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ORIGINAL ARTICLE

Impact of tsunami on texture and mineralogy of a major placer deposit in southwest coast of India

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Abstract The great Indonesian earth quake (26 December 2004) triggered a tsunami wave across the Bay of Bengal and Indian Ocean basins and has brought a major havoc in several countries including India. The coastal segment between Thotapalli and Valiazhikal in Kerala state of southwest India, where considerably rich beach placer deposit with ilmenite percentage of more than 70% is concentrated, has been investigated to understand the impact of tsunami on coastal sediments. The grain size analysis flashes out the significant differences between the pre- and post-tsunami littoral environments. While the mineral grains collected during pre-tsunami period show well-sorted nature, the post-tsunami samples represent moderately to poorly sorted nature. Similarly, unimodal and bimodal distributions of the sediments have been recorded for pre- and post-tsunami sediments, respectively. Further, mineral assemblages corresponding to before and after this major wave activity clearly indicate the large-scale redistribution of sediments. The post-tsunami sediments register increasing trends of garnet, sillimanite and rutile. The total heavy mineral percentage of the post-tsunami sediment also shows an improved concentration, perhaps due to the large-scale transport of lighter fraction. Magnetite percentage of post-tsunami samples reflects higher concentration compared to the pre-tsunami samples, indicating the intensity of reworking process. X-ray diffraction patterns of ilmenite grains have confirmed the increased presence of pseduorutile, and pseudobrookite in post-tsunami samples, which could be due to the mixing of more altered grains. SEM examination of grains also confirms the significant alteration patterns on the ubiquitous mineral of placer body, the ilmenite. The reason for these textural, mineralogical and micromorphological changes in heavy minerals particularly in ilmenite, could be due to the churning action on the deeper sediments of onshore region or on the sediments entrapped in the near shelf region of the area, by the ~ 6 m high tsunami waves.

Introduction

The shelf width is nearly 60 km and featureless in the coastal region, where tsunami was intense in the Kerala state (Fig. 1). Between Thotapalli and Valiazhikal estuary the barrier is 22 km long. As the coast is a low-lying one without any appreciable beach, the narrow barrier is protected by 3–4 m high sea walls. From Perumapalli to Valiazhikal, the sea walls were completely submerged during tsunami waves and its being renovated now by the Government of Kerala. The barrier island is 1–1.5 m high and having width ranging from 50 to 200 m. The beach width at Valiazhikal is only 50 m and the slope is invariably landward. The

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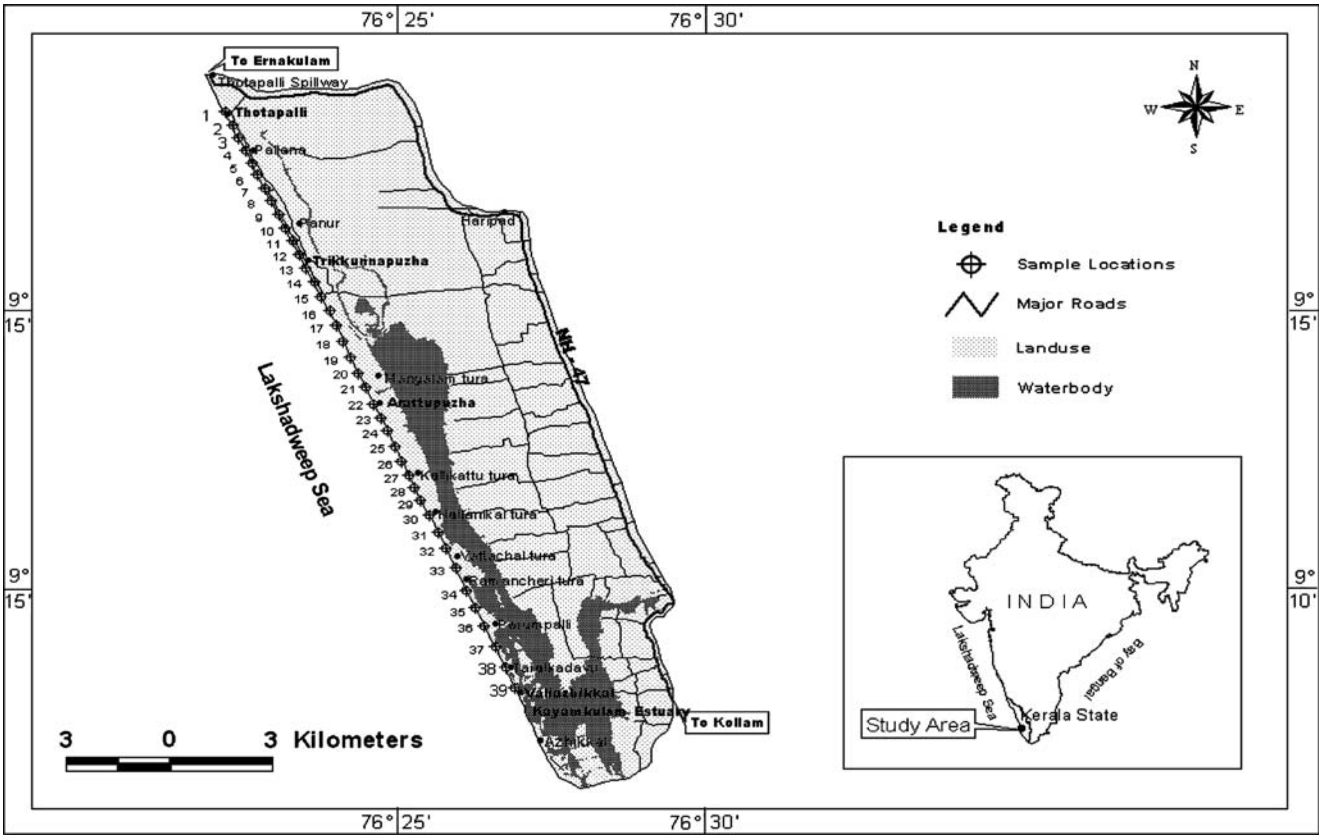


Fig. 1 Study area and sampling location of Thotapalli–Valiazhikal placer deposit

tsunami struck the southern Kerala coast at 11.30 a.m. and the central Kerala coast by 12.30 p.m. on 26 December 2004. The tsunami run-ups resulted in 172 casualties and an estimated loss of property worth Rs. 1,358.6 crores. Eyewitnesses indicate that three waves have struck the low-lying coastal plains consequentially and resulted into considerable damages (Fig. 2a, b). The Thotapalli–Valiazhikal coast is known for the black sand heavy mineral enrichments, but also prone to severe sea erosion. This coast is the northern non-contiguous extension of famous Chavara black sand deposits, which is located in the south of Kayamkulam estuary up to Neendakara. Long shore current and high wave energy were the main reasons for the black sand concentration along this coast. Apart from this process, the recent high intensity tsunami waves have also brought considerable quantities of shelf sediments towards the coast. High tide energy is one of the reasons attributed to the erosion taking place in the Valiazhikal region. A groin constructed recently on either side of the Kayamkulam lake (Bar) for navigation purposes, reportedly encourages beach erosion in the area. Further, the recent violent tsunami waves that first moved towards northerly direction might have hit over the right side of the groin structure and have taken its path towards northern side of the groin, where Valiazhikal, the worst affected area in Kerala is situated.

Heavy minerals are considered as natural tracers and therefore provenance of sediments and longshore transport direction have long been inferred using these minerals, in view of their strong hydrodynamic behaviour and weathering resistance (King 1972; Pettijohn 1975; Frihy and Komar 1993). The Atomic Minerals Division, Government of India (1997, 2000a, b) have reported that the present study area is occupied by 11.01 million tones reserve of heavy minerals. This paper reports the textural and mineralogical changes that took place in the region of beach placer deposits of Kerala state, due to the recent tsunami attack. Systematic mineralo-granulometric evaluation of beach placer sands of Kerala state before and after the tsunami event forms the main focus of this paper. The effects of tsunami on sediments as well as floral and faunal assemblages have been reported elsewhere (Leatherman et al. 1977; Nanayama et al. 2000; Szczucinski et al. 2005; Kumaraguru et al. 2005; Ramachandran et al. 2005;

Fig. 2 **a**, **b** Damaged house and huge deposition of black sands in the settlement area near Valiazhikal due to tsunami waves

Narayana et al. 2005; Gusiakov 2005; Perez-Terrado et al. 2006; Goff et al. 2006).

Study area

The study area falls between 09°5′ and 09°19′ North latitudes and 76°25′ and 76°24′ East longitudes. Geologically, the area consists of crystalline rocks of Archeaen age, sedimentary rocks of Tertiary period and laterite cappings on crystalline and sedimentary rocks belonging to sub-recent-to-recent age. The deposit lies between Thotapalli spill way and Kayamkulam estuary. Coastal length of the deposit is 20 km with average width of 2 km and depth of 10 m. Geomorphologically, the area comprises beach dunes, ancient beach ridges, barrier flats, coastal alluvial plains and flood plains. Shelf width is nearly 60 km and the beach width ranges between 10 and 150 m. Wave height in this zone is 1–2.5 m, which varies from 1 to 3.5 m during monsoon.

Materials and methods

Sample collection was done during December 2004 and January 2005 at an interval of roughly half kilometre from Thotapalli to Valiazhikal coast as far as possible. Pre-tsunami sampling was carried out as part of the regular field programme and the post-tsunami data collection was performed in the first week of January 2005 to verify the degree of mineralo-textural changes in the heavy mineral-rich sediments. All the samples (50 nos.) were initially washed and dried for further laboratory analysis after collecting the berm environment using hand auger. After coning and quartering, carbonates, organic matter and ferruginous coatings were removed from the samples by treating it with 1:10 HCl, 30% by volume H_2O_2 and $SnCl_2$, respectively. The dried samples were then sieved at a +GF + DIN 4188 sieve shaker for 15 min at half-Phi interval (Folk and Ward 1957). The grain size parameters like graphic mean (M_z), inclusive graphic standard deviation (σ_1), inclusive graphic skewness (Sk_1) and graphic kurtosis (K_G) were determined using the package Grain. Heavy mineral separation was carried out using bromoform (Milner 1962) and the count percentage of heavy minerals from selected samples was calculated. The 1–2 and 3–4 Ø size heavy fractions were mounted on slides (~250 grains) and counted under polarized light using a Leitz orthoplan microscope by the line counting method (Galehous 1969). Using a horseshoe hand magnet, magnetic minerals were removed from the separated heavy mineral fractions and their weight percentages were estimated. Further, the samples were subjected to magnetic separation using Frantz isodynamic separator to separate magnetic and non-magnetic fractions. With a forward slope of 15° and a slide tilt of 12° at 0.5 A, 0.4 A and 0.15 A were used to separate non-magnetic, magnetic and ilmenite fractions, respectively and their weight percentages were estimated. X-ray diffraction using Phillips (X'pert pro) powder diffractometer, (2 Ø from 10° to 60°) and SEM studies using Jeol-JSM 5600 LV microscope on ilmenite samples were also carried out to understand mineral alteration and micromorphology.

Results and discussion

Textural evidences

Textural parameters of sediments reflect the energy conditions of the depositional environment (Visher 1969; Sly et al. 1983). The results of sieve analyses are summarized in Table 1. Fine size grain sediments were

Table 1 Textural parameters in the pre- and post-tsunami samples of Thotapalli–Valiazhikal coast

Station no.	Pre-tsunami				Post-tsunami			
	MZ	SD	SK	KU	MZ	SD	SK	KU
1	1.79	0.59	0.23	1.12	2.45	0.41	–0.4	1.19
3	2.11	0.53	–0.14	0.75	2.2	0.49	–0.01	1.05
5	2.07	0.54	–0.08	0.75	2.21	0.48	0	1.05
7	2.04	0.52	–0.05	1.05	2.5	0.31	–0.3	2.46
9	2.13	0.59	–0.03	0.87	1.85	0.61	0.26	0.69
13	2.07	0.52	–0.09	0.76	2.1	0.51	–0.1	0.72
14	2.48	0.32	–0.29	1	1.95	0.6	–0.13	1.03
16	2.2	0.52	–0.09	1.23	1.47	0.85	–0.25	1.15
18	2.05	0.5	–0.07	1.07	1.44	0.84	–0.26	1.22
20	2.16	0.57	–0.1	0.86	1.47	0.8	–0.27	1.85
22	2.14	0.5	–0.12	0.71	2.09	0.53	–0.14	0.75
24	1.95	0.59	–0.19	1.06	2.09	0.52	–0.1	0.73
30	2.44	0.4	–0.38	1.16	1.66	0.55	0.02	1.32
32	2.05	0.53	–0.09	1.07	1.93	0.51	0.36	1.07
34	2.2	0.46	0.05	1.06	2.09	0.56	0.13	0.79
36	2.15	0.44	–0.03	0.59	1.44	0.78	–0.16	1.47
37	1.84	0.6	0.18	1.04	2.55	0.49	–0.19	1.24
38	2.42	0.4	–0.37	1.1	1.77	0.71	0.12	0.93
39	2.16	0.49	–0.14	0.72	2.1	0.6	0	0.84

MZ mean, *SD* standard deviation, *SK* skewness, *KU* kurtosis

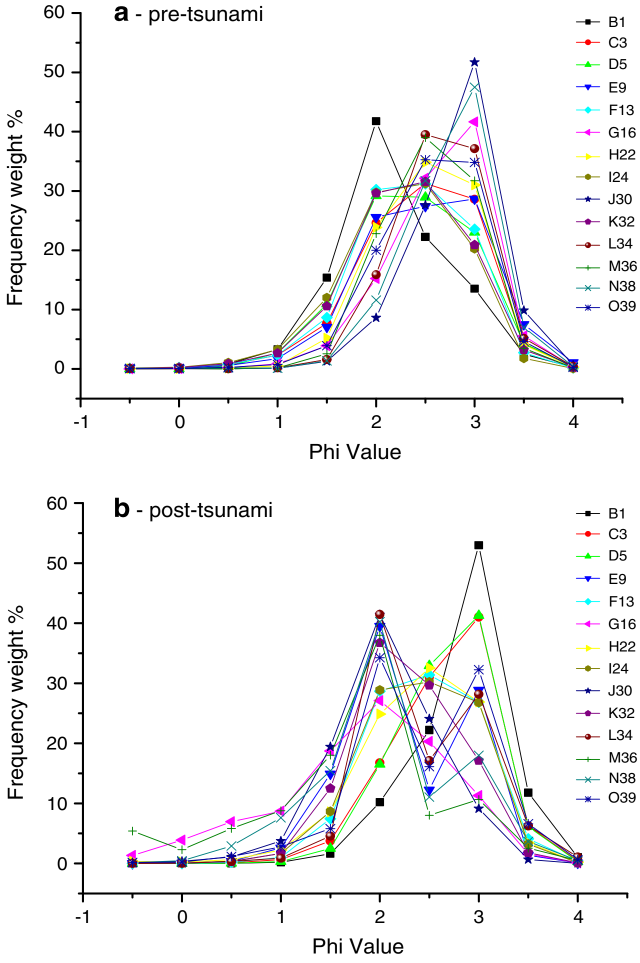


Fig. 3 **a**, **b** Frequency weight% curve for the beach sediments of pre- and post-tsunami periods

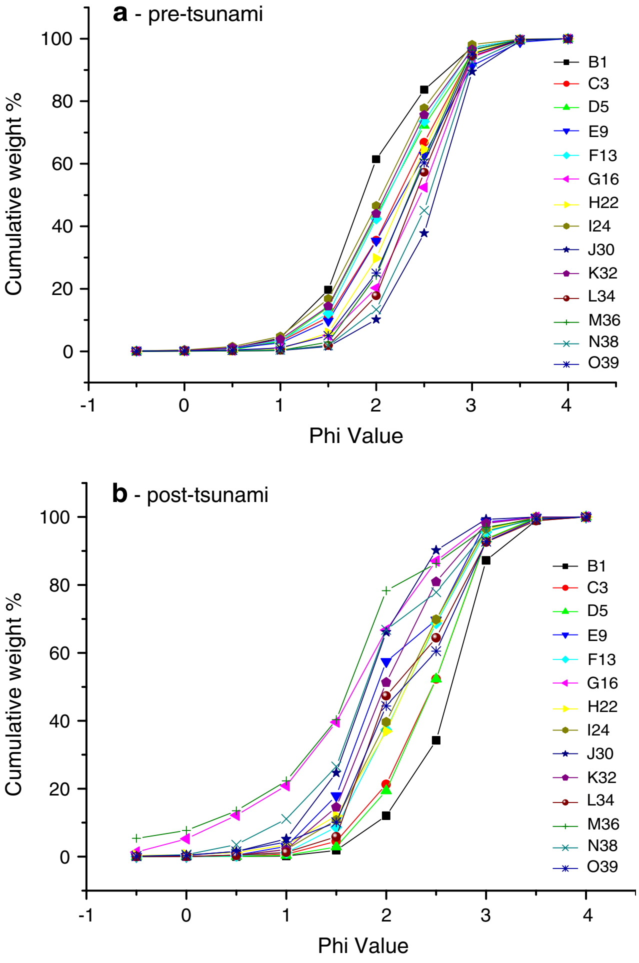


Fig. 4 **a**, **b** Cumulative curves for the beach sediments of pre- and post-tsunami periods

re-distributed to mixture of fine and medium sizes after tsunami waves in the Valiazhikal region, whereas the change is apparently not significant in Thotapalli region. Beach sediments mostly characterized by a sorting of less than 0.50 Ø have got re-arranged into >0.50 Ø in both the regions and the skewness of the same also changed accordingly. Platykurtic samples of the Thotapalli–Valiazhikal indicate a high-energy environment. Friedman (1962) showed that extreme high or low values of kurtosis imply that part of the sediment achieved its sorting elsewhere in a high-energy environment. Folk and Ward (1957) suggested that beach sediments might show extreme kurtosis value due to good sorting achieved in high-energy environment. Good sorting achieved in the Valiazhikal area during pre-tsunami period has been changed into moderate sorting nature due to irregular and giant tsunami waves unlike in the Thotapalli region.

Frequency distribution curves of size parameters of the sands of Thotapalli–Valiazhikal region represent the variations among sand population of these units and the degree of overlap between them (Fig. 3a, b). Mean size for this region (pre-tsunami) shows almost a uniform distribution ranging from –0.5 to 4 Ø with peak at 2 and 3 Ø and shows unimodal nature, i.e. single source of origin, whereas this trend has changed abruptly after tsunami waves. Mean size is not showing uniform distribution and the bimodal distribution curve reveals that source of the deposition is of multilevel origin.

The cumulative curves are plotted on arithmetic probability graph for Thotapalli–Valiazhikal sands (Fig. 4a, b). The size parameters have been calculated from the phi values of the cumulative curves. The cumulative curves of the sediments show over all dominance of saltation load in pre-tsunami samples, whereas mixture of traction and saltation load in post-tsunami samples. The suspension fraction is the least in both the samples in Thotapalli–Valiazhikal. Uniform suspension is found in pre-tsunami samples while post-

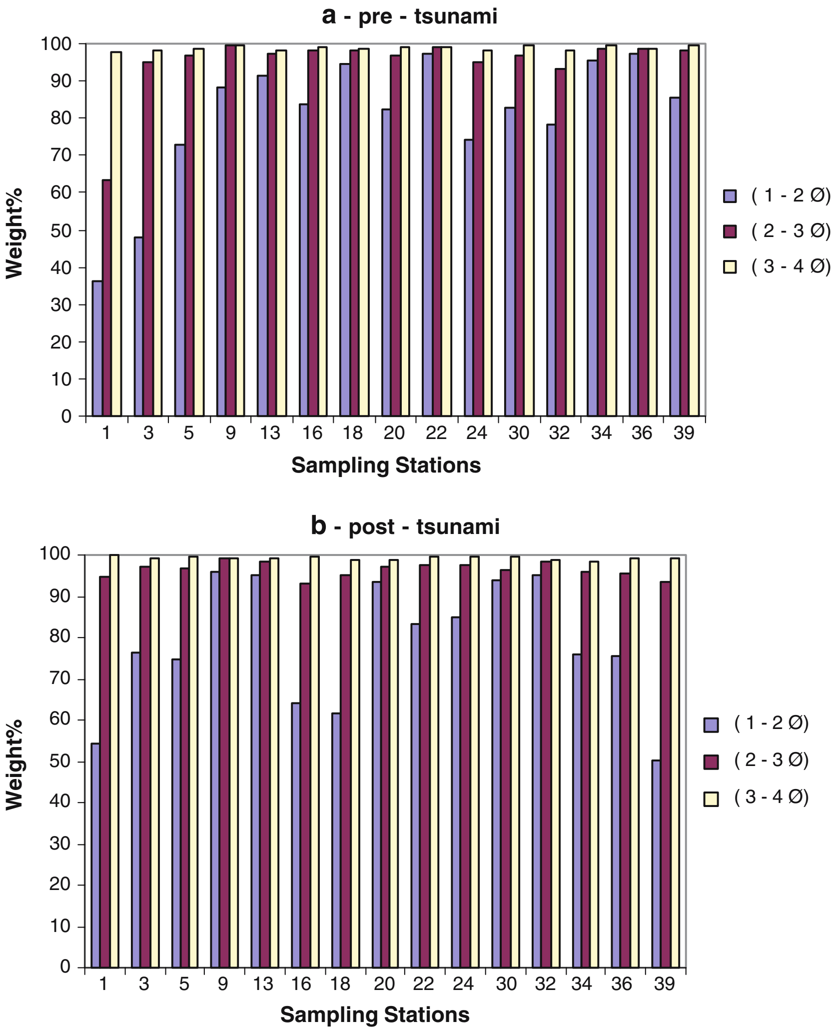


Fig. 5 **a**, **b** Distribution of heavy mineral percentage in different size ranges of Thotapalli–Valiazhikal placer samples during pre- and post-tsunami periods. Refer Fig. 1 for sampling locations

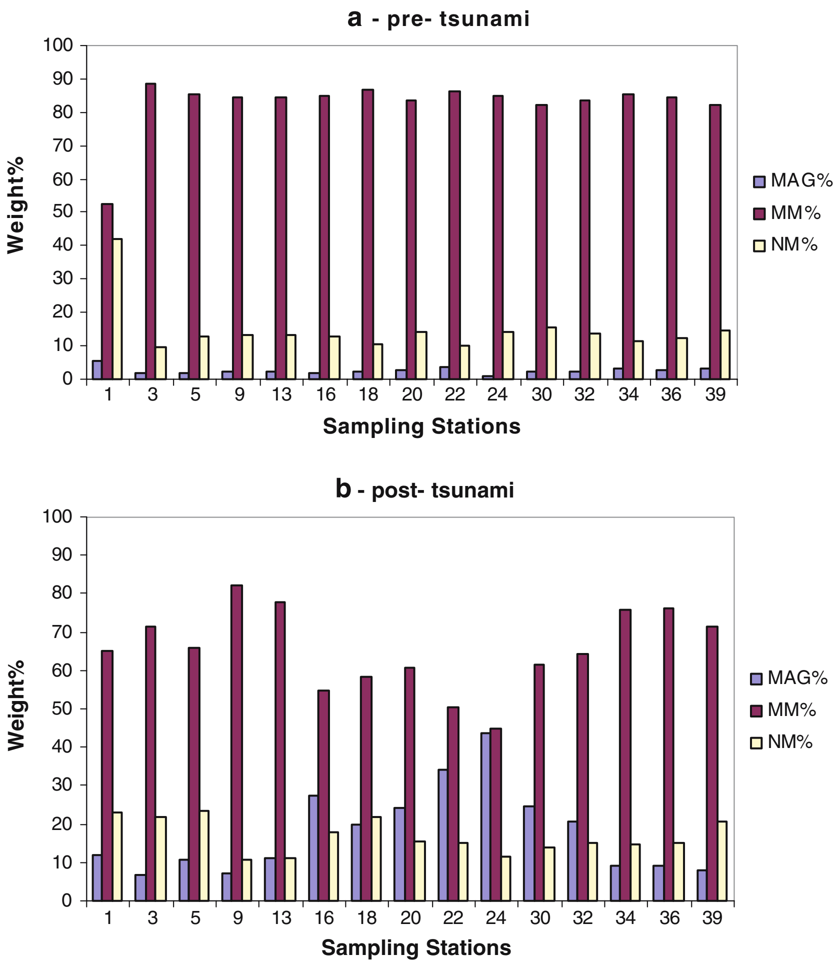
tsunami samples show irregular pattern of traction and suspension (Fig. 4a, b), which implies that irregular tsunami have contributed for this change. In short, the generated high intensity waves have made considerable impact in redistributing the accumulated sediments.

Mineralogical evidences

Heavy mineral distribution in the Thotapalli–Valiazhikal region is displayed in Fig. 5a, b. While the distribution of heavy minerals is almost uniform in the very fine sand of pre and post-tsunami samples, the distribution of same in fine sand is slightly more in post-tsunami samples than in pre-tsunami. More fluctuation in heavy mineral distribution was found in the medium sand of both periods. Weight percentage of the heavy minerals has also increased after the tsunami action in medium and fine sand fractions. It is postulated that the shelf sediments might have been brought out to the beach environment during tsunami attack in the study area. Distribution of magnetite, ilmenite and non-magnetic minerals from the study area is shown in Fig. 6a, b. There is an increase in magnetite percentage in the post-tsunami samples particularly at stations 13, 16, 18, 20, 22, 24, 30 and 32, which could be due to tsunami contribution. Magnetite (density 5.2), being heavier than other associated minerals is apparently not been brought to the shore during normal wave activities.

The total heavy mineral content shows highly enriched in very fine sand of post-tsunami samples. The percentage varies from 98.20% to a maximum of 99.80% at station no.1. In the pre-tsunami samples, percentage of heavies varies from 97.74% (station no.1) to 99.54% (station no. 9) in the very fine sand. In fine sand fraction the heavy mineral percentage ranges from 63.5% (station no. 1) to 99.47% (station no. 9), while in the medium sand fractions, range of percentage is from 36% (station no. 1) to 97.3% (station no. 36). Percentage of heavies in fine sand (post-tsunami) show a variation from 93.10% (station no. 16) to a maximum of 98.99 (station no. 9) while in medium sand minimum of 50.30% (station no. 39) and maximum of

Fig. 6 **a**, **b** Distribution of magnetite, ilmenite and non-magnetic mineral percentage in fine sand of Thotapalli–Valiazhikal placer samples during pre- and post-tsunami periods. Refer Fig. 1 for sampling locations



96% (station no. 9) of heavy mineral concentrations were recorded. Weight% of magnetite, ilmenite and non-magnetic minerals were studied only for fine fraction sand. As the weight percentage of magnetite ranges from 1 to 5.42%, ilmenite shows minimum of 52.55% and maximum of 88.46% and non-magnetic minerals with a concentration of 9.58 to 42.03% in the pre-tsunami samples. In post-tsunami samples, magnetite content varies from 6.77 to 43.74% and that of ilmenite from 44.66 to 82.29%. The percentage of non-

Table 2 Heavy mineral assemblage in the Thotapalli–Valiazhikal placer deposit (count%)—pre-tsunami

S. no.	Minerals	7	9	14	18	24	30	34	36
Medium sand (1–2 Ø)									
1	OP	72.54	77.39	65.23	88.03	75.64	69.62	83.98	79.10
2	SL	23.80	12.63	26.14	5.98	17.95	22.03	7.37	5.67
3	ZR	2.11	4.28	0.76	2.11	0.00	1.01	2.39	8.96
4	RU	0.14	1.02	1.27	0.35	0.51	1.01	1.10	1.49
5	GA	1.41	3.26	3.05	2.46	2.82	0.76	1.47	2.09
6	KY	0.00	0.81	1.78	1.06	2.31	2.28	1.47	0.90
7	MO	0.00	0.61	0.00	0.00	0.00	0.00	0.37	0.90
8	SP	0.00	0.00	0.51	0.00	0.00	0.76	0.18	0.00
9	EP	0.00	0.00	0.51	0.00	0.00	0.76	0.37	0.00
10	AP	–	–	–	–	–	–	–	–
11	OT	0.00	0.00	0.76	0.00	0.77	1.77	1.29	0.90
Very fine sand (3–4 Ø)									
1	OP	76.83	75.37	62.58	56.99	61.91	44.89	45.75	54.39
2	SL	2.54	2.97	1.11	1.29	0.78	0.00	0.00	1.06
3	ZR	16.51	16.56	27.39	36.58	29.88	50.31	48.49	35.90
4	RU	1.27	0.65	2.90	1.10	3.13	1.88	1.37	1.86
5	GA	0.32	0.43	0.00	0.92	0.00	0.00	0.00	1.33
6	KY	0.00	0.00	0.89	0.37	0.59	0.00	0.00	0.80
7	MO	2.53	3.18	4.68	2.76	2.73	2.71	3.84	3.19
8	SP	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00
9	EP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	AP	–	–	–	–	–	–	–	–
11	OT	0.00	0.84	0.45	0.00	0.59	0.21	0.55	1.46

OP Opaque, *SL* sillimanite, *ZR* zircon, *RU* rutile, *GA* garnet, *KY* kyanite, *MO* monazite, *SP* sphene, *EP* epidote, *AP* apatite, *OT* other minerals

Table 3 Heavy mineral assemblage in the Thotapalli–Valiazhikal placer deposit (count%)—post-tsunami

S. no.	Minerals	7	9	14	18	24	30	34	36
Medium sand (1–2 Ø)									
1	OP	77.11	90.91	88.04	71.06	83.43	84.22	74.89	77.84
2	SL	17.11	5.83	8.80	22.59	11.38	11.44	14.47	14.40
3	ZR	0.00	0.00	0.00	3.05	2.79	1.58	0.64	0.00
4	RU	0.67	0.47	0.45	0.71	0.20	0.20	0.00	0.55
5	GA	2.67	2.56	1.81	1.65	1.60	1.97	7.87	6.65
6	KY	1.56	0.00	0.23	0.94	0.60	0.59	0.43	0.00
7	MO	–	–	–	–	–	–	–	–
8	SP	–	–	–	–	–	–	–	–
9	EP	–	–	–	–	–	–	–	–
10	AP	0.00	0.23	0.68	0.00	0.00	0.00	0.85	0.28
11	OT	0.89	0.00	0.00	0.00	0.00	0.00	0.85	0.28
Very fine sand (3–4 Ø)									
1	OP	75.37	75.70	76.04	75.25	67.64	73.10	56.95	76.98
2	SL	0.74	1.56	1.04	1.58	1.46	1.36	4.81	3.24
3	ZR	22.43	22.12	21.18	19.60	27.12	25.27	34.22	18.71
4	RU	0.74	0.00	0.69	2.97	3.50	3.53	1.87	0.36
5	GA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	KY	0.74	0.62	1.04	0.59	0.29	0.82	2.14	0.72
7	MO	–	–	–	–	–	–	–	–
8	SP	–	–	–	–	–	–	–	–
9	EP	–	–	–	–	–	–	–	–
10	AP	–	–	–	–	–	–	–	–
11	OT	–	–	–	–	–	–	–	–

OP Opaque, *SL* sillimanite, *ZR* zircon, *RU* rutile, *GA* garnet, *KY* kyanite, *MO* monazite, *SP* sphene, *EP* epidote, *AP* apatite, *OT* other minerals magnetic minerals in these samples is from 10.70 to 23.54%. The enrichment of heavies in the study area could also be attributed to the selective entrainment due to present day coastal processes, according to Clemens and Komar (1988), heavy minerals undergo not only density sorting but also size sorting, tending to concentrate in finer size fractions (Komar and Wang 1984; Peterson et al. 1986). The increasing trend of total heavies and weight percentage of the magnetite, ilmenite and non magnetic minerals indicate that the shelf sediments have been transported and deposited in the beach environment by the tsunami waves in addition to the regular processes acting in this area. Similar observations have been made in the post-tsunami scenario by studies carried out elsewhere (Leatherman et al. 1977; Nanayama et al. 2000).

Heavy minerals observed in sands of Thotapalli–Valiazhikal (pre-tsunami) in order of abundance are opaque (ilmenite and magnetite), sillimanite, zircon, kyanite, monazite, garnet, rutile and a few other minerals (Tables 2, 3). While in the medium size fraction opaque varies between 65.23 and 88.03% and in the very fine fraction between 44.89–76.82%. Distribution of opaque in all stations shows more or less equal percentage in the medium fraction than in the very fine fractions. The maximum concentration of zircon was found in very fine fraction (16.51–50.31%). In the Valiazhikal region, opaque:zircon ratio is almost equal to that of Thotapalli region. Kayamkulam bar that is situated near the Valiazhikal and its offshore zone might have contributed more zircon population over there. Zircon percentage in medium fraction ranges between 0 and 8.96. In the case of sillimanite, it ranges from 5.67 to 26.14% in medium fraction and from 0 to 2.97% in very fine fraction. Considerable amount of garnet was reported in the medium fraction than very fine fractions. Green colour garnet uvaravite was found rather than the pink and red varieties. But rutile concentration shows almost equal in all the fractions. As far as monazite is concerned, very fine fractions contain nearly equal percentages, while in the medium fraction only the Valiazhikal region shows very low percentage. Size sorting phenomena support these results.

Heavy minerals observed in sands of Thotapalli–Valiazhikal (post-tsunami) in order of abundance are opaque, sillimanite, zircon, garnet, rutile, and a few other minerals. The percentages of sillimanite and garnet are abruptly increased in the post-tsunami samples than pre-tsunami ones in medium size fractions (Table 3). Opaque percentage in very fine sand increased slightly, compared to the pre-tsunami samples. Zircon percentage abruptly decreased in the very fine fraction than in pre-tsunami samples (Table 3). The changes in zircon content reveal that there was an extra deposition of opaque mineral than zircon in the study area due to tsunami waves.

Monomineralic evaluation

X-ray diffraction pattern of the ilmenite concentrate of Thotapalli–Valiazhikal shows the presence of ilmenite and rutile peaks in the pre-tsunami samples, while in the post-tsunami it shows ilmenite, rutile, pseudorutile, and pseudobrookite peaks. This means that the grains are apparently more altered in the post-tsunami samples (Fig. 7), which could be due to the mixing of shelf sediments with the onshore sands. The shelf of the Kerala coast may host older sediments and possibly more altered or the shelf sediments could have been

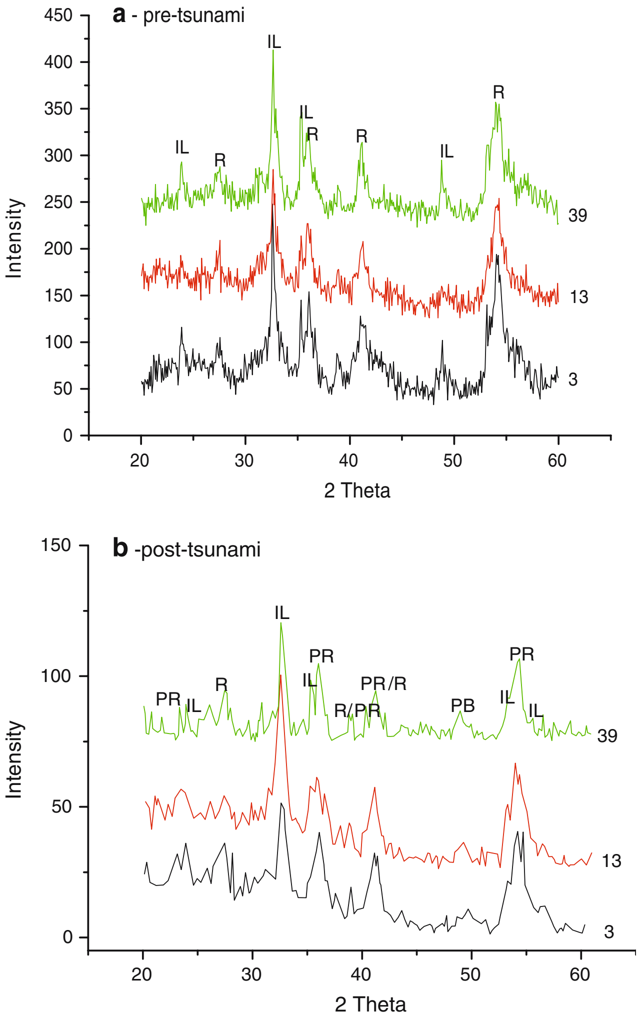


Fig. 7 X-ray diffractograms of the representative ilmenite. Note the presence of ilmenite, and rutile in the pre-tsunami samples and ilmenite, rutile, pseudorutile and pseudobrookite in the post-tsunami samples

subjected to intense weathering due to sub aqueous conditions.

Micromorphological studies of ilmenite of pre-tsunami (Fig. 8a–c) and post-tsunami (Fig. 8d–f) from the study area by SEM depict the development of a number of different micro features on the ilmenite grain which support the XRD evidences. From these features, one could understand the physical and chemical energy gradient, surface and sub-surface dissolution process, and post depositional diagenitic modifications (Setlow and Karpovich 1972; Morton 1984). Krinsley and Doornkamp (1973) used the surface textures of quartz grains in order to achieve an understanding of the post-depositional or diagenitic history of the sediments. Pre-tsunami ilmenite grains exhibit subrounded shape along with impact 'V'' marks and deep pits are seen resulting from mechanical collision and later from solution activity (Fig. 8a). Mechanical feature like V-shaped pits suggest that grains are formed by grain-to-grain collision in an aquatic medium (Higgs 1979; Mallik 1986). Crescentic structures and pits are produced by solution activity (Fig. 8b). Due to long residence time, this type of features might have developed on the grains. Sets of grooves oriented at different angles developed over the grains clearly indicate the solution activity process (Fig. 8c). More precipitation-corroded features are visible in the post-tsunami ilmenite grain (Fig. 8d), which were presumably developed due to the chemical activity. Similar features have been observed in non-opaques along the East Coast of India (Cherian et al. 2004). Undulatory wavy surfaces formed due to solution effect and removal of blocks were also observed on post-tsunami ilmentie grains (Fig. 8e, f). The post-tsunami sediments might have been transported from the Shelf region of Kerala Coast or partly formed due to the reworking of deeper onshore sediments that were lying below the water table.

Conclusion

With respect to texture, uniform grain size of Thotapalli–Valiazhikal heavy minerals has changed to non-uniform type after the tsunami. Further, well-sorted nature has changed into moderately sorted and unimodal distribution has been changed to bimodal nature. This reveals that more than two sources of energy were involved in redistribution of the sediments. Domination of saltation during the earlier regime has changed to traction and saltation load during tsunami period. Mineralogically, there is an increasing trend in total heavy mineral due to tsunami waves. Heavy minerals such as ilmenite, sillimanite and garnet percentages have been increased abruptly. There is an increase in magnetite percentage in the post-tsunami

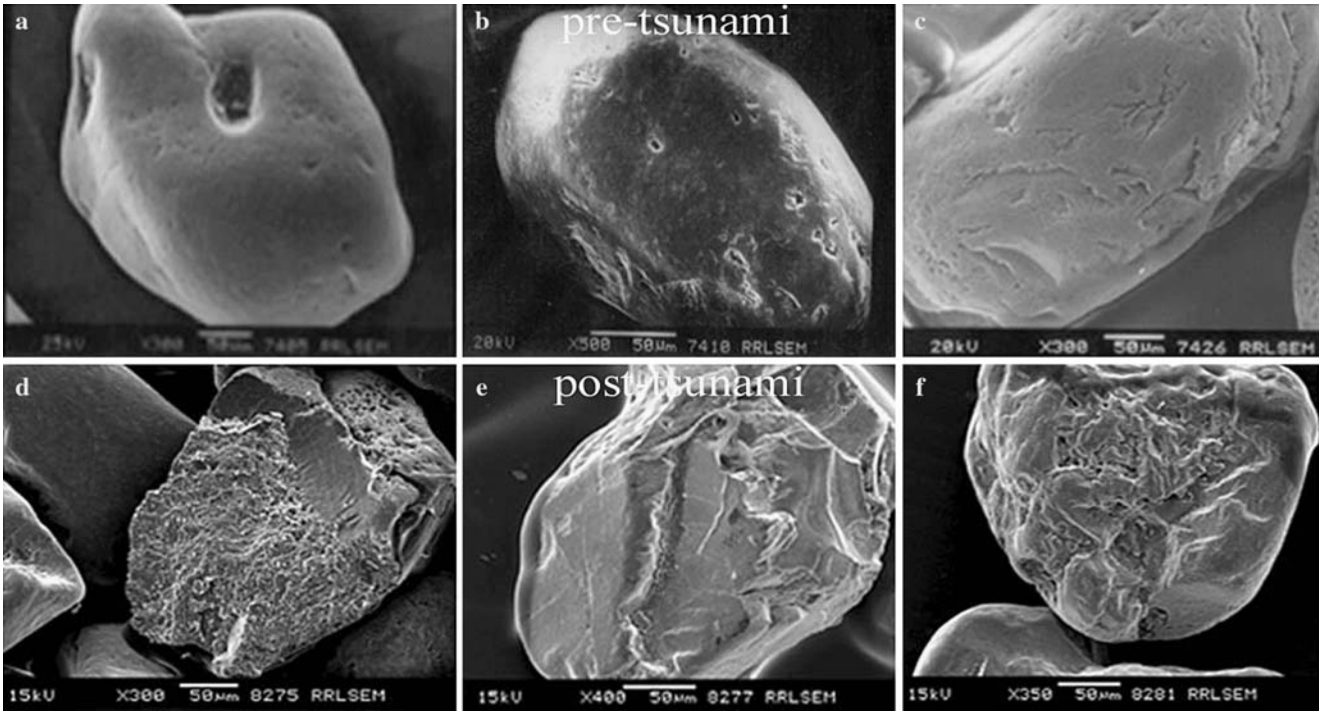


Fig. 8 **a**–**f** Scanning electron microscopic view of ilmenite grains separated from pre- and post-tsunami samples. Note the intensity changes in the post-tsunami samples (**d**, **e**, **f**)

samples which could be due to tsunami contribution. More alteration is also noticed in the minerals of the post-tsunami samples, particularly in ilmenite. Since tsunami waves have reworked the shelf sediments significantly, the texture and mineralogy of onshore deposit might have got completely changed up to at least about 20–50 cm depth.

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