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Sediment characterisation of the 26 December 2004 Indian ocean tsunami in Andaman group of islands, bay of Bengal, India

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Abstract The large tsunami, which was generated by an earthquake on 26 December 2004, affected most of the countries around the Indian Ocean. A total of 48 tsunamigenic surface sediments have been collected from various coastal geomorphological features such as beaches, estuaries/creeks and mangrove areas in the Andaman group of islands. These samples were analysed for sediment characteristics such as sediment texture, granulometric studies. The studied tsunamigenic sediments, deposited by the 26 December 2004 tsunami in the Andaman group of islands consist of poorly sorted, coarse sand to medium sands, and are similar to depositional effects of previously reported earthquake-generated tsunami waves. The tsunamigenic sediment consists of a coarse sand layer with abundant reworked shell and other carbonate fragments. The tsunami sediments were mainly composed of boulders of corals and sand which determines the high-energy environment throughout the study area. The variation in Φ mean size, therefore, reveals the differential energy conditions that lead to the deposition of these kinds of sediments in different locations. The tsunamigenic sediments were mainly poorly sorted, moderately well sorted and well sorted during the post-tsunami (2005) and whereas they were mainly moderately well sorted to well sorted during the post-monsoon (2008). The symmetry of the samples varies from strongly fine skewed to strongly very coarse skewed in the post-tsunami (2005) and post-monsoon (2008). The Kurtosis of the tsunami sediments were mainly Platykurtic, Mesokurtic and Lepokurtic during the post-tsunami (2005) and mainly Mesokurtic and Lepokurtic in post-monsoon (2008).

Keywords Tsunamigenic sediments · Grain size · Texture · Andaman group of islands

Introduction

Worldwide tsunami catalogues from different parts of the world list far more than 2000 tsunami events during the past 4,000 years. (e.g., Heck 1947; Iida et al. 1967a, b; Papadopoulos and Chalkis 1984; Zhou and Adams 1986; Nakata and Kawana 1995; Tinti and Maramai 1996; Lander and Whiteside 1997; NGDC 2001). In many places in the world, the written record of tsunamis is too short to accurately assess the risk of tsunami, although sedimentary deposits left by tsunamis can be used to extend the record of tsunamis to improve risk assessment. When sediment is deposited by a tsunami and preserved, a geologic record of that event is created. By looking at the sedimentary record in an area, geologists may be able to identify such deposits and infer the occurrence of past tsunamis. The recognition of deposits from past tsunamis allows geologists to extend the relatively short or non-existent historical record of tsunamis in an area. Because scientists cannot yet predict when a tsunami will occur, obtaining a geologic record of past events may be one of the only means to assess future risk.

Tsunami waves are known to be able to cause significant alterations in coastal systems (Dawson 1994; Bryant et al. 1996; Bryant 2001 and Scheffers and Kelletat 2003). From the geological viewpoint, tsunamis are notable as short lived but extremely powerful agents with a very complex pattern of erosion and deposition, leaving large volumes of sediment on the seafloor and coastal areas (Bondevik et al.

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1997). In particular, studies of the sedimentary deposits from the Okushiri, Japan tsunami (Sato et al. 1995; Nishimura and Miyaji 1995), and the Flores Island, Indonesia tsunami (Dawson 1994; Shi et al. 1995) describe the pattern of sedimentation associated with a tsunami. For example, Shi et al. (1995) find that the grain-size fines landward in the deposit on Flores Island.

A tsunami deposit is usually identified by sedimentary context (e.g. deposited on soil associated with coseismic subsidence), larger grain size than surrounding sediments indicating higher-energy depositional conditions, spatial distribution of the deposit, and by ruling out other high energy depositional modes (e.g. storm surges or floods). For example, in Cascade, paleotsunami deposits are identified as being anomalous sand layers in low energy marsh or lacustrine environments (Atwater 1987; Clague et al. 2000). There is additional information which indicates a seaward source of sediments, such as microfossils (Hemphill-Haley 1995a; b) or geochemical signature (Schlichting 2000), which also useful for determining that a deposit was formed by a tsunami. Generally tsunamis are classified into three categories, distant (>750 km from the source), regionals (100–750 km from the source), and local (<100 km from the source).

Grain size analysis is the epicenter of any sedimentological research. It is a fundamental descriptive measure of sediments and sedimentary rocks. Grain size studies of sediments can give information about various depositional processes like nature of the particle, mode of weathering and changes occur during transportation from place to place. Also grain size parameters are being used as indicators of sediment size distribution and depositional environments. From the beginning of nineteenth century onwards many remarkable works have been carried out to appreciate the grain size characteristics of sand (Udden 1914; Wentworth 1929; Krumbein 1937; Krumbein and Pettijohn 1938; Otto 1939; Keller 1945; Klovan 1966). Grain size studies for delineating the subtle difference in depositional environments were brought out clearly by Folk and Ward (1957). Various authors have attempted to discriminate the environments like river, beach and dune using textural parameters (Mason and Folk 1958; Friedman 1961, 1967; Moiola and Weiser 1968). A few efforts have been made to distinguish beach sand from dune sand and from river sand using textural parameters (Sevon 1966). Keller (1945) has indicated that dune sediments can be distinguished from beach sands on the basis of shape of the size frequency curves. Inman (1949) has established a relationship between the dynamics involved during sedimentation and the resulting textural characteristics of the sedimentary rocks. The statistical method has been applied in diagnosing the finer differences that may exist within a particular environment of the same physiographic unit's viz., dune, berm, high tide, mid tide and low tide sediments (Mohan and Rajamanickam 1998, 2001). In the present study, an endeavor has been made to make use of the grain size characteristics of sediments collected from different part of the environment that are subjected to various degree of erosion, transportation and depositional mechanisms.

The micropaleontological criteria also rely on specific hydrologic and geodynamic conditions. In fact depending on the hydrodynamic of the shoreline, the geomorphology of the coast and the behaviour of the tsunami waves, the fossil record will present particular/different characteristics. The micropaleontological assemblages depend, for example, on the habitats crossed by the tsunamis waves when traveling towards the coast. Hussain et al. 2006 studied and identified the presence of Ostracods in the recent 26 Dec 2004 tsunamigenic sediments in Andaman Islands.

Methodology

This study aims to contribute to a better understanding of the effects of tsunami on coastlines and what evidence they may leave in the coastal stratigraphy by analysing the tsunamigenic sediments. These observations of modern tsunami sedimentation will ultimately improve the identification and interpretation of palaeotsunamis in the geologic record. The recognition of deposits from past tsunamis allows geologists to extend the relatively short or non-existent historical record of tsunamis in an area. Because scientists cannot yet predict when a tsunami will occur, obtaining a geologic record of past events may be one or the only means to assess future risk. Hence the present study has been taken up to investigate the characteristics of the tsunami deposits along the coast of Andaman group of Islands. The entire group of Andaman Islands has been taken for this study. Extensive fieldwork was carried out during May–June 2005, post-tsunami (2005) and March 2008, post-monsoon (2008). The locations of tsunamigenic sediments surface samples were recorded using a GPS. A total of 48 tsunamigenic surface samples were collected from the study area from various geomorphological tsunami inundated features such as beaches, estuaries/creeks, backwaters and mangrove swamps, with the help of crab. Collected samples were transferred to our geo-chemical laboratory for further analysis. The collected surface samples were air dried and homogenized. After homogenization, sand, silt and clay ratios were determined following the procedure given by Carver (1971). The carbonate content of all the surface samples was determined by adopting the procedure of Loring and Rantala (1992), as it is an important component of coastal marine sediments that serves as a dilutor for trace metals. Organic matter was estimated in the form of organic carbon based on the procedure suggested by Gaudette et al. (1974) to assess the role played by organic carbon in the retention of trace metals. Sieving was carried out in ASTM at quarter ϕ interval (25, 35, 45, 60, 80, 120, 170, 230, 325 and Bottom). The sieve sets, stacked in the descending order of their sizes, were shaken using Ro-tap sieve shaker continuously for about 20 min. During sieving, proper attention was paid to minimize the sand loss from the sieve sets. The sieved materials were collected separately for weighing. Weight of the individual fractions was tabulated for further granulometric studies. Granulometric study is essential to understand the mode of transportation and depositional environment of sediments. Using graphic (Folk and Ward 1957) and moment methods (Friedman 1961, 1967, 1979) the weight percentage data of 48 (two seasons) samples were processed using a personal computer by the modified programme of Schlee and Webster's (1967) procedure. The mentioned characteristics of the sediments and the mechanisms were utilized to study the size analysis. Textural attributes of sediments and sedimentary rocks namely mean (Mz), standard deviation (σ1), skewness (SkI) and kurtosis (KG) are widely used to reconstruct the depositional environments of sediments and sedimentary rocks (Amaral 1977). For the present study, *GRADISTAT-VERSION-4.0 programme* developed by Sumaon Blatt and Kenneth Pye (2001) is utilized. From the statistical parameters, frequency curves, mean size, standard deviation, skewness, kurtosis and a comparative statement was drawn for the analysis proceedings.

Study area

The entire group of Andaman Islands has been taken for this study. Extensive fieldwork was carried out from June 2005 post-tsunami and during March 2008, post-monsoon (2008). The Andaman and Nicobar Islands comprising of 572 islands/islets, extend over an area of 8,249 Km^2. These islands are located between 6^o 45″ and 13^{o}41″ North latitudes, and 92^o 12″ and 93^o 57″ East longitudes. However, only 38 Islands are inhabited having a total population of 3,56,152, according to the 2001 Census. Although, 94 are designated as sanctuaries, including six areas as national parks, two of which are marine national parks, two areas and two islands as tribal reserves in the Andamans. The land area of 6,408 km² in the Andamans constitutes 90% as reserves and protected areas of which 36% are tribal reserves. The entire Nicobar group is a tribal reserve and has four wildlife sanctuaries, two national parks and one biosphere reserve. The status, flora, fauna and profiles of all the protected areas for both island groups has been discussed in detail (Pande et al. 1991; Andrews and Sankaran 2002; ANET 2003).

The locations of the tsunamigenic surface sediments were recorded using GPS and are given in the Table 1. The study are has been further segmented into the North Andaman, Middle Andaman, South Andaman and Little Andaman. Diglipur and Mayabandar which come under the study areas of North Andaman Islands, where Rangat, Baratrang and the Havelock Island cover the Middle Andaman. Similarly Port Blair, Siphighat creek, Corbins Cove Beach, Chatham Islands, Ross Island, Rutland Islands and Chidiyatapu areas come under the South Andaman and finally the Hut Bay, in Little Andaman Islands (Fig. 1). The Andaman and Nicobars are fringed by one of the most spectacular reefs in the world and currently they are not only significant for the Indian Ocean region, but are also globally (Kulkarni 2000; Vousden 2000; Turner et al. 2001; Andrews and Sankaran 2002).

Historical earthquake in the Indian ocean

Even though tsunami is a common phenomenon in the Pacific region, some destructive tsunamis have also occurred in the Indian and Atlantic Oceans (Altinok and Ersoy 2000). As far as the Indian Ocean is concerned, the main tsunamigenic sources are past and potential earthquakes generated at its eastern boarder great subduction zone ranging from Myanmar to Indonesia through Nicobar and Andaman Islands (Fig. 2). The recurrent tsunami events (triggered by seismic activity) of the Indian Ocean indicate that more than 80% of them are originated from the Java Sumatra and Andaman/Nicobar subduction zone (Rastogi and Jaiswal 2006). Mega-earthquakes and associated tsunamis have approximately a 2 century period of recurrence while the one of smaller but significant event is of the order of few decades (Rastogi and Jaiswal 2006). In this study we have updated former catalogs of tsunami events in the Indian Ocean (about 90) (Newcomb and McCann 1987; Heck 1947; Berninghausen 1966; Lisitzi 1974 and USGS 2005).

Description of 26 December 2004 tsunami

On Sunday, 26 December 2004 at 00:58:53 UTC, a great earthquake with a moment magnitude of 9.0—or possibly greater (Stein and Okal 2005)—nucleated 250 km southwest of the north tip of Sumatra, Indonesia. A large tsunami was generated and severely damaged coastal communities in countries along the Indian Ocean, including Indonesia, Thailand, Sri Lanka, India, Maldives, and Somalia (Synolakis and Kong 2006; Synolakis et al. 2005) where distances of more than 6,000 km, which correspond to wave travel time up to ~8 hrs. The original earthquake and aftershocks

Table 1 Sample locations with GPS values and the distance from the shoreline

S.No.	S.ID	Lat	Long	Sample location	Distance from the shore line (m)
1	DG1	13°13′28″	93°02′42″	Kalipur	6
2	DG2	13°16′08″	93°02′25″	Old Jetty Durgapur	5
3	DG3	13°16′11″	93°02′24″	Durgapur	10
4	DG4	13°16′36″	93°01′51″	Old fisher colony	1
5	DG5	13°16′54″	93°01′36″	Ariel Bay Jetty	30
6	MB1	12°55′07″	92°55′56″	Avis island	20
7	MB2	12°56′30″	92°57′14″	Sound island	17
8	MB3	12°57′40″	92°55′19″	Extension of Mayabandar	0.51
9	MB4	12°56′27″	92°54′03″	Orchid island	5.9
10	MB5	12°56′12″	92°53′25″	Curlew island	2
11	MB6	12°55′56″	92°53′27″	Egg island	1
12	MB7	12°55′45″	92°53′13″	Dotterl island	6
13	MB8	12°54′33″	92°52′33″	Shallow bay	20
14	MB9	12°50′50″	92°56′20″	Karmatang	8
15	RA1	12°35′45″	92°57′27″	Rangat coast	0.12
16	RA2	12°35′41″	92°57′26″	Rangat coast	0.78
17	RA3	12°35′35″	92°57′26″	Rangat coast	0.47
18	RA4	12°35′34″	92°57′50″	Rangat coast	0.24
19	RA5	12°30′42″	92°57′57″	Aamkunj beach	0.57
20	BA1	12°06′36″	92°44′37″	Estuaries	20
21	BA2	12°03′54″	92°46′11″	Estuaries	6
22	BA3	12°06′27″	92°48′00″	Estuaries	0.25
23	BA4	12°11′32″	92°52′43″	Boat fan broken	4
24	BA5	12°11′36″	92°52′32″	Limestone cave	10
25	SA1	11°30′26″	92°41′58″	Chidiyatapu	130
26	SA2	11°29′31″	92°36′57″	Jolly boys island	10
27	SA3	11°29′29″	92°39′19″	Rutland island	20
28	SA4	11°30′41″	92°36′58″	Red skin island	5
29	SA5	11°35′01″	92°36′04″	Alexandra island	30
30	SA6	11°35′01″	92°36′41″	Grub island	15
31	SA7	11°39′31″	92°43′49″	South coast	11
32	SA8	11°34′45″	92°44′16″	Junglighat	5
33	SA9	11°34′47″	92°44′13″	Junglighat	8
34	SA10	11°39′31″	92°43′49″	Junglighat	10
35	HA1	11°59′03″	92°57′13″	Radha Nagar beach	5
36	HA2	12°01′10″	93°00′32″	Dolphin beach	2
37	HA3	12°02′30″	92°58′49″	Havelock Jetty	15
38	SC1	11°36′24″	92°41′16″	Sipighat estuaries	1,500
39	SC2	11°36′27″	92°41′17″	Sipighat estuaries	1,460
40	SC3	11°36′34″	92°41′17″	Sipighat estuaries	1,300
41	SC4	11°36′46″	92°41′28″	Sipighat estuaries	808
42	SC5	11°36′46″	92°41′32″	Sipighat estuaries	780
43	HB1	10°37′25″	92°32′63″	Nethaji Nagar	25
44	HB2	10°35′34″	92°32′35″	Hut bay	75
45	HB3	10°35′20″	92°33′20″	Jetty harbour	193
46	HB4	10°35′04″	92°33′56″	Back waters	55
47	HB5	10°34′26″	92°33′56″	Vetinary hospital	265
48	HB6	10°33′55″	92°33′33″	Harmindar bay	325

DG Diglipur, *MB* Mayabandar, *RA* Rangat, *BA* Baratrang, *SA* South Andaman, *HA* Havelock, *SC* Sipighat creek, *HB* Hut Bay, *RUT* Rutland Island and *JUN* Junglighat

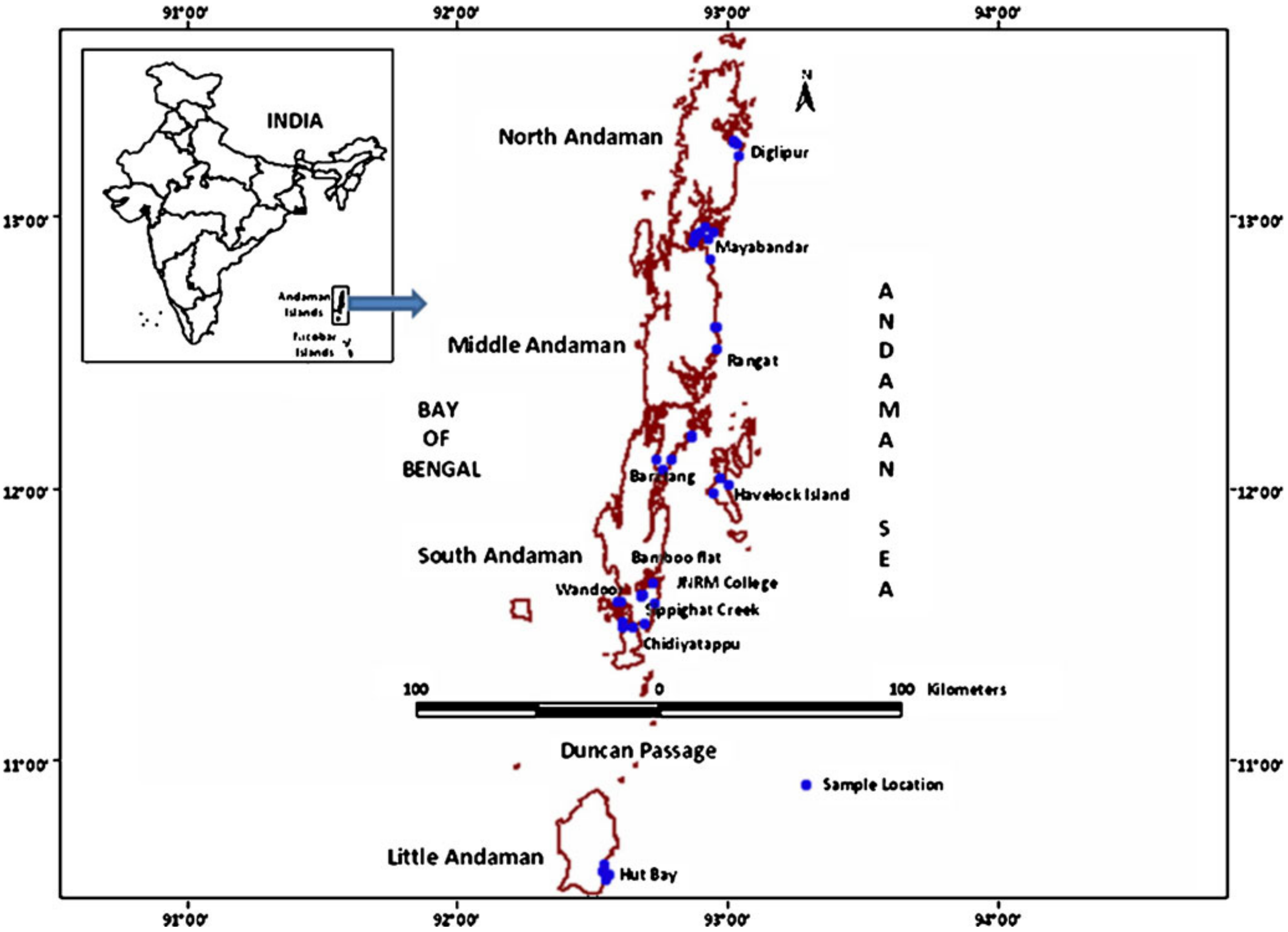
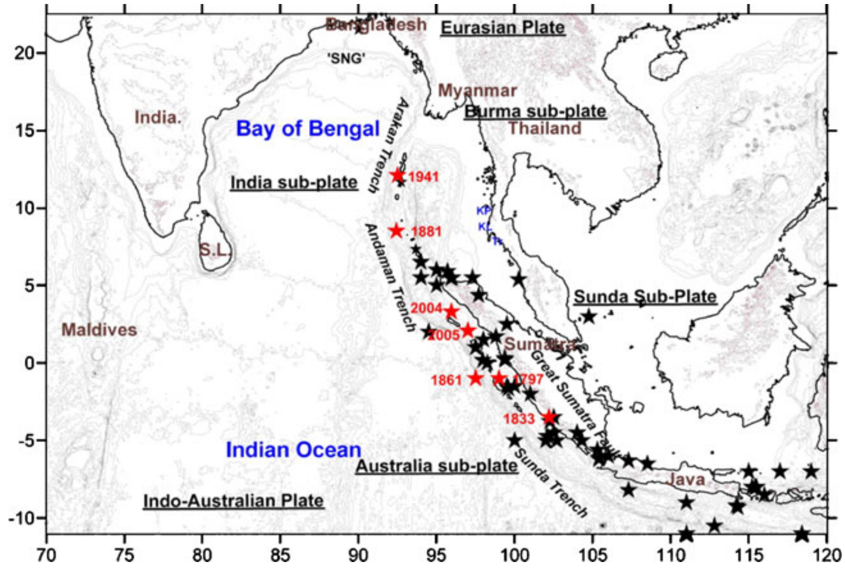


Fig. 1 Map of study area showing field-sampling locations

Fig. 2 Morphology of the most seismic area of the Indian Ocean. The tsunamigenic earthquakes are reported (★) (Major event are in *red* (★). The events have been reported in Rastogi and Jaiswal (2006). S. L. is for Sri Lanka and 'SNG' is for 'Swatch of No Ground' Canyon. In blue: KL is for Khao Lak, KP is for Kho Pratong and Tr is for Trang. The bathymetry/topography is derived from 2' ETOPO-2 data set



indicate that approximately 1,200 km of this fault ruptured along the northern Sunda Trench (Fig. 3). The first 650 km of the rupture appears to be the source zone responsible for the generation of the principal tsunami that resulted in loss of life on remote shorelines-sea floor deformation here was rapid compared to the propagation speed of the tsunami.

This is the fourth largest earthquake in the world since 1900 of which the largest is the Chile earthquake in 1960, with Mw 9.5, followed by the 1964 Prince William Sound, Alaska earthquake Mw 9.2 and the Kamchatka in 1952 with the Mw 9.0. The 26 Dec 2004 tsunami caused more casualties than any other in recorded history. In total, more than 157,577 people were killed, 26,763 are still listed as missing and 1,075,350 were displaced in South Asia and East Africa. At least 110,229 people were killed by the earthquake and tsunami in Indonesia. Tsunamis killed at least 30,922 people in Sri Lanka, 10,749 in India, 5,303 in Thailand, 150 in Somalia, 81 in Maldives, 68 in Malaysia, 59 in Myanmar, 10 in Tanzania, 3 in Seychelles, 2 in Bangladesh and 1 in Kenya (USGS 2005). Even though tsunami is a common phenomenon in the Pacific region, some destructive tsunamis have also occurred in the Indian and Atlantic Oceans (Altinok and Ersoy 2000). Oceanic waves caused by the 27 August 1883 Krakatoa volcanic explosion in Indonesia, was the earliest record of tsunami attack in India (Murty and Bapat 1999). The earthquake of Mw 8.25 occurred on 28 November 1945 near Karachi

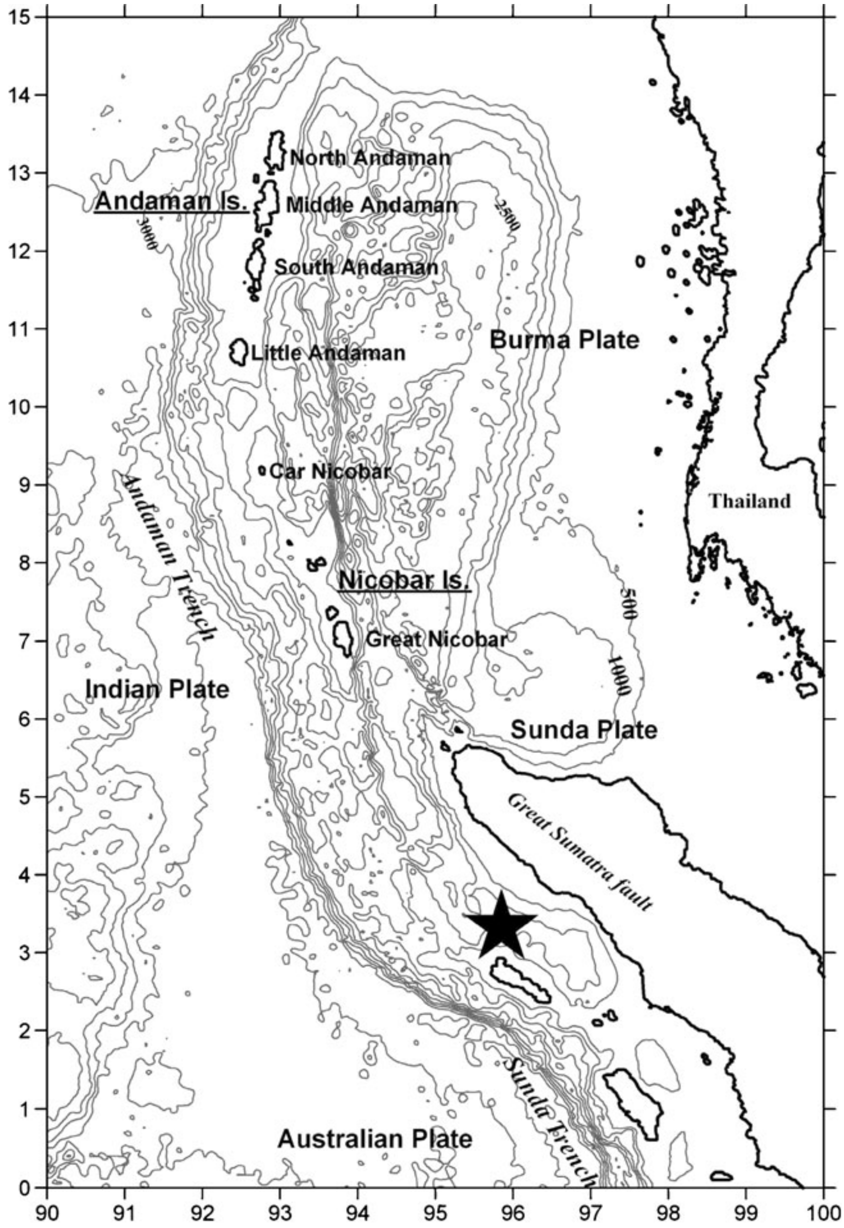


Fig. 3 The epicenter of the 26 December 2004 earthquake (*)

Table 2 Minimum, maximum and average concentration of tsunamigenic surface samples during the post-tsunami (2005)

S.ID	Range	Sand (%)	Mud (%)	Caco3 (%)	Om (%)	Sediment type
DG	Min	98.20	1.60	2.87	0.14	Sand
	Max	98.40	1.80	3.89	0.54	
	Ave	98.28	1.72	3.35	0.34	
MB	Min	93.00	0.80	10.65	0.10	Sand
	Max	99.20	7.00	18.75	0.52	
	Ave	97.81	2.08	15.39	0.27	
RA	Min	98.20	1.40	0.32	1.01	Sand
	Max	98.60	1.80	1.47	1.43	
	Ave	98.40	1.58	0.68	1.28	
BA	Min	97.00	1.60	1.12	0.19	Sand
	Max	98.40	3.00	4.75	0.64	
	Ave	97.86	2.14	2.82	0.37	
SA	Min	95.00	1.00	2.35	0.10	Sand
	Max	99.00	5.00	15.47	10.32	
	Ave	97.82	2.18	7.77	3.93	
HA	Min	89.80	0.80	10.42	0.21	Sand
	Max	99.20	10.20	12.64	2.57	
	Ave	95.73	4.27	11.84	1.40	
SC	Min	98.20	0.80	0.14	13.95	Sand
	Max	99.20	1.80	1.45	17.84	
	Ave	98.78	1.22	0.58	16.14	
HB	Min	98.20	1.30	11.76	0.16	Sand
	Max	98.70	1.80	16.03	0.63	
	Ave	98.42	1.58	13.93	0.32	

created large waves of height 11 to 11.5 m in Kutch region.

Results and discussion

Tsunamigenic sediment characteristics

Sand-silt-clay ratio (texture)

It is essential to study the sand, mud (silt and clay) characteristics in sediment samples to understand the geochemical behaviour of trace elements. Trefethen's (1950) textural nomenclature has been in the study to describe the sediment texture. The relative abundance of sand, mud in the tsunamigenic sediments samples was estimated (Tables 2 and 3), as a result the tsunamigenic sediments of both periods post-tsunami (2005) and post-monsoon (2008) are mainly composed of sand (Figs. 4 and 5).

Organic matter (OM)

Organic matter is a major constituent, and also a good index of the environment in which sediments are deposited. OM in the sediments indicates the biological activity, fertility of overlying water and also the status of pollution of the aquatic ecosystem (Alagarsamy 1991). Determination of organic matter helps to understand the mobilisation, precipitation and retention of trace elements in the sediments (Ramesh and Anbu 1996). Organic matter in the sediments of an ecosystem is brought from land through run-off and weathering of soils. The important source for organic matter is plant and animal matter from the adjacent ecosystem (Shankaranaraya Guptha 1979).

The study of organic matter and calcium carbonate in estuarine and coastal environments is important as organic carbon is used as a tool for predicting of pollution (Shimp et al. 1971; Schoettle and Friedman 1973). Calcium carbonate, on the other hand, is an indicator of provenance and dispersal of terrigenous material (Loring and Nota 1973). Organic matter in sediments has highly variable sources, including primary plankton production, terrestrial components such as humic acid-rich particulates, pollen, leaves and residues of which include the remains of living organisms, as well as various constituents produced as a result of the action of various agents on the original living matter.

Organic matter plays an important role in the transport of metals, since it is able to bind trace metals, and in the diagenetic processes that take place after deposition on (Hunter 1979; Balistrieri et al. 1981). Moreover, the

Table 3 Minimum, maximum and average concentration of the tsunamigenic surface samples during the post-monsoon (2008)

S.ID	Range	Sand (%)	Mud (%)	Caco3 (%)	Om (%)	Sediment type
DG	Min	96.20	3.60	2.87	0.14	Sand
	Max	96.40	3.80	3.89	0.54	
	Av	96.28	3.72	3.35	0.34	
MB	Min	91.00	2.80	10.65	0.10	Sand
	Max	97.20	9.00	18.75	0.52	
	Av	95.81	4.19	15.39	0.27	
RA	Min	95.70	3.90	0.32	1.01	Sand
	Max	96.10	4.30	1.47	1.43	
	Av	95.90	4.10	0.68	1.28	
BA	Min	93.80	4.80	1.12	0.19	Sand
	Max	95.20	6.20	4.75	0.64	
	Av	94.66	5.34	2.82	0.37	
SA	Min	92.20	3.80	2.35	0.10	Sand
	Max	96.20	7.80	15.47	10.32	
	Av	95.02	4.98	7.77	3.93	
HA	Min	87.50	3.10	10.42	0.21	Sand
	Max	96.90	12.50	12.64	2.57	
	Av	93.43	6.57	11.84	1.40	
SC	Min	96.80	2.20	0.14	13.95	Sand
	Max	97.80	3.20	1.45	17.84	
	Av	97.38	2.62	0.58	16.14	
HB	Min	95.80	3.70	11.76	0.16	Sand
	Max	96.30	4.20	16.03	0.63	
	Av	96.02	3.98	13.93	0.32	

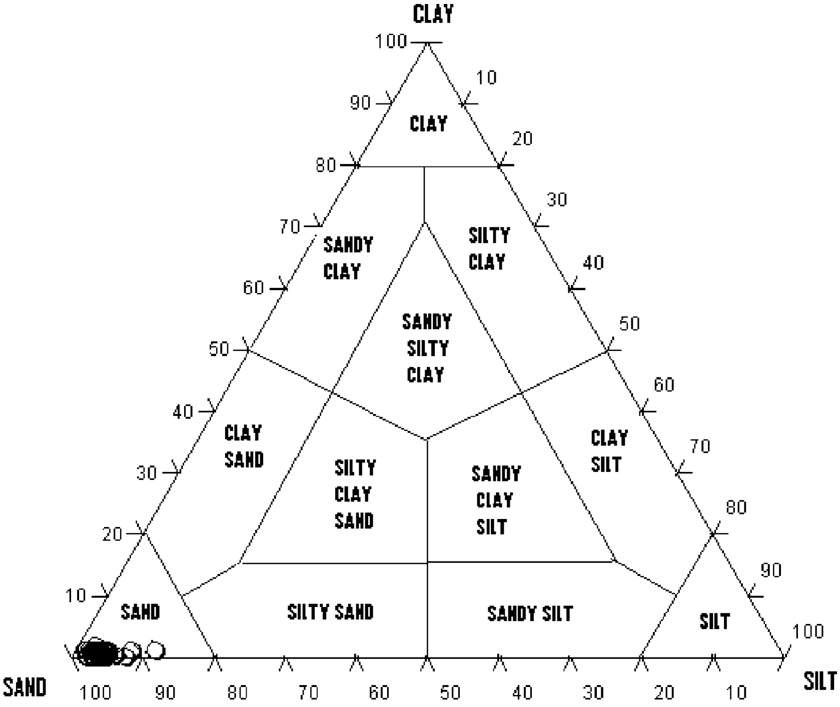
sedimentation of organic matter through water removes organic pollutants from the water column (Mackereth 1965) and is closely associated with the removal of certain heavy metals (Pita and Hyne 1974). Organic matter percentage in tsunami surface samples of post-tsunami (2005) in the Diglipur area ranges from 0.23 to 0.67% (average 0.37%), the Mayabandar area ranges from 0.10 to 1.12% (average 0.50%), the Rangat area ranges from 0.11 to 0.89% (average 0.48%), the Baratrang area ranges from 0.13 to 0.78% (average 0.31%), the South Andaman area ranges from 0.10 to 14.27% (average 5.78%), the Havelock area ranges from 0.22 to 2.79% (average 1.26%), the Sipighat creek area ranges between 12.93 to 15.95% (average 14.66%), the Hut Bay area ranges between 0.10 to 0.45% (average 6.66%) (Table 2). The high percentage (14.66%) of organic matter is seen in the Sipighat creek area with low percentage (0.31%) is recorded in the Baratrang areas.

Organic matter percentage in tsunami surface samples of post-monsoon (2008) in the Diglipur area ranges from 0.14 to 0.54% (average 0.34%), the Mayabandar area ranges from 0.10 to 1.52% (average 0.27%), the Rangat area ranges from 1.01 to 1.43% (average 1.28%), the Baratrang area ranges from 0.19 to 0.64% (average 0.37%), the South Andaman area ranges from 0.10 to 10.32% (average 3.93%), the Havelock area ranges from 0.21 to 2.57% (average 1.40%), the Sipighat creek area ranges between 13.95 to 17.84% (average 16.14%), the Hut Bay area ranges between 0.16 to 0.63% (average 0.32%) (Table 3). The high percentage (16.14%) of organic matter is seen in the Sipighat creek area with low percentage (0.27%) is recorded in the Baratrang areas.

Calcium carbonate (CaCO$_3$)

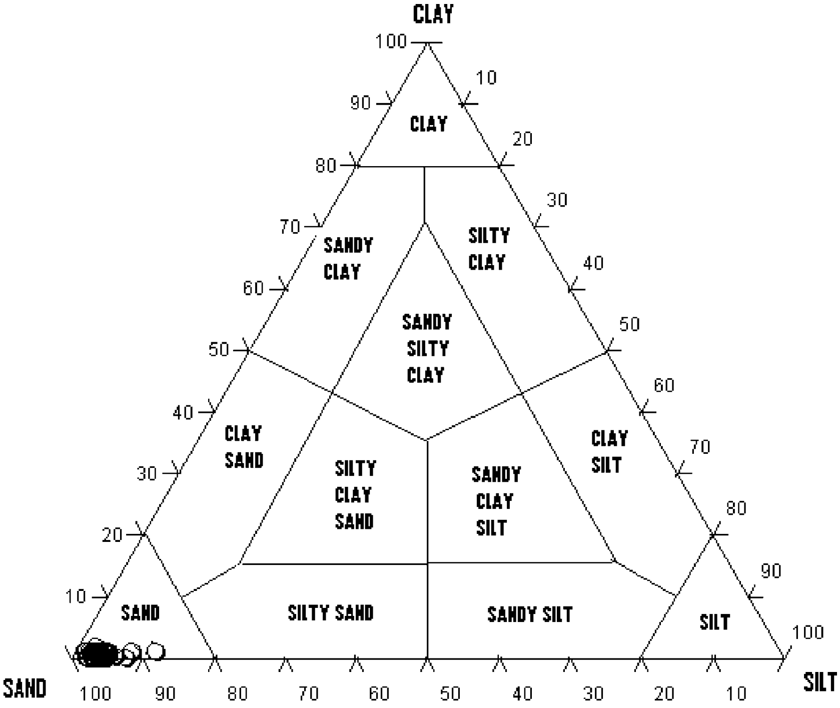
Carbonate is an important component of marine sediments and has been found to be an important indicator of provenance and dispersal of terrigenous material (Loring and Nota 1973). Likewise, organic carbon matter is determined to assess the role played by the organic fraction of sediments in the transport, deposition and retention of trace metals (Loring and Rantala 1992). In addition, the nature and amount of organic matter and carbonate content of the shelf sediments are used as tools for the recognition of paleoshorelines (Mohan and Rajamanickam 1994). The grain size, organic matter and calcium carbonate content maybe critical factors other than pollution that influence metal distributions in sediments (Salomons and Forstner 1984; Cauwet 1987; Windom et al. 1989).

Fig. 4 Trilinear plots of Sand-Silt-Clay of surface samples during post-tsunami (2005) (after Trefethen's 1950)



Hence, the distribution patterns of calcium carbonate in the study area was determined to know the ecology and its relationship. The percentage of $CaCO_3$ in the analysed surface sample of post-tsunami (2005) in Diglipur area ranges between 4.39 to 8.89% (average 5.42%), the Mayabandar area ranges between 2.69 to 19.49% (average 15.92%), the Rangat area ranges between 1.58 to 6.59% (average 3.12%), the Baratrang area ranges from 3.47 to 15.60% (average 7.56%), the South Andaman area ranges between 3.59 to 18.60% (average 9.37%), the Havelock area ranges between 16.30 to 18.70% (average 17.16%), the Sipighat creek area ranges between 0.68 to 0.88% (average 0.76%), the Hut Bay area ranges between 18.10 to 19.25% (average 10.73%) (Table 2). High percentage (17.16%) of

Fig. 5 Trilinear plots of Sand-Silt-Clay of surface samples during post-monsoon (2008) (after Trefethen's 1950)



$CaCO_3$ has been recorded in the Havelock area and the lowest percentage (3.12%) has been recorded in the Rangat area.

The percentage of $CaCO_3$ in the analysed surface sample of post-monsoon (2008) in Diglipur area ranges between 2.87 to 3.89% (average 3.72%), the Mayabandar area ranges between 10.65 to 18.75% (average 15.39%), the Rangat area ranges between 0.32 to 1.47% (average 0.68%), the Baratrang area ranges from 1.12 to 4.75% (average 2.82%), the South Andaman area ranges between 2.35 to 15.47% (average 7.77%), the Havelock area ranges between 10.42 to 12.64% (average 11.84%), the Sipighat creek area ranges between 0.14 to 1.45% (average 0.58%), the Hut Bay area ranges between 11.76 to 16.03% (average 13.93%) (Table 3). High percentage (17.16%) of $CaCO_3$ has been recorded in the Havelock area and the lowest percentage (3.12%) has been recorded in the Rangat area.

Granuometric analysis

Granulometric studies of the beach sediments on the east and west coasts of India have been carried out by Chakrabarti (1977); Chaudhri et al. (1981); Rajamanickam and Gujar (1984, 1988, 1997); Chauhan et al. (1988); Chauhan and Chaubey (1989); Chauhan (1990); Mohan and Rajamanickam (1998); Mohan et al. (2000); Rao et al. (2005); Angusamy and Rajamanickam (2006).

Tsunami sediments in the studied locations are mainly in the form of continuous sheet (few cm to few tens of cm thick), of coarse and medium sand. Their thickness depends on many local factors. The average of these sediments at various places has been given in the Table 4 for post-tsunami (2005) and in Table 5 for post-monsoon (2008) of the analysis. The sediments are classified as coarse sand to medium sand during the period of post-tsunami (2005) (Table 4). Whereas during the period of post-monsoon (2008) the sediments range from fine sand to medium sand (Table 5). In general the 26 December 2004 tsunami deposits mainly consist of coarse sand in Diglipur, Rangat, Mayabandar, Baratrang and Hut Bay area, while the deposits mainly consist of sand in South Andaman and Havelock Islands and medium sand in the Sipighat creek. Most of the sediments are delivered from erosion of nearshore and beach zone. The observed differences in grain size are caused by local factors.

Mean size and standard deviation

The analysed post-tsunami (2005) samples consist of sheets of very fine sand to medium sand. Most of the sediments are moderately well sorted (Table 4). Standard deviation ($\sigma 1$) measures the sorting of sediments and indicates the fluctuations in the kinetic energy or velocity conditions of the depositing agent (Sahu 1964). The best sorting is presented in samples from Rangat (RA) and is mainly unimodal, well sorted. The worst sorting (poorly sorted) obtained samples consisting of trimodal, poorly sorted at Diglipur (DG) and in Hut Bay (HB). The sample from Mayabandar (MB), Baratrang (BA) and Sipighat (SC) consists of moderately well sorted. The mean size indicates that the coarse sands were deposited at a high energy conditions and well sorted medium sand were deposited at a moderate energy conditions. The variation in phi mean size, therefore, reveals the differential energy conditions leads to the deposition of these kinds of sediments in different locations. The post-monsoon (2008) sediments are moderately sorted (Table 5). The sample type at most of the locations consists of moderately sorted very fine sands at Mayabandar (MB) and Sipighat (SC).

Skewness

Skewness is a measure of grain-size distribution symmetry. Most of the analysed post-tsunami (2005) samples, in the Mayabandar, Rangat, Baratrang, and Havelock consist of excess of coarse material (coarse and very coarse skewed). On the other hand the samples are fine skewed in Diglipur, South Andaman, Siphighat and Hut Bay Table (4). The post-monsoon (2008) samples are mainly of coarse skewed (Table 5).

Kurtosis

Kurtosis is a measure of the grain-size distributions, whether they are peaked or flat relative to normal distribution. The analysed samples during the post-tsunami (2005) are platykurtic in Diglipur, most of the samples in Mayabandar, South Andaman, Havelock and Hut Bay are mesokurtic and samples at Rangat, Baratrang and Sipighat are lepokurtic in nature (Table 4). Most of the post-monsoon (2008) samples are mesokurtic except in Mayabandar which is lepokutric (Table 5).

Sediment ecology

The sand silt clay ratios clearly indicate the dominance of sand in both the post-tsunami (2005) as well the post-monsoon (2008). The sandy nature may be due to the transportation of sediments form the offshore bed to the low-lying environment. The samples were mainly collected from the creek, bays and estuaries where deposition of the organic matter is favoured. Further, due to the environmental conditions where organic matter vs mud that favor organic matter positively in the mud rich samples. The turbidly is very low inside this creek and this may also favor organic matter. The coastal flats have an admixture of

Table 4 Average grain-size and sediment type of the analysed samples during post-tsunami (2005)

S.L	Mean	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis	Skewness	Kurtosis	Sample type	Sediment name
	Logarithmic method				Folk and Ward method							
DG	2.415	1.073	0.016	2.439	2.399	1.081	−0.1	0.8	Fine skewed	Platykurtic	Trimodal, poorly sorted	Poorly sorted coarse sand
MB	1.568	0.691	0.997	4.123	1.534	0.68	0.3	1	Very coarse skewed	Mesokurtic	Unimodal, moderately well sorted	Moderately well sorted coarse sand
RA	1.112	0.561	2.38	11.397	1.067	0.507	0.4	1.2	Very coarse skewed	Leptokurtic	Unimodal, well sorted	Well sorted coarse sand
BA	1.608	0.772	1.189	4.655	1.56	0.767	0.3	1.2	Very coarse skewed	Leptokurtic	Unimodal, moderately well sorted	Moderately well sorted coarse sand
SA	2.218	0.895	0.076	3.007	2.219	0.912	0	1	Fine skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted medium sand
HA	1.391	0.814	1.44	4.614	1.344	0.78	0.5	1.1	Very coarse skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted coarse sand
SC	2.447	0.744	−0.17	5.77	2.495	0.697	−0.2	1.4	Fine skewed	Leptokurtic	Unimodal, moderately well sorted	Moderately well sorted medium sand
HB	2.16	0.868	0.087	3.225	2.157	0.88	−0.1	1	Fine skewed	Mesokurtic	Trimodal, poorly sorted	Poorly sorted coarse sand

Table 5 Average grain-size and sediment type of the analysed samples during post-monsoon (2008)

S.L	Mean	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis	Skewness type	Kurtosis type	Sample type	Sediment name
	Logarithmic method				Folk and Ward method							
DG	1.538	0.625	1.633	10.5	1.518	0.61	0.3	1.1	Coarse skewed	Mesokurtic	Unimodal, very well sorted	Very well sorted coarse sand
MB	2.084	0.857	0.547	7.28	2.091	0.83	0	1.2	Fine skewed	Leptokurtic	Unimodal, moderately sorted	Moderately sorted very fine sand
RA	1.781	0.879	0.937	3.9	1.738	0.88	0.3	1	Coarse skewed	Mesokurtic	Unimodal, moderately well sorted	Moderately well sorted medium sand
BA	1.915	0.738	0.529	3.78	1.886	0.72	0.1	1.1	Coarse skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted medium sand
SA	1.821	0.729	0.643	3.66	1.793	0.74	0.1	0.9	Coarse skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted very fine sand
HA	1.691	0.867	0.976	4.95	1.664	0.87	0.2	0.9	Coarse skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted coarse sand
SC	2.532	0.973	−0.239	2.4	2.514	1.01	−0.2	0.9	Fine skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted fine sand
HB	1.86	0.869	0.593	3.13	1.834	0.86	0.1	0.9	Coarse skewed	Mesokurtic	Bimodal, moderately sorted	Moderately sorted medium sand

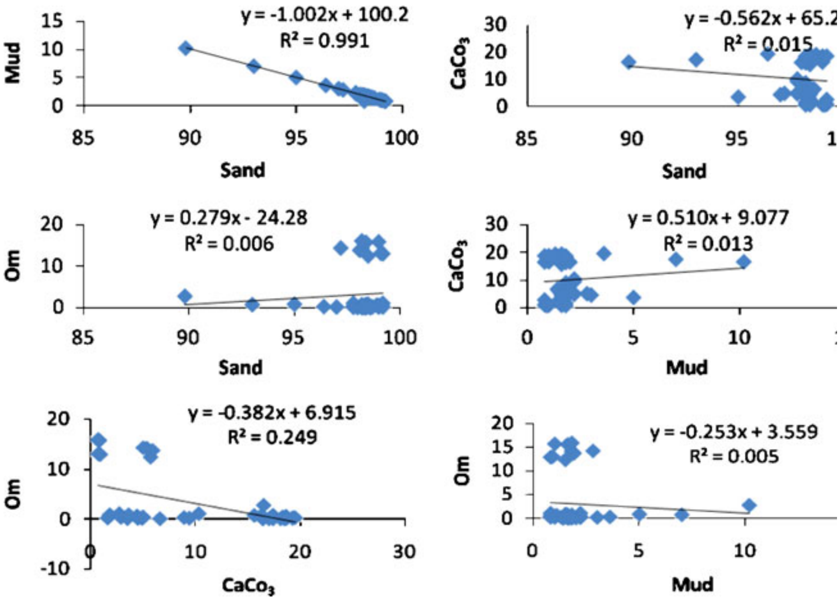


Fig. 6 Scatter plot for sand, mud, calcium carbonate and organic matter in post-tsunami (2005)

sand, silty clay and diluvial material with fine fragments of coral lime. Coralline rocks are exposed in the coastal segments of the Andaman Islands and the fringing reefs that are arranged around the chain of islands may favor the organic matter and carbonate content in this region. That the organic matter vs sand does not show relative correlation may be due to erosional activities of the sediments. The study mainly focused on the nature of sediment and its characteristics with respect to grain size, during the post-tsunami (2005) and post-monsoon (2008) of Andaman group of islands. From the scatter plots, it was found that there is no good relation between the organic matter and mud during the post-tsunami (2005) but there is a good positive correlation (R^2 = 0.183) for the post-monsoon (2008).

Calcium carbonate shows a correlation (R^2 = 0.015) during the post-tsunami (2005) (Fig. 6). Carbonate content is high in the beach samples when compared to estuaries, creeks and mangrove areas during the post tsunami. The higher carbonate content at creeks and estuary are probably due to the accumulation of high order broken shell debris. During the post-monsoon 2008 (Fig. 7) the correlation is (R^2 = 0.004) may be due heavy rainfall causing erosional activities near the coastal locations.

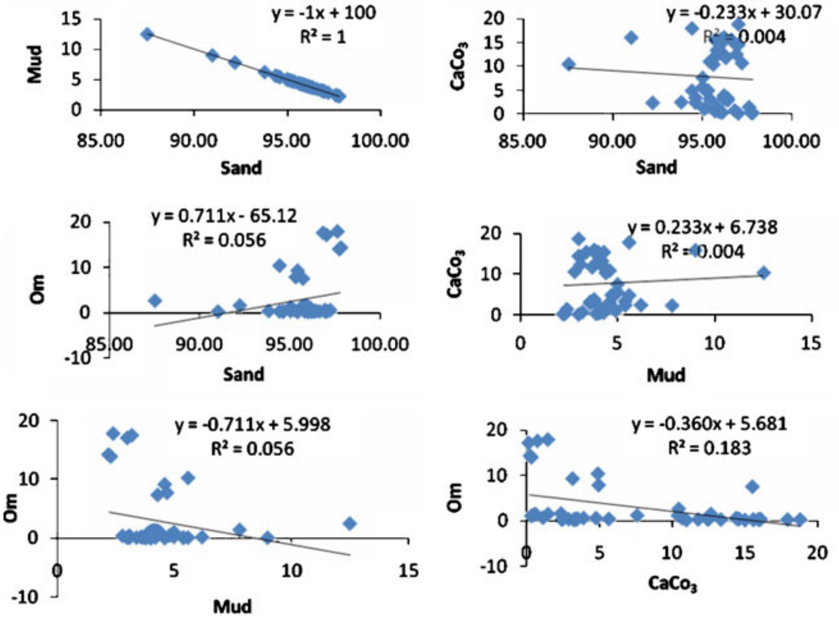
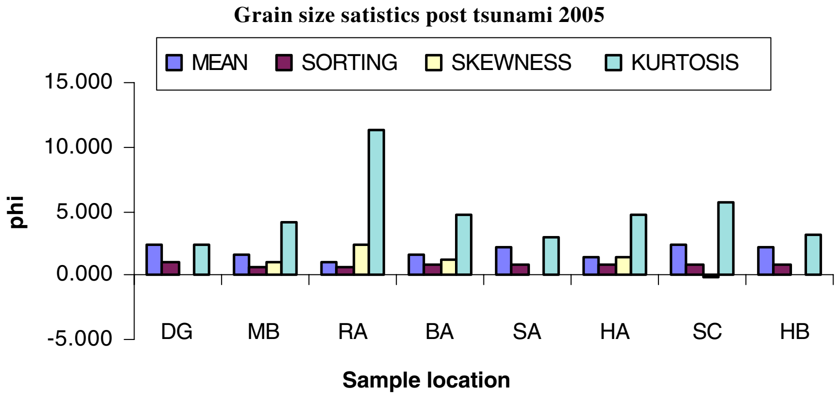


Fig. 7 Scatter plot for sand, mud, calcium carbonate and organic matter in post-monsoon (2008)

Fig. 8 Grain size statistics, during post tsunami 2005 (logarithmic method)



There is a good correlation (Fig. 6) between the calcium carbonate and organic matter during the post-tsunami (2005) but during the post-monsoon (2008) the level of correlation is less. This clearly indicates that during the time of tsunami inundation the waves had eroded the coral beds in the near offshore region and deposited the sediments with number of broken shell fragments.

Sediment texture

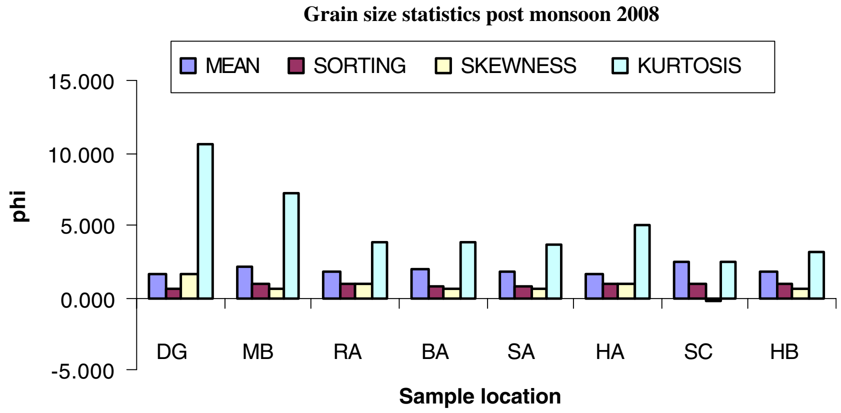
The phi mean size of the samples varies from 1.112 (Rangat) to 2.415 (Sipighat) with an average mean of 1.865 (Fig. 8) during the post-tsunami (2005). The majority of the sediments sample falls in coarse sand category and the rest in medium sand category. The mean size indicates that the fine sands were deposited at moderately low energy conditions and the medium sand were deposited at moderate energy conditions. The variation in phi mean size, therefore, reveals the differential energy conditions that lead to the deposition of these kinds of sediments in different locations. The phi mean size of the samples varies from 1.538 (Digilipur) to 2.532 (Siphighat) with an average mean of 1.903 (Fig. 9) during the post-monsoon (2008).

The sorting of the tsunami sediments varies from 0.561 (Digilipur) to 1.073 (Rangat) with an average mean of 0.802 (Fig. 8) during the post-tsunami (2005). The sorting of the tsunami sediments were mainly poorly sorted, moderately well sorted and well sorted during the post-tsunami (2005). The sorting of the tsunami sediments varies from 0.625 (Digilipur) to 0.973 (Siphighat) with an average mean of 0.817 (Fig. 9) during the post-monsoon (2008). The sorting of the tsunami sediments were mainly moderately well sorted to well sorted during the post-monsoon (2008).

The skewness values range between −0.170 (Siphighat) and 2.380 (Rangat) with an average value of 0.752 during the post-tsunami (2005) (Fig. 8). The symmetry of the samples varies from strongly fine skewed to strongly very coarse skewed nature. The strongly fine skewed and fine skewed sediments generally imply the introduction of fine material or removal of coarser fraction (Friedman 1961) or winnowing of sediments (Duane 1964). The skewness values range between −0.239 (Siphighat) and 1.633 (Diglipur) with an average value of 0.702 during the post-monsoon (2008) (Fig. 9).

The kurtosis values range between 2.439 (Digilipur) and 11.397 (Rangat) with an average value of 4.904 during the

Fig. 9 Grain size statistics, during post monsoon 2008 (logarithmic method)



post-tsunami (2005) (Fig. 8). The Kurtosis of the tsunami sediments were mainly Platykurtic, Mesokurtic and Lepokurtic. Friedman and Sanders (1978) suggested that extreme high or low values of kurtosis imply that part of the sediment achieved its sorting elsewhere in a high energy environment. The variation in the kurtosis values is a reflection of the flow characteristics of the depositing medium (Seralathan and Padmalal 1994; Baruah et al. 1997). The kurtosis values range between 2.395 (Siphighat) and 10.524 (Digilipur) with an average value of 4.950 during the post-monsoon (2008) (Fig. 9). The kurtosis of the tsunami sediments where mainly Mesokurtic and Lepokurtic.

Conclusions

This study contribute to a better understanding of the effects of tsunami on coastlines and the evidence that left in the coastal stratigraphy by the analysed tsunamigenic sediments. These observations of modern tsunami sedimentation will ultimately improve the identification and interpretation of palaeotsunamis in the geologic record. The studied sediments, deposited by the 26 December 2004 tsunami in Andaman group of islands belong to poorly sorted, coarse sand to medium sands, and are similar to depositional effects of previously reported earthquake-generated tsunami waves. From the textural analysis it is inferred that the type of the sediments is mainly composed of sand in Diglipur and Havelock Islands and with sandy silt in the Mayabandar and silty sand in the South Andaman areas. Generally the texture of the sediments is mainly of sand which indicates the high-energy environment i.e., tsunami waves have deposited some sediments in the low energy area. The grain size analyses of the sediments show a distinct difference between the deposition of sediments by normal cycle of waves and by tsunami waves. The sediment texture, organic matter and carbonate studies clearly indicate the high energy deposition environments. The majority of the sediments sample falls in coarse sand category and the rest in medium sand category. The mean size indicates that the fine sands were deposited at a moderately low energy conditions and the medium sand were deposited at a moderate energy conditions. The variation in phi mean size, therefore, reveals the differential energy conditions leads to the deposition of these kinds of sediments in different locations. The sorting of the tsunami sediments were mainly poorly sorted, moderately well sorted and well sorted during the post-tsunami 2005. The sorting character concludes that the sediments were from beach whereas mainly moderately well sorted to well sorted during the post-monsoon 2008. The symmetry of the samples varies from strongly fine skewed to strongly very coarse skewed nature in the post-tsunami 2005 and post-monsoon 2008. The Kurtosis of the tsunami sediments where mainly Platykurtic, Mesokurtic and Lepokurtic during the post-tsunami 2005 and mainly Mesokurtic and Lepokurtic in post-monsoon 2008 which indicates multiple environment and primarily of their original characters of marine environment.

References

Alagarsamy R (1991) Organic carbon in the sediments of Mandovi estuary, Goa. Indian J Mar Sci 20:221–222

Altinok Y, Ersoy S (2000) Tsunamis observed on and near the Turkish coast. Nat Hazards 21:185–205

Amaral EJ (1977) Depositional environment of the St. Peter sandstone deduced by textural analysis. J Sediment Petrol 47:32–52

Andrews HV, Sankaran V (2002) Sustainable management of protected areas in the Andaman and Nicobar Islands. ANET, IIPA, FFI, New Delhi

ANET (2003) Andaman and Nicobar Islands Union Territory biodiversity strategy and action plan. Prepared under the National biodiversity strategy and action plan-India. GOIUNDP:145

Angusamy N, Rajamanickam GV (2006) Depositional environment of sediments along the southern coast of Tamil Nadu, India. Oceanologia 48(1):87–102

Atwater BF (1987) Evidence for great Holocene earthquakes along the outer coast of Washington State. Sci 236:942–944

Balistrieri L, Brewer PG, Murray JW (1981) Scavenging residence times of trace metals and surface chemistry of sinking particles in the deep ocean. Deep-Sea Res 28:101–121

Baruah J, Kotoky P, Sarma JN (1997) Textural and geochemical study on river sediments: a case study on the Jhanji River, Assam. J Indian Assoc Sedimentol 16:195–206

Berninghausen WH (1966) Tsunamis and seismic seiches reported from regions adjacent to the Indian Ocean. Bull Seismol Soc Am 56(1):69–74

Bondevik S, Svendsen JI, Johnsen G, Mangerud J, Kaland PE (1997) The Storegga tsunami along the Norwegian coast, its age and runup. Boreas 26(1):29–54

Bryant E (2001) Tsunami. The underrated hazard. Cambridge University Press, Cambridge, p 320

Bryant E, Young R, Price D (1996) Tsunami as a major control of coastal evolution, Southeastern Australia. J Coast Res 12:831–840

Carver RE (1971) Procedures in sedimentary petrology. Wiley-Interscience, New York, p 653

Cauwet G (1987) Influence of sedimentological features on the distribution of trace metals in marine sediments. Mar Chem 22:221–234

Chakrabarti A (1977) Mass-spring-damper system as the mathematical model for the pattern of sand movement for an eroding beach around Digha, West Bengal, India. J Sediment Petrol 47:311–330

Chaudhri RS, Khan HMM, Kaur S (1981) Sedimentology of beach sediments of the west coast of India. Sed Geol 30:79–94

Chauhan OS (1990) Sedimentological parameters of beach sediments on the east coast of India. J Coast Res 6:573–585

Chauhan OS, Chaubey AK (1989) Comparative studies of moment, graphic and phi measures of the sands of the East coast beaches, India. Sediment Geol 65:183–189

Chauhan OS, Verma VK, Prasad C (1988) Variations in mean grain size as indicators of beach sediment movement at Puri and Konark beaches, Orissa, India. J Coast Res 27–35

Clague JJ, Bobrowsky PT, Hamilton TS (2000) A review of geological records of large tsunami at Vancouver Island, British Columbia and implications for hazard. Quat Sci Rev 19:849–863

Dawson AG (1994) Geomorphological effects of tsunami run-up and backwash. Geomor 10:83–94

Duane DB (1964) Significance of skewness in recent sediments, western Pamlico Sound, North Carolina. J Sediment Petrol 34 (4):864–874

Folk RL, Ward MC (1957) Brazos river bars: a study in the significance of grain size parameters. J Sediment Petrol 27:3–27

Friedman GM (1961) Distinction between dune, beach and river sands from their textural characteristics. J Sediment Petrol 28:151–153

Friedman GM (1967) Dynamic Processes and Statistical parameters compared for size frequency distribution of beach river sands. J Sediment Petrol 37:327–354

Friedman GM (1979) Differences in size distribution of populations of particles among sands of various origin. Sed 26:13–32

Friedman GM, Sanders JE (1978) Principles of sedimentology. Wiley, New York, p 792

Gaudette HE, Flight WR, Toner L, Folger DW (1974) An inexpensive titration method for the determination of organic carbon in recent sediment. J Sediment Petrol 44:249–254

Heck NH (1947) List of seismic sea waves. Bull Seismol Soc Am 37:269–286

Hemphill-Haley E (1995a) Diatom evidence for earthquake induced subsidence and tsunami 300 years ago in southern coastal Washington. Geol Soc Am Bull 107:367–378

Hemphill-Haley E (1995b) Intertidal diatoms from Willapa Bay, Washington: application to studies of small-scale sea-level changes. Northwest Sci 69:29–45

Hunter LPS (1979) The surface charge of Suspended particles in estuarine and coastal waters. Nature 282:823–825

Hussain SM, Krishnamurthy RR, Suresh Gandhi M, Ilayaraja K, Ganesan P, Mohan SP (2006) Micropaleontological investigations of tsunamigenic sediments of Andaman Islands. Curr Sci 91:1655–1667

Iida K, Cox DC, Pararas-Carayannis G (1967a) Preliminary catalogue of tsunami occurring in the Pacific Ocean. University of Hawaii, Hawaii Institute of Geophysics, Honolulu, p 274

Iida K, Cox DC, Pararas-Carayannis G (1967b) Preliminary catalogue of tsunami occurring in the Pacific Ocean. *HIG 67-10*, Data-report no. 5. University of Hawaii, Honolulu, p 274

Inman DL (1949) Sorting of sediments in the light of fluid mechanics. J Sediment Petrol 19:51–70

Keller WD (1945) Size distribution of sand in some dunes, beaches and sandstones. Bull Am Assoc Pet Geol 29:215–221

Klovan JE (1966) The use of factor analysis in determining depositional environments from grain size distributions. J Sediment Petrol 36:115–125

Krumbein WC (1937) Flood deposits of Arroyo Seco, Los Angeles Country, California, I. Bull Geol Soc Amer 53:1355–1402

Krumbein WC, Pettijohn FJ (1938) Manual of sedimentary petrography. I Appleton-Century Crofts Inc., New York, p 549

Kulkarni S (2000) Ecological assessment of coral reefs in Mahatma Gandhi Marine National Park, Wandoor, Andaman and Nicobar Islands: Conservation implications. Wildlife Institute of India, Dehradun

Lander J, Whiteside LS (1997) Caribbean tsunami, an initial history. Mayaguez Tsunami Workshop, Puerto Rico

Lisitzi E (1974) Sea level changes. Elsevier Oceanographic Series, 8, New York, p 273

Loring DH, Nota DJG (1973) Morphology and sediments of the Gulf of St. Lawrence. Bull Fish Res Board Can 182:147

Loring DH, Rantala RTT (1992) Manual for the geochemical analyses of marine sediments and suspended particulate matter. Earth-Sci Rev 32:235–283

Mackereth FJH (1965) Chemical investigation of lake sediments and their interpretation. Proceedings of the Royal Soc 161:285–309

Mason CL, Folk RL (1958) Differentiation of beach, dune and aeolian flat environments by size analysis, Mustang Islands, Texas. J Sediment Petrol 28:211–226

Mohan PM, Rajamanickam GV (1994) Organic matter and carbonate in the southwest continental shelf of India. J Geol Soc India 44:575–580

Mohan PM, Rajamanickam GV (1998) Depositional environments inferred from grain size along the coast of Tamilnadu, India. J Geol Soc India 52:25–28

Mohan PM, Rajamanickam GV (2001) Indian beach placers—a review: Hand book of Placer deposits, Edited by G. Victor Rajamanickam, New Academic, pp 23–52

Mohan PM, Shepherd K, Suresh Gandhi M, Rajamanickam GV (2000) Evolution of quaternary sediments along the coast between Vedaranyam and Rameshwaram, Tamil Nadu. J Geol Soc India 56:271–283

Moiola RJ, Weiser D (1968) Textural parameters: an evaluation. J Sediment Petrol 38:45–53

Murty TS, Bapat A (1999) Tsunamis on the coastlines of India. Sci Tsunami Hazards 17(3):167–172

Nakata T, Kawana T (1995) Historical and prehistorical large tsunami in the southern Ryukyus, Japan. In: Tsuchiya Y, Shuto N (eds) Tsunami, progress in prediction disaster prevention and warning. Kluwer, Dordrecht, pp 211–221

Newcomb KR, McCann WR (1987) Seismic history and tectonics of the Sunda Arc. JGR 92(B1):421–439

NGDC (2001) Tsunami database at NGDC. URL: http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml

Nishimura Y, Miyaji N (1995) Tsunami deposits from the 1993 Southwest Hokkaido Earthquake and the 1640 Hokkaido Komagatake Eruption, Northern Japan. Pure Appl Geophys 144 (3/4):719–733

Otto GH (1939) A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments. J Sediment Petrol 9:62–75

Pande P, Kothari A, Singh S (1991) Directory of National Parks and Sanctuaries in Andaman and Nicobar Islands. Management status and profiles. Indian Institute of Public Administration, New Delhi, p 171

Papadopoulos GA, Chalkis BJ (1984) Tsunamis observed in Greece and the surrounding area from antiquity up to the present times. Mar Geol 56:309–317

Pita FW, Hyne NJ (1974) The depositional environment of zinc, lead and cadmium in reservoir sediments. Water Res 9:701–706

Rajamanickam GV, Gujar AR (1984) Sediment depositional environment in some bays in central west coast of India. Indian J Mar Sci 14:13–19

Rajamanickam GV, Gujar AR (1988) Interpretation of environment of deposition from multivariate discriminant analysis. Indian J Mar Sci 15:234–247

Rajamanickam GV, Gujar AR (1997) Grain size studies on the nearshore sediments of Jaigad, Ambwah and Varvada Bays, Maharashtra, India. J Geol Soc India 49:567–576

Ramesh R, Anbu M (1996) Chemical methods for environmental analysis. Macmillan India Lit., Madras-2

Rao GN, Yao YD, Chen YL, Wu KT, Chen JW (2005) Particle size and magnetic field-induced optical properties of magnetic fluid nanoparticles. Phys Rev 72:031408

Rastogi BK, Jaiswal RK (2006) A catalog of tsunamis in the Indian Ocean. Sci Tsunami Hazards 25(3):128–143

Sahu BK (1964) Depositional mechanisms from the size analysis of clastic sediments. J Sediment Petrol 34:73–83

Salomons W, Forstner U (1984) Metals in hydrocycle. Springer-Verlag, New York, pp 63–98

Sato H, Shimamoto T, Tsutsumi A, Kawamoto E (1995) Onshore tsunami deposits caused by the 1993 Southwest Hokkaido and 1983 Japan sea earthquakes. Pure Appl Geophys 144(3/4):693–717

Scheffers A, Kelletat D (2003) Sedimentologic and geomorphologic tsunami imprints worldwide—a review. Earth-Sci Rev 63:83–92

Schlee J, Webster J (1967) A computer programme for grain size data. Sed 8:45–53

Schlichting RB (2000) Establishing the inundation distance and overtopping height of paleotsunami from the late-Holocene geologic record at open coastal wetland sites, central Cascadia margin: Masters Thesis, Portland State University, pp 166

Schoettle M, Friedman GM (1973) Effect of man's activities on distribution of trace elements in sub-bottom sediments of Lake George, New York. Sed 21(3):473–478

Seralathan P, Padmalal D (1994) Textural studies of the surficial sediments of Muvattupuzha river and central Vembanad Estuary, Kerala. J Geol Soc Indian 43:179–190

Sevon WD (1966) Sediment variation on farewell spit, New Zealand. NZ J Geol Geophys 9(1–2):60–75

Shankaranaraya Guptha MV (1979) Sediments of the Western continental shelf of India—environmental significance. J Geol Soc Indian 20:107–113

Shi S, Dawson AG, Smith DE (1995) Coastal sedimentation associated with the December 12th, 1992 Tsunami in Flores, Indonesia. Pure Appl Geophys 144(3/4):525–536

Shimp NF, Schleicher JA, Ruch RR, Heck DB, Leland HV (1971) Trace element and organic carbon accumulation in the most recent sediments of southern Lake Michigan. Illinois Geol Sur Envir Geol Note 41

Stein S, Okal E (2005) Speed and size of the Sumatra earthquake. Nature 434:581–582

Sumaon B, Kenneth P (2001) Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf Processes Landf 26:1237–1248

Synolakis CE, Kong L (2006) Runup measurements of the December 2004 Indian Ocean Tsunami. Earthq Spectra 22(3): 67–91

Synolakis CE, Fritz HM, Titov VV (2005) Field survey of the Indian Ocean tsunami on Sri Lanka's south coast. Proc., 5th Int. Conf. on Ocean Wave Measurement and Analysis, WAVES 2005, Madrid, Spain.

Tinti S, Maramai A (1996) Catalogue of tsunami generated in Italy and in Cote d'Azur, France, a step towards a unified catalogue of tsunami in Europe. Ann Geophys 39:1253–1300

Trefethen JM (1950) Classification of sediments. Am J Sci 248:55–62

Turner JR, Vousden D, Klaus R, Sutryanarayana C, Fenner D, Venkataraman K, Rajan PT, Subba Rao NV (2001) Remote sensing and rapid site assessment survey. Report of Phase 1: April 2001. GOI/UNDP GEF. Coral reef ecosystems of the Andaman Islands, New Delhi

Udden JA (1914) Mechanical composition of clastic sediments. Geol Soc Amer Bull 25:655–744

USGS (2005) Magnitude 9.0—Sumatra—Andaman island earthquake, off the west coast of northern Sumatra, 2004 December 26 at 00:58:53 UTC, USGS, NEIC, World Data Center for Seismology, Denver. (http://earthquake.usgs.gov/eqinthenews/2004/usslav)

Vousden D (2000) The management of coral reefs ecosystems of the Andaman and Nicobar Islands. Mission report-GOI-UNDP GEF, PDF-B Phase, New Delhi

Wentworth CK (1929) A scale of grade and class terms for clastic sediments. J Geol 30:377–392

Windom HL, Schropp SJ, Calder FO, Ryan JD, Smith RG, Burney LC, Lewis FG, Rawlinson CH (1989) Natural trace metal concentrations in estuarine and coastal marine sediments of the southeastern United States. Environ Sci Technol 23:314–320

Zhou Q, Adams WM (1986) Tsunamigenic earthquakes in China, 1831 BC to 1980 AD. Sci Tsunami Hazards 4:131–148