolidated sediments. The present evidence of faulting off erstwhile Dhanushkodi township is documented with geo-scientific clues from offshore field evidences, and hence stands out as a unique study. The fault throw of ~5 m discerned in the study area may be only a surficial manifestation of a deep-seated and major faulting at depth, whose actual and destructive effect has not reached the surface. The faulting has understandably caused severe loss to the coastal zone, its inhabitants and their properties.

This event of subsidence along with field evidence of faulting does not warrant any dating method to prove the age of this faulting, because according to eyewitnesses and land-survey records, this geological event occurred during AD 1948–49. Most likely, this Dhanushkodi fault is the latest neo-tectonic movement ever recorded along the east coast of India.

1. Ramasamy, S. M., GIS-based animation of changing terrain features in Rameswaram Island, Tamil Nadu, during the last century. *Proc. Indian Natl. Sci. Acad. Part A*, 2003, **69**, 251–256.
2. Bahuguna, A., Nayak, S. and Deshmukh, B., IRS views the Adam's Bridge (bridging India and Sri Lanka). *J. Indian Soc. Remote Sensing*, 2003, **31**, 237–239.
3. Loveson, V. J., Rajamanickam, G. V. and Anbarasu, K., Remote sensing application in the study of sea level variation along the Tamil Nadu coast. In National Seminar on Sea Level Variation and its Impact on Coastal Environment (ed. Rajamanickam, G. V.), Tamil University, Thanjavur, 1990, pp. 179–197.
4. Vaz, G. G. and Banerjee, P. K., Middle and late Holocene sea level changes in and around Pulicat Lagoon, Bay of Bengal, India. *Mar. Geol.*, 1997, **139**, 261–271.
5. Vaz, G. G., Mohapatra, G. P. and Hariprasad, M., Geomorphology and evolution of barrier-Lagoon coast I part of north Andhra Pradesh. *Mem. Geol. Soc. India*, 2002, **49**, 30–40.
6. Banerjee, P. K., Vaz, G. G., Sengupta, B. J. and Bagchi, A., A qualitative assessment of seismic risk along the Peninsular coast of India, south of 19°N. *J. Geodyn.*, 2001, **31**, 481–498.

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Occurrence of fluoride in the groundwaters of Pandharkawada area, Yavatmal district, Maharashtra, India

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Hydrogeological investigations have been carried out in the rural parts of Yavatmal district, Maharashtra, where agriculture is the main occupation. The area is mainly occupied by Deccan basalts, except in the southern part, where limestone and shale belonging to the Penganga Group occur. Groundwater occurs under unconfined conditions in the weathered and fractured portions of rocks, and semi-confined to confined conditions in fractured rocks. The groundwater of the area is of bicarbonate (HCO_3^-)-type and high fluoride (F^-) concentration is observed in deeper aquifers compared to shallow aquifers. Physicochemical conditions like decomposition, dissociation and subsequent dissolution along with long residence time might be responsible for leaching of F^- into the groundwater.

Keywords: Deccan basalts, groundwater, fluoride, rocks.

SOME elements are essential in trace amounts for human beings, while higher concentration of these elements causes toxic effects, and fluoride (F^-) is one of them[1]. Concentration of F^- between 0.6 to 1.0 mg/l in potable water protects tooth decay and enhances bone development[2,3]. Indian drinking water standards have suggested[3] permissible limit of F^- in drinking water at 1.0 mg/l, which is lower than the maximum tolerance limit (1.5 mg/l) of F^- in drinking

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