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TSUNAMI- SEDIMENT SIGNATURES IN THE MANAKUDY ESTUARY ALONG THE WEST COAST OF INDIA

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ABSTRACT

The December 26, 2004 tsunami left its imprints along the southern coast of India especially the coastal areas of Manakudy in Kanyakumari district of Tamil Nadu. In the study area - Manakudy estuary - the post-tsunami sediment texture is predominantly coarser as inferred from textural analysis. Granulometric analysis indicates a shift of well-sorted, coarse skewed and platykurtic nature during the pre-tsunami season, to moderately sorted, fine skewed and leptokurtic behavior, after the tsunami. Violent hydrodynamic conditions have prevailed during the post-tsunami deposition of sediments. The unimodal nature of the post-tsunami sediments as distinct from the bimodal pre-tsunami sediments is reflected from the frequency curves. The CM diagram and the log probability curves confirm these observations.

1. INTRODUCTION

Sedimentological analyses of undisturbed surface sediments often provide a useful tool to unravel the mechanism of complex dynamic systems where transition between terrestrial and marine environment occurs. Granulometric analyses of unconsolidated sediments serve as an indicator of the depositional environment. Detailed knowledge of these processes is a prerequisite for the reconstruction of paleo-environmental changes from the sedimentary rock. The rate of sediment transport and accumulation in coastal environments are affected by tidal currents and river discharges (Hall et *al*., 1987). The sedimentary record is an integrated record of the pollution and also accounts for the process of diagenetic remobilization (Ridgeway and Price, 1987). Generally, during the monsoon season and heavy flooding, the accumulation rate of sediments is very high. However, during the post-monsoon season resuspension of minerals occurs because of shallow water depth and prevailing air currents (Jing Zhang *et* al., 1988). Texturally, the river sediments are sandy silt and are coarse grained, whereas in an estuary the sediments are clayey silt and fine grained (Muraleedharan Nair and Ramachandran, 2002) - though at the head of the estuary, sand is dominant. Grain size parameters such as mean size (M_Z) and standard deviation (S_D) reflect the energy conditions of the depositional environment (Visher, 1969; Sly Thomas and Pehetier, 1982) as the difference in size distribution is mainly due to variation in wave energy reaching the point of sampling and extent of turbulence affecting the environment. The coarser riverine sediments are moderately sorted while the finer estuarine sediments are poorly sorted (Mohan, 1995). Negative skewness (S_K) is characteristic of coastal environments that are undergoing erosion or non-deposition, while positive skewness characterizes the areas of deposition. Also, positive skewed sediments indicate an abundance of fine-grained sediments relative to the mean size (Datta and Subramanian, 1997). The variation in the kurtosis is a reflection of transport processes/depositional mechanisms of sediments (Baruah et al., 1997; Prabhakara Rao *et* al., 2001; Malvarez *et* al., 2001). However, during a rare geological event such as a tsunami, unpredictable changes are bound to occur in the granulometric characteristics.

Destructive cyclones are much more frequent in the Indian Ocean than tsunamis. However, the December 26, 2004 Sumatra earthquake, with a magnitude up to Mw9.3 generated the most destructive tsunami in recorded history, in terms of loss of life and property damage. The Manakudy Estuary is on the west coast of India and not in the direct path of the tsunami. Yet, the strength of the tsunami in this area was so enormous that a massive concrete bridge was uprooted and carried several hundred meters away. The impact in the estuary was rated as high compared to the low and medium categories assigned for most of the east and west coastal zones of India (Chandrasekhar et al., 2006). The sand ridges in the area, are indicative of a dynamic coast transgression and regression in the geological past. Bahlburg and Weiss (2007) reported that the sediments that were deposited by the tsunami along the coasts of Tamil Nadu were predominantly medium sands (350-700 µm) with a maximum thickness of 0.3m. In view of these observations, it was imperative to evaluate the dynamics of the tsunami's impact on the West coast of India, with further study of the grain size distribution in the Manakudy Estuary.

2. MATERIALS AND METHODS

The study area and sampling locations are depicted in Fig. 1. In August 2004 (pre-tsunami period) and in early January 2005 (post-tsunami period), eighty sediment samples were collected from 40 different locations using grab samplers. The sediment samples were homogenized and air- dried at 60^{o} C to a constant weight. After the removal of carbonates, organic matter and possible iron oxides by wet sieving, the granulometric composition was determined using the pipette method (Folk, 1974; Gee and Bauder, 1986). Then, the values were fed into the ternary diagram (Shephard, 1954) and textural classifications were made. The grains were sieved in a Ro-Top machine with ASTM sieves from +45 to +230 mesh sizes so as to maintain quarter Φ interval and the various statistical parameters were evaluated.

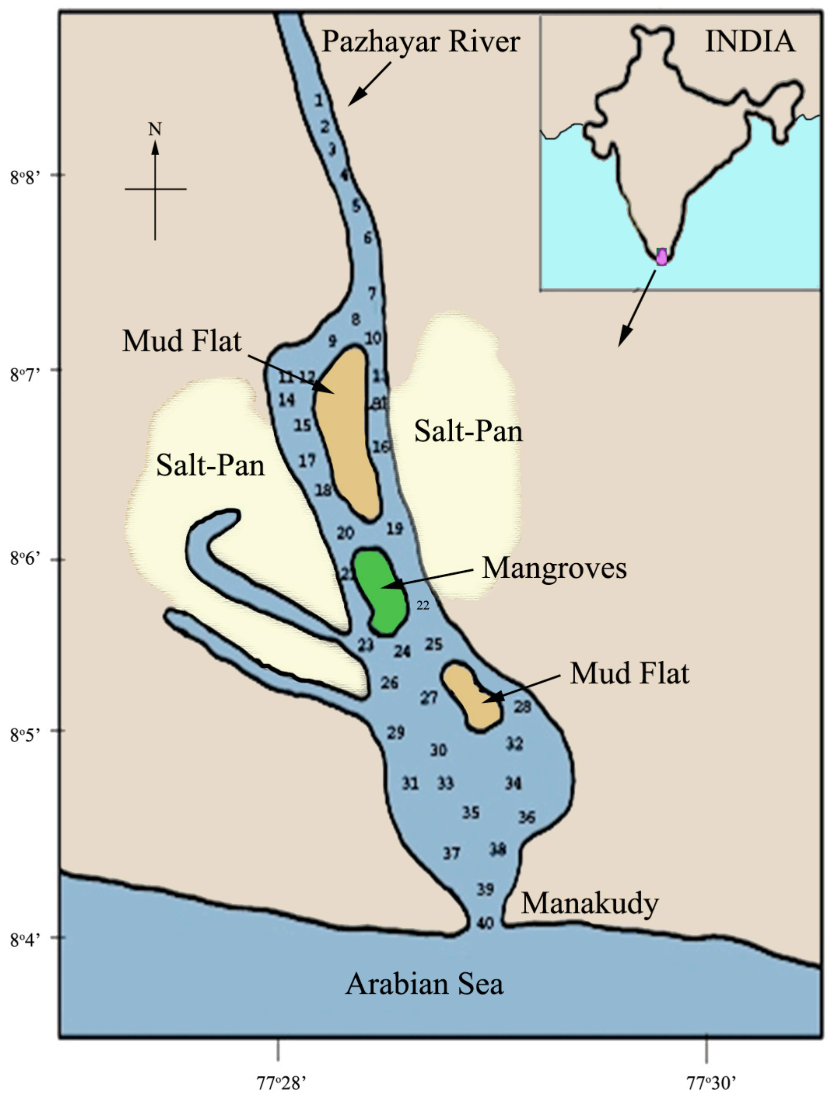


Figure 1: Sampling Area along Manakudy Estuary

3. RESULTS AND DISCUSSION

Most of the sediments that were measured fall into four distinct textural classes: sand, silty sand, clayey sand and sand silt clay, as illustrated in the triangular diagram (Fig. 2). The silty sand alone constitutes nearly 50% of the samples collected before and after tsunami. The high silt content in general, could be attributed to flocculation, followed by fine colloidal aggregates settling during estuarine mixing in the post-tsunami sediments (Kranck, 1975).

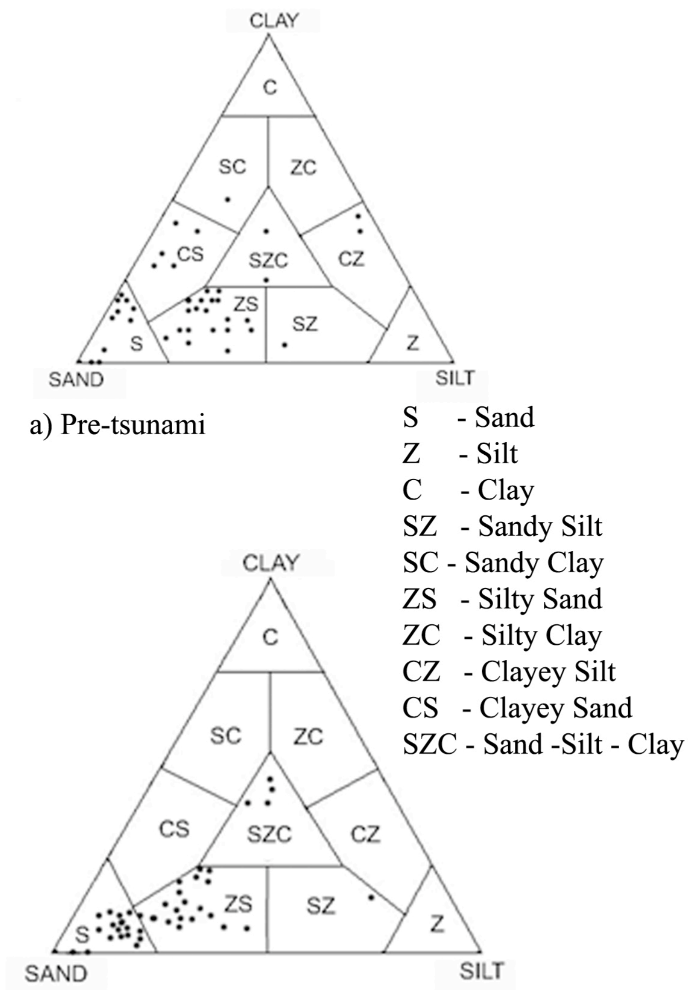


Figure 2: Textural classification - Triangular diagram

According to Morten Pejrup (1988), a constant clay/mud ratio can explain different degree of flocculation of the suspended sediment, which in turn is strongly influenced by turbulence of the estuary. The line of constant clay content can be used for a simple description of the hydrodynamic condition during sedimentation. The decreasing clay content from sections I to IV in the diagram (Fig.3) would indicate increasingly violent hydrodynamic conditions. High clay content in the mud fraction, would represent a quiet hydrodynamic condition. Over one third of the pre-tsunami sediments have populated segments I and II, indicating high clay content and relatively calm hydrodynamics. On the other hand, most of the post-tsunami sediments are confined to lower clay segments III and IV, indicating more violent hydrodynamic conditions during sedimentation.

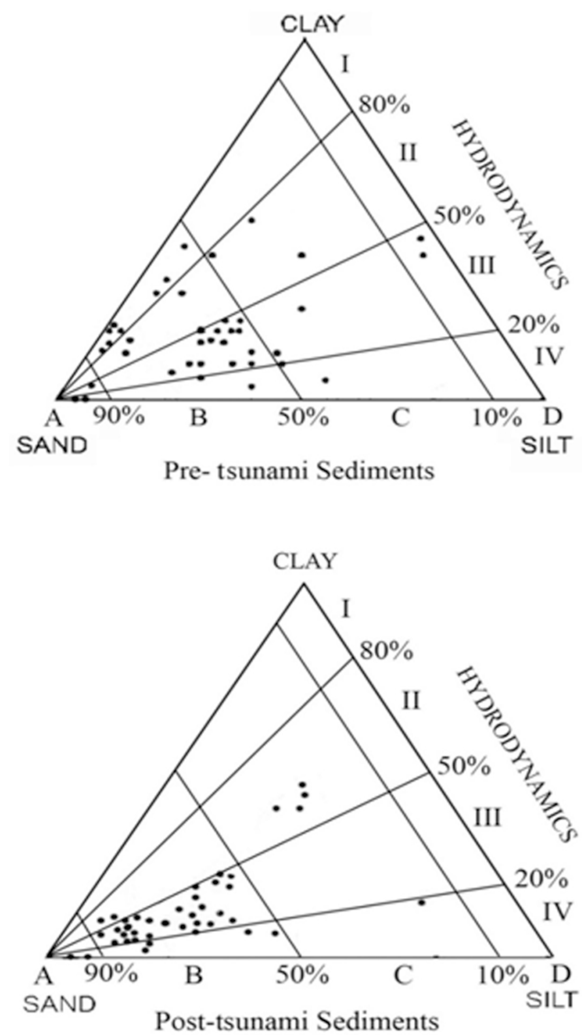


Figure 3: Hydrodynamics of Manakudy Estuary

The grain size statistics are used to distinguish between high and moderate energy environments. The grain size distribution is controlled by the physical transportation of sediment, including sediment aggregation and deposition, gravitational circulation, tidal pumping and tidal trapping (Wai *et* al., 2004). Grain size distribution of estuarine sediments has unraveled the existence of statistical relationships between the different size characteristics such as mean size, standard deviation, skewness and kurtosis. All the statistical parameters have been arrived at for all samples using the graphical method in which the cumulative weight percentage vs. quarter Φ values are plotted on a log probability chart to give the percentiles, followed by calculations (Table 1).

Mean size is an index to measure the nature as well as the depositional environment of the sediments. It represents the average size of the sediments influenced by the supply, transporting medium and the energy conditions of the depositing environment. The mean grain size (Φ) ranges from 0.98-2.37 in the pre-tsunami samples and 0.87- 2.07 for post-tsunami sediments. The mean diameter also indicates that most of the sediments in the pre-tsunami consist of very fine sand. The mean size indicates that the fine sands were deposited at a moderately low energy conditions. The decrease in size for the post-tsunami sediments may be due to a variation in wave energy reaching and the extent of turbulence affecting the environment due to the tsunami waves. The variation in Ø, therefore, reveals the different energy conditions which lead to the deposition of these kinds of sediments.

Standard deviation measures the sorting of sediments and indicates the fluctuations in the kinetic energy or velocity conditions of the depositional agent. The standard deviation ranges from 0.32 to 0.96Φ for the pre-tsunami and 0.56 to 1.04 Φ for the post-tsunami sediments respectively. The pre-tsunami sediments fall into the well sorted to moderately well sorted region, while most of the post-tsunami sediments are in the moderately sorted region. This sorting nature of the sediments may be due to the intermixing and influx of the sediments from sea as well as the river. The presence of fine sand and the well-sorted nature suggests effective wave action to scour the sediments during the break of tsunami waves.

Skewness measures the asymmetry of the frequency distribution. The values of skewness in the Manakudy estuary range between -0.51 and + 0.4 for pre-tsunami and -0.04 to +0.37 for post-tsunami sediments indicating that the normal size distribution is influenced by finer sizes (fine skewed). Skewness is positive (fine skewed) in the post-tsunami, whereas both positive as well as negative (coarse skewed) in the pre-tsunami season. The symmetry of the samples varies from fine skewed to coarse skewed nature. The fine skewed sediments generally imply the introduction of fine material or removal of coarse fraction or winnowing of sediments (Duane, 1964). The post-tsunami sediments have been deposited under high energy conditions as indicated by the positive skewness (fine skewed) compared to the pre-tsunami samples which are coarse skewed at the tail of the estuary, an indication of deposition under calm conditions.

Kurtosis measures the ratio between the sorting in the tails (leptokurtic) of the distribution and sorting in the central portion (mesokurtic) of the distribution and better sorted than the central portion (platykurtic) in the distribution. Kurtosis varies from 0.69-1.47 in the pre-tsunami and 0.77-1.44 in the post-tsunami seasons respectively. Most of the pre-tsunami sediments are platykurtic to mesokurtic while post-tsunami sediments are leptokurtic to mesokurtic. Jaquet and Vernet (1976) have used

Table 1. Grain Size Parameters

Sample No.	Pre-tsunami				Post-tsunami			
	M_z	S_D	S_k	K_G	M_z	S_D	S_k	K_G
1	2.35	0.78	-0.21	0.94	1.31	0.62	0.03	0.99
2	2.37	0.81	-0.19	0.94	1.80	0.79	0.33	1.34
3	2.33	0.95	-0.27	1.06	1.02	0.87	-0.04	1.23
4	1.68	0.40	-0.05	1.23	1.14	0.80	0.30	1.10
5	1.62	0.92	0.09	0.905	1.66	0.95	0.15	0.93
6	1.77	0.91	-0.16	0.86	1.89	0.92	0.19	0.81
7	1.21	0.84	-0.18	0.99	1.14	1.04	0.02	1.04
8	1.67	0.35	0.03	1.22	1.45	0.81	0.11	1.36
9	2.27	0.66	-0.29	0.84	1.38	0.77	0.13	1.07
10	2.25	0.72	-0.51	0.77	1.12	0.83	0.07	1.44
11	1.67	0.76	-0.15	0.98	0.98	0.70	-0.01	1.04
12	1.70	0.78	-0.10	0.72	1.40	0.65	0.10	1.22
13	1.86	0.70	-0.13	0.91	1.41	0.66	0.08	1.42
14	2.37	0.60	-0.41	0.90	1.13	0.87	0.21	1.04
15	1.88	0.76	-0.13	0.99	1.41	0.67	0.08	1.14
16	2.14	0.69	0.21	0.86	1.57	0.69	0.18	1.33
17	1.93	0.76	-0.03	0.88	1.76	0.75	0.11	0.92
18	1.90	0.82	0.22	0.87	0.87	0.99	0.11	1.15
19	1.55	0.51	-0.03	1.10	1.22	0.89	0.26	1.10
20	1.80	0.81	0.16	1.01	1.12	1.00	0.06	0.85
21	1.85	0.64	0.26	1.08	1.18	0.94	-0.03	1.03
22	1.82	0.72	0.15	0.99	1.28	0.52	0.10	1.10
23	1.97	0.70	0.34	0.88	1.23	0.64	0.08	1.13
24	1.72	0.54	0.29	1.43	1.69	0.73	0.20	1.30
25	1.90	0.57	0.35	1.03	1.39	0.64	0.11	1.26
26	1.63	0.44	-0.13	1.41	1.57	0.79	0.19	1.40
27	0.98	0.86	-0.09	0.69	1.36	0.68	0.09	1.20
28	1.78	0.32	0.20	1.47	1.16	0.60	0.07	1.11
29	2.13	0.73	0.15	1.05	1.32	0.56	0.04	1.08
30	1.62	0.61	0.28	1.30	1.23	0.80	-0.03	1.16
31	2.08	0.77	0.25	0.90	1.33	0.71	0.14	1.38
32	1.91	0.73	0.40	0.79	2.07	0.99	0.14	0.77
33	2.14	0.82	0.29	0.78	1.30	0.88	0.10	1.10
34	1.88	0.77	0.22	0.81	2.00	0.99	0.18	0.85
35	2.00	0.61	0.28	0.84	1.73	0.89	0.24	1.23
36	2.03	0.69	0.13	0.82	1.53	0.82	0.19	1.20
37	2.04	0.66	0.25	0.92	1.70	0.93	0.37	0.93
38	2.26	0.65	0.10	0.92	1.33	0.65	0.14	1.34
39	2.06	0.44	0.19	0.97	1.54	0.82	0.19	1.26
40	2.06	0.96	0.26	0.83	1.32	0.82	0.02	1.09

M_z-Mean Size, S_D-Standard Deviation, S_k-Skewness, K_G-Kurtosis graphic kurtosis to recognize the characters of population, as strongly platykurtic curves are found to be bimodal with sub equal amounts of the two modes. The frequency distribution curves of the pre-tsunami sediments have confirmed the bimodal-platykurtic behavior of the sediments and the post-tsunami unimodal sediments are mesokurtic to leptokurtic (Fig.4).

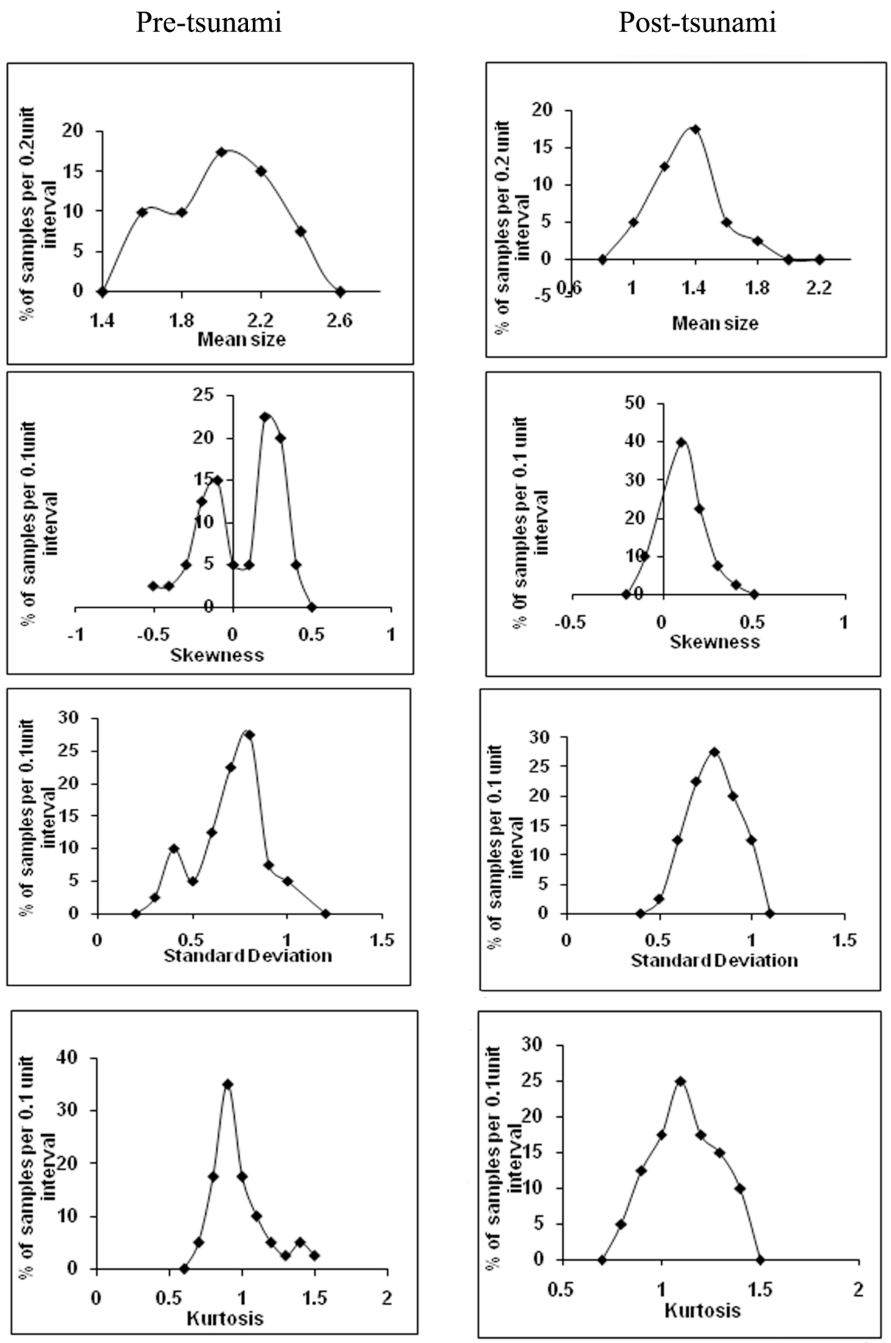


Figure 4: Frequency Distribution Curves (Samsuddin,1986)

The modal behavior is further confirmed by the frequency curves of Folk (1974), as depicted in Fig. 5.

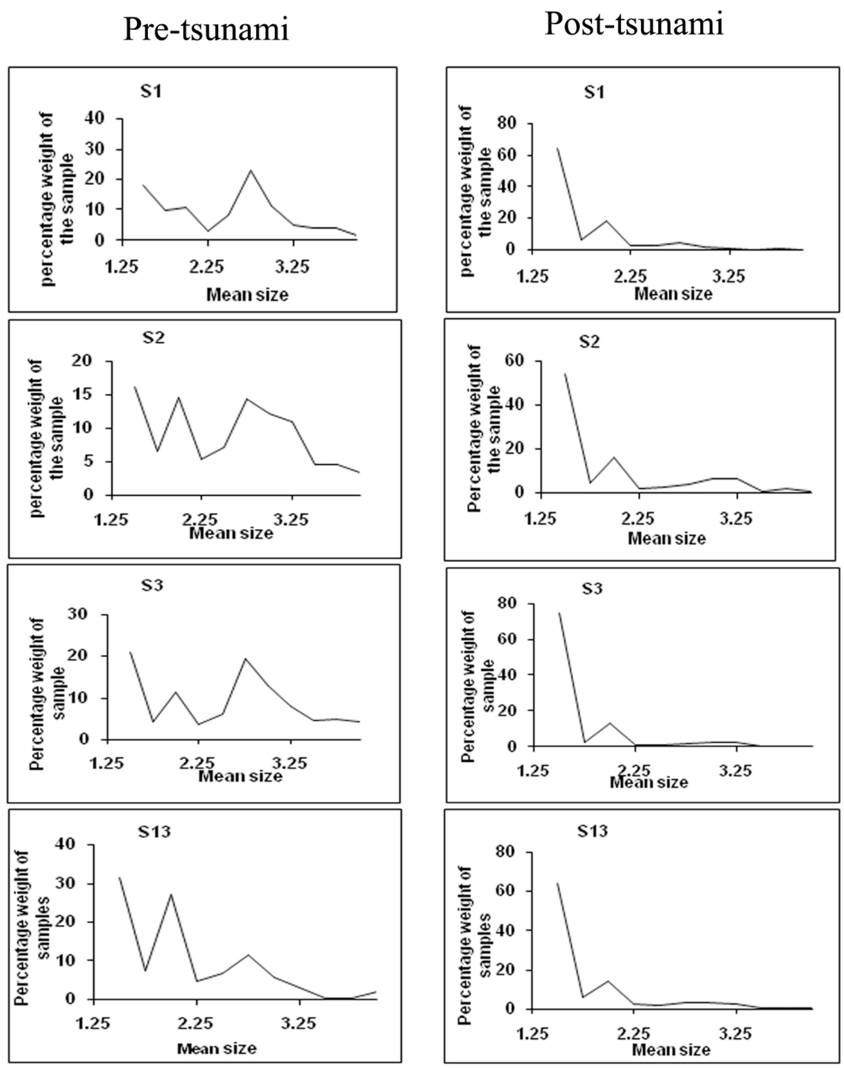


Figure 5: Frequency Curves (Folk, 1974)

The bivariate plots Fig. 6 (a-f) also confirm the above observations, as seen from the distinct different behavior of post-tsunami sediments.

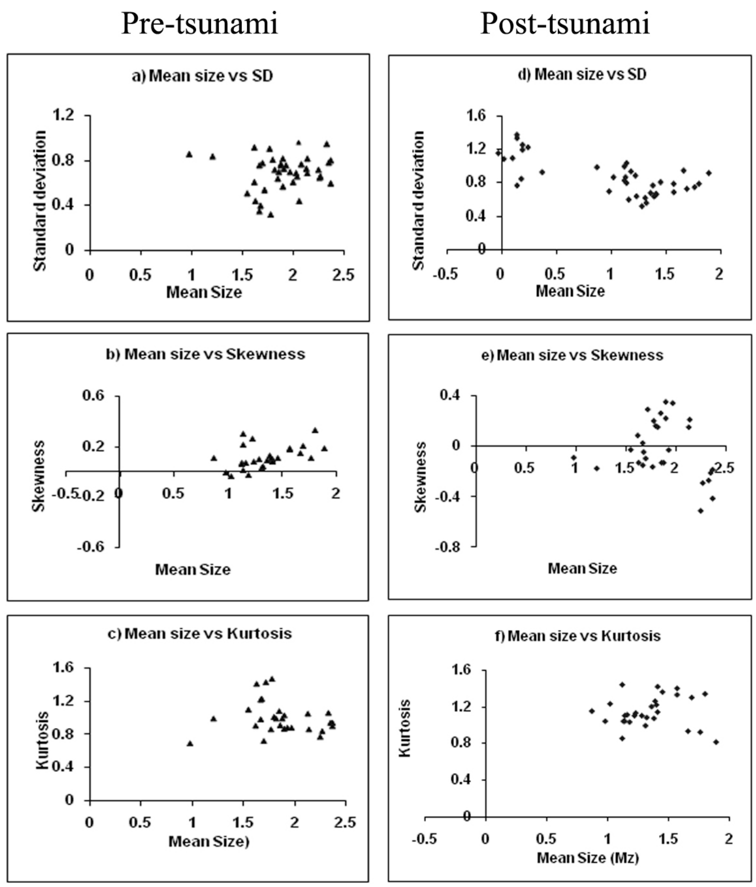
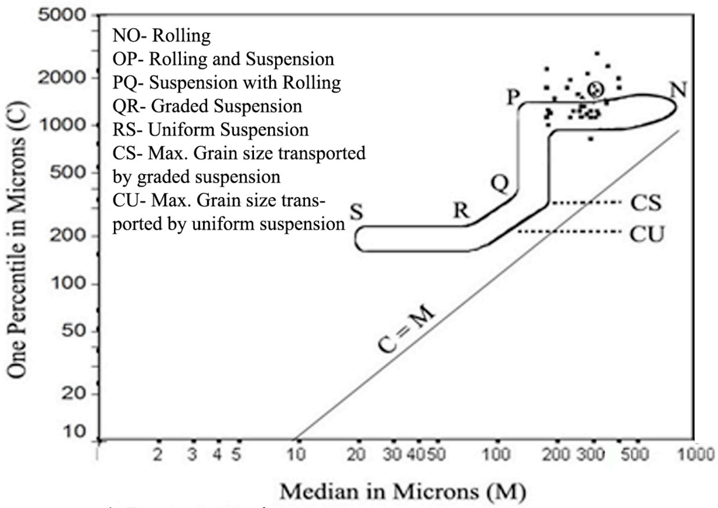
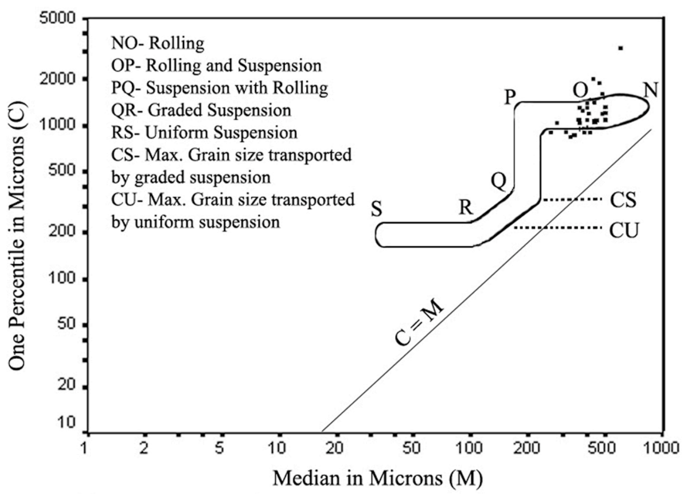


Figure.6. Bivariate plots- Pre-tsunami vs Post-tsunami

The C=M pattern offers a platform for deducing transportation modes of sediments. The area of a complete C=M pattern may be divided into sections which are related to sedimentary environments. The location of the plotted points for a single deposit within the area of a complete C=M pattern indicates the probable conditions of transport before deposition. In the pre-tsunami and post-tsunami patterns for the sediments of Manakudy estuary (Fig.7) the OPQ segment is populated indicating mostly the estuarine characteristics of the sediments (Ramanathan et al.2009). Some of the sediments are found in the high turbulent discriminate OP, and the less turbulent discriminate PQ, are indications of rolling of the sediments with suspension as well as suspension with rolling. Most of the sediments during the pre-tsunami season fall outside OPQ parallel to C=M between 200 and 400 microns indicate good sorting as established elsewhere. The post-tsunami sediments have two distinct segments NO and OP strongly populated, which is an indication that the majority of the sediments are transported by rolling and a small part by rolling and suspension. Some of the post-tsunami sediments are falling outside NOP segments shows a considerable influence by the marine currents under post-tsunami conditions. Moreover, C is above 1000 microns (1000-3000 microns) for most of the post-tsunami sediments infer violent hydrodynamic condition prevalent due to tsunami tidal waves, leading to coarser sandy deposition.



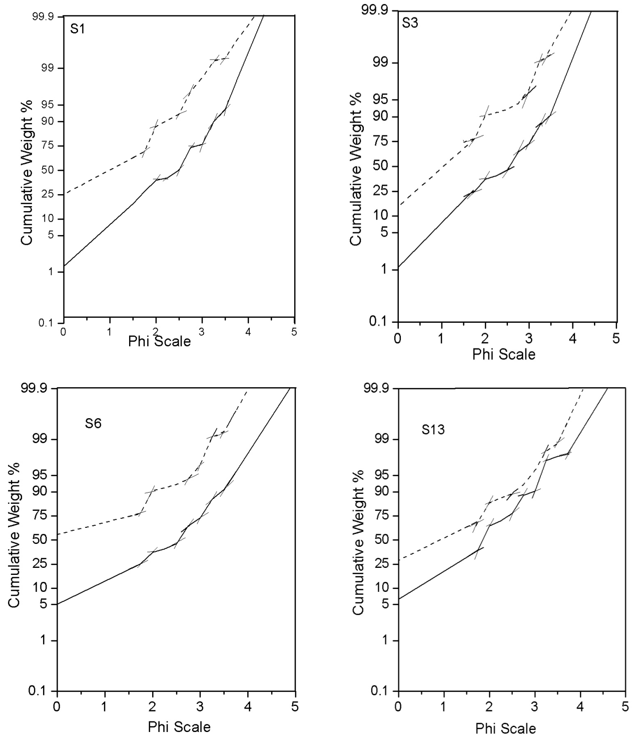
a) Pre-tsunami



b) Post-tsunami

Figure 7: C=M Pattern of Sediments

The log probability distribution curves have been used to recognize the different populations (Visher, 1969) suspension, saltation and surface creep (traction). The grain size pattern of the log probability curves (Fig. 8) shows at least three segments each defined by four control points (Weltje and Prins, 2007). Each population is truncated and joined with the next population to form a single distribution, as grain size distributions do not follow a simple log normal law but are composed of several log-normal populations with different mean and standard deviation. Hence each transportation process is reflected in a single grain size distribution plot with different percentage of population, degree of mixing, size range and degree of sorting providing insight into the currents, waves, rate of deposition and provenance.



-----Pre-tsunami - - - -Post-tsunami

Figure. 8. Vishers log Probability curves

The high saltation population (>50%) for the pre-tsunami grains reveals calm conditions prevailing during pre-tsunami period. On the other hand for post-tsunami grains, saltation population is low (<30%) which is indicative of violent hydrodynamic conditions. The position of the truncation point may also reflect the turbulent energy conditions at the depositional interface. The post-tsunami sediments have a very fine truncation point for the saltation population (3.5-3.6) revealing violent energy conditions. Also strong mixing of the suspension and saltation population indicates highly variable energy conditions. Hence it is established that the sediment transport occurs from the estuarine mouth due to winnowing action of the oscillatory waves followed by tidal action, which is an intermediate characteristic between those of fluvial and beach sediments during pre-tsunami season. The deposition of post-tsunami sediments is due to the erosion and transportation of sandy sediments from the backwash of the tsunami wave.

4. CONCLUSIONS

The pre-tsunami sediments are bimodal and fine (silty sand) compared to the unimodal and coarser (sand) behavior of the post-tsunami deposits. The post-tsunami grains bear marine characteristics under violent hydrodynamics, whereas the pre-tsunami grains are mostly fluvial, deposited under low energy conditions. The tsunami signatures are witnessed in the post-tsunami texture of the sediments as established from the statistical parameters of the grains. Their deposition under high-energy conditions is further evident from the C=M pattern and Vishers diagram.

REFERENCES

Bahlburg, H.Weiss, R.2007.Sedimentology of the December 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya Int. J. Earth Sci.96, 1195-1209

Baruah .J kotoky. P and Sarma J.N (1997): textural and geochemical study on river sediments: A case study on the Jhanji River, Assam. Jour Indian Assoc. Sedimentologists.16.p.195-206

Chandrasekhar, N. Loveson, V.J. and Rajamanickam, G.V, 1996. Distribution of organic matter and calcium carbonate content in the sediments of salt-marsh area, Tuticorin Gulf of Mannar, J. Indian Association of Sedimentologists, V.15, No.1, pp.59-66

Chandrasekar, N. Saravanan, S. Immanuel, L. Rajamanickam, J. and Rajamanickam, G.V. (2006) Classification of tsunami hazards along the southern coast of India: An initiative to safeguard the coastal environment from similar debacle. Science of Tsunami Hazards, Vol. 24, No. 1, page 3 (2006)

Datta.D.K. Subramanian., 1997. Texture and Mineralogy of sediments from the Ganges-Brahmaputra-Meghna river system in the Bengal Basin, Bangladesh and their environmental implications, Environmental Geology 30(3/4)

Duane, D.R.1964. Significance of skewness in recent sediments, Western Pamlico Sound, North Carolina, J. Sediment, Petrol, 34:864-874

Folk, R.L. and W.C.Ward.1957, Brazos River bar: a study in the significance of grain size parameter. J Sedimentary Petrology, 27:3-26.

Gee, G.W. and Bauder, J.W.1986. Particle size Analysis. In: A. Klute. Methods of Soil Analysis.part1: Physical and Mineralogical Methods, 2nd edition ASA and SSSA, Maidison, WI. pp, 383-411.

Hall, M.J, Nadeau, J.E and Nicilich, M.1987. The use of trace metal content to verify sediment transport from Delaware Bay on to the New Jersey inner shelf, J. Coastal Res V.3, pp 469-474

Jaquet, J.M. and Vernet, J.P. (1976) Moment and graphic size parameters in the sediments of Lake Geneva, Switzerland, J. Sediment Petrol, V. 46 p.305-312

Jing-Zhang, Weiwen Huang and Jean Marie Martin.1988, Trace metals distribution in Huange (Yellow River) Estuarine sediments Estuarine Coastal and Shelf Sci.V.26, pp.499-516

Kranck 1975 Sediment deposition from flocculated suspensions, Sedimentology, V.22, pp.111-124

Malvarez, G.C., Cooper. J.A.G. and Jackson D.W.T (2001): Relationship between wave induced currents and sediment grain size on a sandy tidal flat. Jour.Sed.Research.71, p.705-712

Mohan, P.M. 1995. Distribution of heavy minerals in Parangi pettai (Port Nova) Beach Tamil Nadu Journal Geological Society of India.46: 401-408.

Moore, A. Nishimura, Y. Gelfenbaum, G. Kamataki, T.Triyono, R.2006. Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia. Earth planets Space 58,253-258

Morten Pejrup (1988) the triangular diagram used for classification of estuarine sediments: A new approach. Tide Influenced Sedimentary Environments and Faces, p.289-300

Muraleedharan Nair, M.N., Ramachandran, K.K., 2002.Textural and trace metal distribution in sediments of Beypore estuary. Indian J. of Mari Science, 31:295-304.

Prabhakara Rao.A. Anilkumar.V, Yugandhar Rao.A Ravi G.S and Krishnan.S (2001): Grain size parameters in the interpretation of depositional environments of coastal sediments between Bendi Creek and Vamsadhara River, East Coast, India, Jour. Indian Assoc. Sedimentologists. V.20.no. 1.p. 106-116.

Ramanathan, A.L Rajkumar, K. Jayjit Majumdar.Gurmeet Singh, Behra, P.N Santra, S.C and Chidambaram, S.2009. Textural characteristics of the surface sediments of a tropical mangrove sundarban ecosystem India Indian Jour. of Mar. Sci vol.38 (4), p.397-403

Ramkumar, M., P. Sudha Rani, Gandhi, M.S., Pattabhi Ramayya, M 2000 Textural characteristics and prepositional sedimentary Environments of the Modern Godavari Delta. Jour. Geol. Soc. of India, V. 56, pp. 471-487.

Ridgeway, I.M. and Price, N.B. (1987) geochemical associations and post-depositional mobility of heavy metals in coastal sediments: Loch Etive, Scotland. Marine Chemistry v.21, p. 229-248

Samsuddin (1986) Textural differentiation of the foreshore and breaker zone sediments on the Northern Kerala Coast, India.Sediment.Geol.V.46, p.135-145

Shepard, F.P. (1954) Nomenclature based on Sand-Silt-Clay ratios.J.sed.Pet.v.24.p.155-158.

Sly, P.G., Thomas, R.L and Pelletier, B.R (1982) Comparison of sediment energy-Texture relationships in marine and lacustrine environments HydrobiologiaV.91, p.71-84

Wai, O.W.H. Wang, C.H., Li, Y.S., Li, X.D., 2004.The formation mechanisms of turbidity maximum in the Pearl River estuary, China Marine Pollution Bulletin 48, 441-448

Weltje, G.J and Prins, M.A., 2007.Geetically meaningful decomposition of grain size distributions. Sedimentary Geology 202.409-424.

Visher, G.S. (1969): Grain size distribution and depositional process. Jour. Sed. Pet., 39.p. 1074-1106.