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Proxy mineral magnetic and elemental analyses for 2004 tsunami impact deposit along the Muttukadu backwater, East Coast of India: Scope of the palaeotsunami studies

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ABSTRACT

Following the line of approach enumerated in the tsunami toolkit of Chagué-Goff et al. (2011), 'Expanding the proxy toolkit to help identify past events - Lessons from the 2004 Indian Ocean Tsunami and the 2009 South Pacific Tsunami, Earth Sci. Rev. 107 (1–2), 107–122', measurements of elemental and mineral magnetic properties coupled with textural parameters have been used to evaluate the 2004 Indian Ocean Tsunami (IOT) induced sediments on the Muttukadu backwaters, East Coast of India. To investigate the sediment provenance, specific Fe, Mn and Pb elemental concentrations were measured in surface sediments and compared with the previously published pre-tsunami database of backwater/inner continental shelf sediments. We found the enrichment of Fe and Pb, against depletion of Mn concentration in present tsunami sediments as compared with pre-tsunami Muttukadu sediments, reflecting the variation of the sediment source area. However, the present data of Fe and Pb enrichment and Mn depletion correlates well with continental shelf sediments hinting at sedimentary routes, processes of erosion and wave propagation. The studied tsunami deposits are characterized by dominant ~40–85% coarse sand fractions and higher proportion of detrital low and high coercivity Fe-Ti oxides, such as magnetite, titanomagnetite and hematite, reflected by magnetic concentration (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM)) and coercivity-dependent parameters (soft isothermal remanent magnetization (Soft IRM), Hard IRM, magnetomineralogical S-Ratio and saturation IRM (SIRM)). So, it can be shown that the random spatial variability and the inverse relationship between magnetic concentration χ, ARM and SIRM parameters and grain-size ARM/χ, SIRM/χ and ARM/SIRM ratios as diagnostic criteria for the tsunami impacted the distribution of magnetic parameters in coastal backwater environments. Contrasting mineral magnetic and geochemical properties together with more sand (mean 65%) when compared with silt (mean 25%) content in tsunami sediments indicates that the area was affected by high-energy tsunami waves. The study validates environmental magnetism as a proxy, which is fast and robust for identifying the tsunami or palaeotsunami deposits.

1. Introduction

Tide influenced inlets interfacing terrestrial and marine systems are geomorphologically best archives for hunting palaeotsunami/palaeo-storm deposits, as they exhibit higher preservation potential (Pethick, 2000; Ballukraya, 2005; Jankaew et al., 2008; Shukla et al., 2010; Prendergast et al., 2012; Andrade et al., 2014). Backwaters and estuaries, because of their location at the confluence of sea and river, are important as centers of terrestrial sediment sinks. Tsunami deposits have often been reported in the onshore and offshore regions (Dawson and Shi, 2000; Goff et al., 2001, 2008; Kumar and Achyuthan, 2006; Srinivasalu et al., 2007; Jankaew et al., 2008; Jonathan et al., 2012; Prendergast et al., 2012; Prizomwala et al., 2015). However, very few studies have been carried out combining the signatures of run-up and return flow deposits (Dawson et al., 1995; Goff et al., 2001). The rapid water flow displayed by tsunami can transport variety of grain sizes ranging from clay, silt to boulders (Goff et al., 2001). It is known that individual tsunami waves reach a point of zero water velocity prior to

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backwash flow, at which point large volumes of sediment carried by the water column may be deposited onto the surface.

Sometimes these sediment sheets are seen to be structure-less and massive accumulations of sand while others exhibit evidence of grading (Dawson and Shi, 2000; Srinivasalu et al., 2007). Several techniques have been used to decipher palaeotsunami from other deposits, viz., grain size, enrichment in specific elemental concentrations, heavy mineral enrichments, foraminiferal assemblages etc. However, there is no conclusive proxy available which would essentially be marked as a marker proxy for palaeotsunami deposit in different coastlines of the world. Tsunami can initiate widespread modification and reorganization of coastal geomorphic systems into a new dynamic state (Andrade, 1992; Goff et al., 2008). The recognition of deposits from past tsunamis allows geologists to extend the relatively short or non-existent historical record of tsunamis in an area, thus improving assessment of tsunami hazard. Also the understanding of palaeotsunami history enables us to access how past human settlements along the coastline would have been affected by such catastrophic events.

The 2004 Sumatra–Andaman earthquake and Indian Ocean Tsunami (IOT) killed nearly 220,000 people in 14 countries and caused severe harm to the coastal population of the entire oceanic basin and damage to coastal infrastructure (NGDC/WDC, 2010). Tsunami deposit research has expanded considerably following the 2004 IOT (Srinivasalu et al., 2007; Goff et al., 2008; Jankaew et al., 2008; Fujino et al., 2009; Chagué-Goff et al., 2011; Jonathan et al., 2012; Prendergast et al., 2012). One of the important direct impacts of the IOT was the deposition of sedimentary beds on the affected coastal land surfaces. This also does not discount for the occurrence of such events in past record which might have affected the ancient civilizations of southeast (SE) coastline of India. Hence, the driving force behind the present paper is to study deposits laid down by the IOT in the coast of SE India near Chennai, and develop new approaches such as mineral magnetic and geochemical studies as proxy to assess the tsunami left imprints on the sedimentary deposits.

The Chennai coast is susceptible to the tsunami juggernaut which can deposit continuous and discontinuous sediment sheets over relatively wide areas and considerable distances inland. This paper reports the investigation of the mineral magnetic and geochemical properties of tsunami laid backwater surface sediments and compares it with characteristics of sediments deposited prior to tsunami in backwaters and inner continental shelf.

2. Description of study area

Muttukadu backwater is located 36 km from Chennai city, and extends for a distance of 20 km from the mouth i.e. estuarine. It runs at right angle to the SE coast for a distance of ∼3 km and branches into the southern - northern wings (Fig. 1). The backwater is normally cut off from the Bay of Bengal during May–September due to formation of a longitudinal sand bars by littoral drift. The same sand bars get eroded due to the fresh water inflow from the upper reaches during October–December months from the NE monsoon, restoring the connection with the sea. The width of the inlet ranges from 80 to 100 m reaching a maximum depth of ∼1–2 m at a few places. We study the 2004 tsunami impact on Muttukadu sediments using magnetic and geochemical properties.

3. Materials and methods

The Mutthukadu backwaters were affected by the 2004 IOT juggernaut with run-up of 6 m in the adjoining regions (Jayakumar et al., 2005). Almost four-years after the 2004 IOT disaster, ∼30 surface sediment samples were collected in the month of January and February 2008 using a Van-Veen grab and boat at a regular interval of 16 m using GPS (Fig. 1). The sampling was carried out with a preamble that owing to the lack of active sedimentary processes in Mutthukadu backwaters, the surface sediment samples would represent the signatures of 2004 IOT. Geochemical and magnetic measurements used in the present study were all carried out at Environmental Magnetism Laboratory, Indian Institute of Geomagnetism, Navi Mumbai, India. Geochemical assessment was performed on finely ground 30 bulk tsunami samples using Spectro XEPOS XRF spectrometer by Turboquant-Powders method. The precision of the analysis was better than 5% for major elements and 10% for trace elements. We analyzed grain-size with a CILAS 1060 laser particle size analyzer and calculated percent of clay, silt and sand grain-size values with the Wentworth-phi scale (Krumbein, 1934).

Standard environmental magnetic measurements like mass specific magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM), wherein saturation IRM (SIRM) represents maximum field of 1 T in the forward direction and then with 300 mT field in the opposite direction, were carried out using Bartington susceptibility meter with dual-frequency sensor, Molspin pulse magnetizer and Molspin spinner magnetometer. The interparametric ratios of magnetic data (ARM/χ SIRM/χ and ARM/SIRM) are used to infer magnetic grain-size and S-Ratio$_{-300}$ (simplified here as IRM$_{-300}$/SIRM) gives the relation proportion of low versus high coercivity ferromagnetic particles with high values corresponding to a high proportion of low coercivity minerals (i.e. magnetite and titanomagnetite). Also Soft IRM (SIRM–IRM$_{-20mT}$), which represents the amount of magnetite and titanomagnetite in the samples and Hard IRM (SIRM–IRM$_{-300mT}$), which represents the amount of hematite, were also derived from the magnetic parameters (Thompson and Oldfield, 1986; Basavaiah, 2011).

4. Results and discussion

4.1. Detrital Fe, Ti, Al and Si elements and sediment sources

The geochemical Fe, Ti, Si and Al elemental concentrations are suitable for investigating the nature and source of sediments owing to their resistant to weathering and post depositional diagenesis properties (Staubwasser and Sirocko, 2001; Prizomwala et al., 2014). We have plotted in Fig. 2, the percentage distribution of Fe, Ti, Si and Al along the two transects A and B across the coastline. The trend distribution of Fe and Ti is consistent in their variation. In other words, both Ti and Fe contents show either high or low together with a mean concentration of 0.6 and 1.4% respectively (see Table 1). The concentrations of Ti and Fe were used as indicators of a high energy sedimentological environment (e.g. Babu et al., 2007; Chagué-Goff, 2010; Costa et al., 2012) and the presence of detrital Fe-Ti oxides, such as magnetite, titanomagnetite and hematite in the samples (e.g. Dearing, 1999).

The percentage distribution of Si concentration ranging from 28 to 37% with a mean value of 32% shows inverse relationship with Fe, Ti and Al (Fig. 2, Table 1). It is often believed that Si content is dominant in sand fraction, whereas Al is often enriched in clay content. The Si/Al ratio values range from 4.2 to 7.0 in both A and B transects with higher values towards coastline side (Fig. 2), including the highest value of 18.6 at coastal station 16 (Table 1). Srinivasalu et al. (2007), Jonathan et al. (2012) and Switzer et al. (2012) noted the higher Si/Al ratio away from the coast might have been the impact of 2004 tsunami outflow deposits.

4.2. Geochemical signatures of IOT event

The concentration of various elements in the sediments is a function of the different mineral assemblages present therein, which is due to their source characteristics, transport processes and degree of chemical weathering (Prizomwala et al., 2014). However, in case of instantaneous events like tsunami, elemental concentrations are result of source sediment characteristics (Dawson et al., 1995; Goff et al., 2001, 2008; Chagué-Goff, 2010). Since backwater sediments are made of

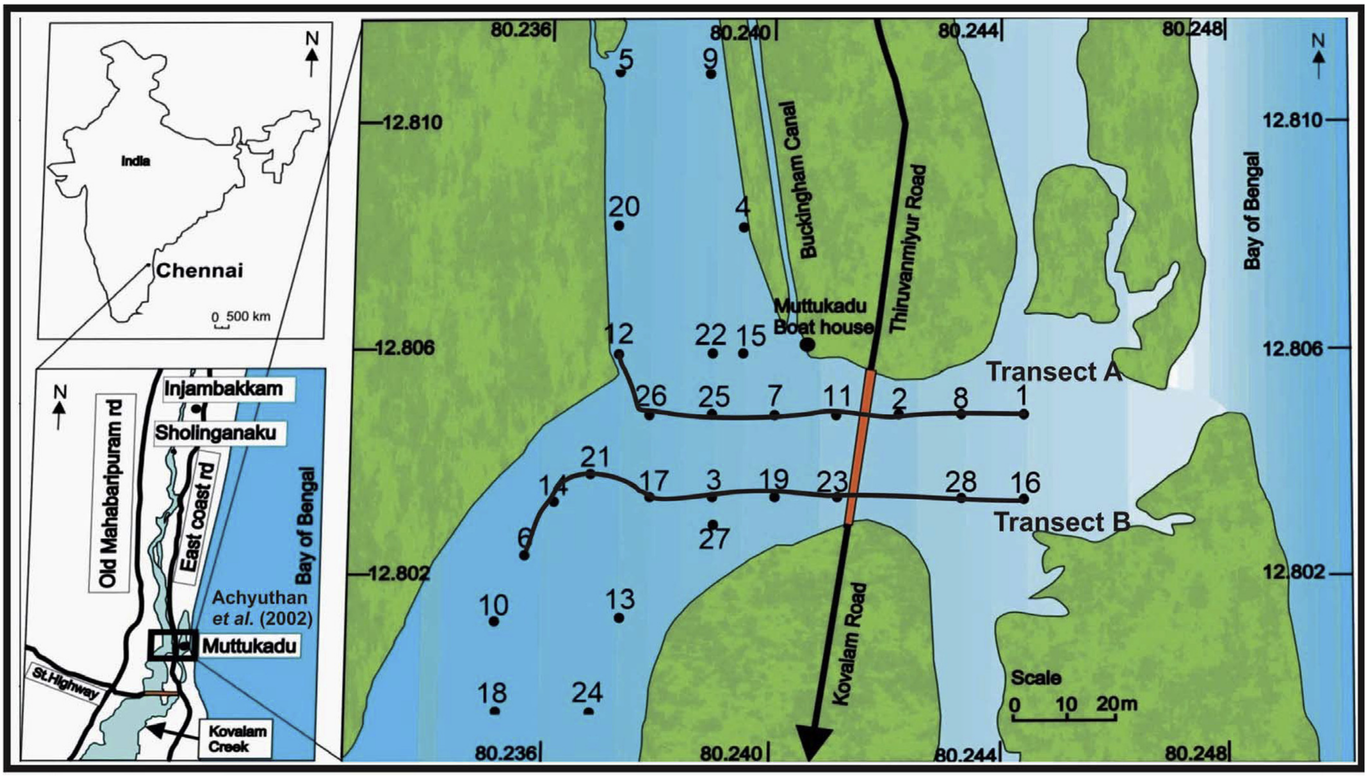

Fig. 1. An overlay of the sampling map showing 30 surfacial sediment sampling points along with location of Mutthukadu backwaters. Inset shows the view of India along southeastern coastline.

terrestrial and marine sources, the sediments display physical and chemical characteristics of both domains, thus, tsunami impact can be identified in the sediments record using geochemical proxies of the concentration of elements (Font et al., 2010, 2013).

The Muttukadu backwater, situated in SE coast of India was sampled prior to 2004 IOT and studied for elemental chemistry by Achyuthan et al. (2002). This study serves as a 'pre-tsunami database' which can be compared to other post-tsunami studies. Similarly, Thangadurai et al. (2005) sampled the inner continental shelf sediments for selected major and trace elemental geochemistry prior to IOT. On account of a tsunami event, the likely process is that the offshore/littoral sediments are eroded and deposited on more landward side (Goff et al., 2001; Kumar and Achyuthan, 2006; Jankaew et al., 2008; Andrade et al., 2014). Hence, we plotted the results of Achyuthan et al. (2002) and Thangadurai et al. (2005) along with our data for comparison (Fig. 3a). Here, we present the results of selected elemental concentration (Fe, Mn and Pb) which helps in understanding the process involved during a tsunami event. Fig. 3a shows an interesting variation of Fe, Pb and Mn in sediments of Muttukadu backwater compared to pre-tsunami sediments.

The continental shelf sediments are rich in Fe (i.e. 1.0%–3.1%) compared to pre-tsunami Muttukadu backwater sediments (0.6%–1.7%) (Fig. 3a). Our results from Muttukadu sediments show range of Fe from 0.34% to 2.3%, indicating enrichment compared to pre-tsunami Muttukadu sediments (Fig. 3a). Srinivasalu et al. (2008) reported a two-fold increase in Fe content in onshore sediment after tsunami compared to the offshore sediment from nearby Nagapattinam coast. Similarly the pre-tsunami sediments of Muttukadu backwater show enriched concentration of Mn (above 400 ppm), whereas continental shelf sediments show 200 ppm–400 ppm of Mn. Hence the post-tsunami sediments at Muttukadu backwater show dilution compared to pre-tsunami concentration of Mn with range from 64 ppm to 400 ppm (Fig. 3a).

A similar process of Mn depletion was reported by Ranjan et al. (2008) for the 2004 the IOT sediments. Another trace element found abundantly in SE coast of India was Lead (Pb). The pre-tsunami concentrations at Muttukadu backwater were ranging between 1 and 10 ppm (Achyuthan et al., 2002). Whereas continental shelf had enriched amounts of this element with a range from 11 to 20 ppm (Thangadurai et al., 2005), our data clearly showed enrichment of Pb concentration with range from 10 to 40 ppm (Fig. 3a), which even though small amount, but a clear match with continental shelf sediments.

Elevated contents of Pb have earlier been reported from tsunami deposits from India (Ranjan et al., 2008; Srinivasalu et al., 2007) and from Thailand (Szczucinski et al., 2005), suggesting metals enrichment as common compounds in backwaters. Chaudhary et al. (2006) detected distribution of considerable amounts of pollutants across the tsunami-impacted coastal zones in India. Therefore, high metal contents are interpreted as representing an effect of the relocation of anthropogenic pollution, and data (Fig. 3 and Table 1) suggested that they are controlled by tsunamigenic sediment source in the study area rather the man-made activities.

It has been believed that a tsunami wave propagates from offshore regions on account of submarine earthquake, volcano or landslide and deposits offshore sediments on landward side. Fig. 3b shows typical scenario as found in present study. The enrichment of Fe and Pb can most likely be explained by erosion of Fe-Pb rich sediment from continental shelf and the littoral, thereby deposition on Muttukadu backwater region. Similarly the continental shelf sediments are depleted in Mn concentration compared to coastal sediments, which is also visualized by lower amount of Mn observed in Muttukadu backwater sediments post 2004 IOT. We believe there are many processes which lead to depletion and accumulation of elements in coastal environments, however these processes takes longer time. The sampling was carried out in January 2008 just four years post 2004 tsunami, which suggests limited period for elemental mobilization by other coastal processes.

Henceforth, our preamble is that the geochemical analysis

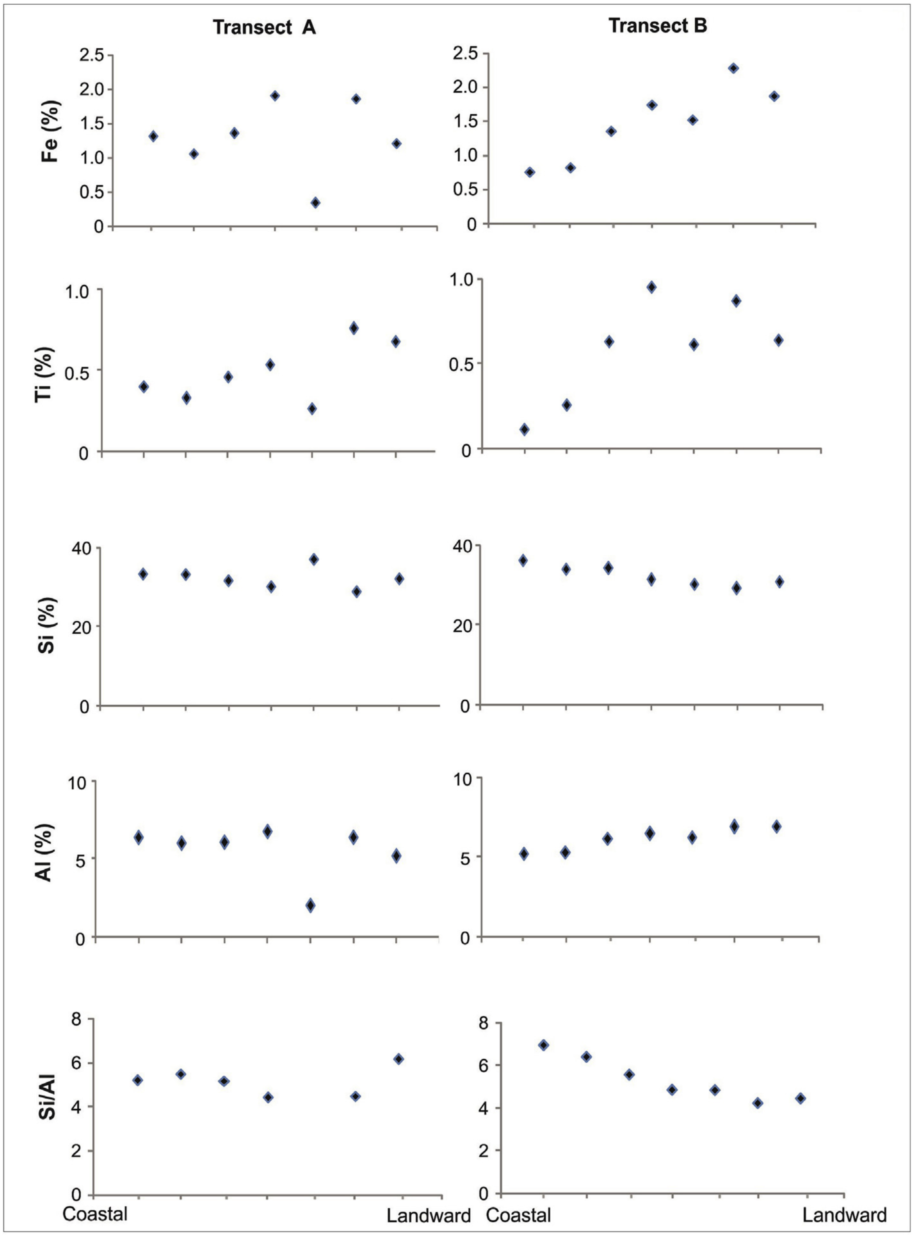

Fig. 2. Across the coast, variation of Fe, Ti, Al, Si and Si/Al concentrations in post-tsunami surface sediments of Muttukadu backwater.

successfully shows the characteristic of 2004 IOT tsunami deposition and helps in visualizing the associated processes (Fig. 3b). It should also be noted that the present day processes also obscure the tsunami signature in active (sediment transport/erosional) environments, hence leading to non-discriminatory palaeotsunami deposits. It is still debatable as how much older palaeotsunami deposits can be identified, due to continuous sediment depletion/enrichment processes.

4.3. Mineral magnetic signatures of IOT event

In case of the 2004 IOT, Srinivasalu et al. (2009) reported that organic carbon in 2004 IOT deposits is lacking because of the transport of fine-grained sediment by backwash flows into deep water in Tamil Nadu, India. To circumvent this, we apply environmental magnetic technique to examine the post-2004 IOT depositional sediment from coastal backwater environment. For example, Font et al. (2010) suggested that a very low χ of sand as a proxy criterion for discriminating tsunami deposits based on the case study of Portugal 1755 Lisbon tsunami. Babu et al. (2007) attributed the increase of magnetite in the post-2004 IOT sediments to the intensity of reworking during the tsunami. On the other hand, magnetic properties of minerals are an integral part of any natural system and can be used to track the depositional and erosional pattern of sediments in fluvial (Basavaiah et al., 2010; Prizomwala et al., 2014) and beach (Gawali et al., 2010; Prizomwala et al., 2013) environments in particular. However, these mineral magnetic characteristics related to the sediment source and environmental change have seldom been used in probing tsunami deposits (Font et al., 2010, 2013; Goguitchaichvili et al., 2013).

Fig. 4a and b along with a supplementary table of all dataset shows selected magnetic parameters illustrating magnetic concentration, grain-size and mineral composition from coastal to landward stations along two transects A and B. Our data show χ variations between 1 and 7.3×10^{-7} m^3kg^{-1} with a mean value of 3.1 (Fig. 4a). Similar range of χ from 2.5 to 4.0×10^{-7} m^3kg^{-1} was reported earlier by Veerasingam et al. (2014) by studying shallow core from near shore region of SE coast. The mineralogy of magnetic minerals as illustrated by S-Ratio varies between 0.75 and 0.95 (Table 1) for our data with a mean value of 0.93 (Fig. 4b). Similar results were reported by Veerasingam et al.

Table 1
The range and mean values for elemental concentrations, mineral magnetic and textural parameters of post-tsunami Muttukadu backwater sediments along SE coast of India.

Elemental Concentrations									
Statistics	Ti %	Fe %	Si %	Al %	Mn %	Pb ppm	Ni ppm	Al/Si	Si/Al
Average	0.59	1.43	32.14	6.07	0.02	19.40	17.94	0.19	6.06
Maximum	1.28	2.28	37.08	7.64	0.04	43.30	30.30	0.24	18.60
Minimum	0.11	0.34	28.80	1.99	0.01	7.20	7.70	0.05	4.24
Mineral Magnetic Parameters[a]									
	χ	**ARM**	**SIRM**	**Soft IRM**	**Hard IRM**	**SIRM/χ**	**ARM/χ**	**ARM/SIRM**	**S-Ratio**
Average	3.1	7.8	225.4	129.4	15.7	12.9	3.0	3.6	0.92
Maximum	7.2	9.6	336.8	262.5	54.2	21.6	4.9	5.1	0.99
Minimum	0.9	4.3	128.3	36.8	0.5	4.9	1.3	2.8	0.75
Particle Size Parameters									
	Sand %		**Coarse Silt %**		**Fine Silt %**		**Clay %**		
Average	65.27		28.56		4.47		1.70		
Maximum	85.72		47.21		9.59		2.85		
Minimum	40.52		10.99		1.37		0.81		

[a] Units for mineral magnetic parameters are same as given in Fig. 4a and b.

(2014) with S-Ratio from 0.8 to 0.9. Environmental magnetism has been identified as robust and suitable tool for sediment provenance discrimination (Oldfleld and Yu, 1994; Maher et al., 2009; Liu et al., 2010; Wang et al., 2010). The magnetic susceptibility, ARM and SIRM tend to decrease towards the landward side in both transects A and B. The onshore sediments are enriched in ferrimagnetic minerals (Fig. 4a) as earlier reported by Veerasingam et al. (2014). Our magnetic dataset reported here would serve as database of mineral magnetic, geochemical and textural properties of sediments laid down by 2004 IOT along SE coast of India and would be helpful for future palaeotsunami studies (Supplementary Table).

Tsunami-effects on sediment magnetic records are manifested without any systematic spatial variability as indicated by highly variable χ, ARM, SIRM, Soft IRM, Hard IRM and S-Ratio including random magnetic grain-size SIRM/χ and ARM/χ variability (Fig. 4a and b). The correlation of the curves for χ, ARM, SIRM, and Soft IRM values can easily be seen (Fig. 4a). High χ, ARM, SIRM, and Soft IRM values indicate higher proportions of the lower coercivity ('softer') ferro(i) magnetic Fe–Ti oxides such as magnetite (Fe_3O_4), titanomagnetite (Fe_3TiO_4) and members of Ti-poor titanomagnetite ($FeTiO_3$), pointing to a distinctive feature of the quartz-rich sand contents of the tsunamigenic sediments (Fig. 4a and b). The dominant paramagnetic

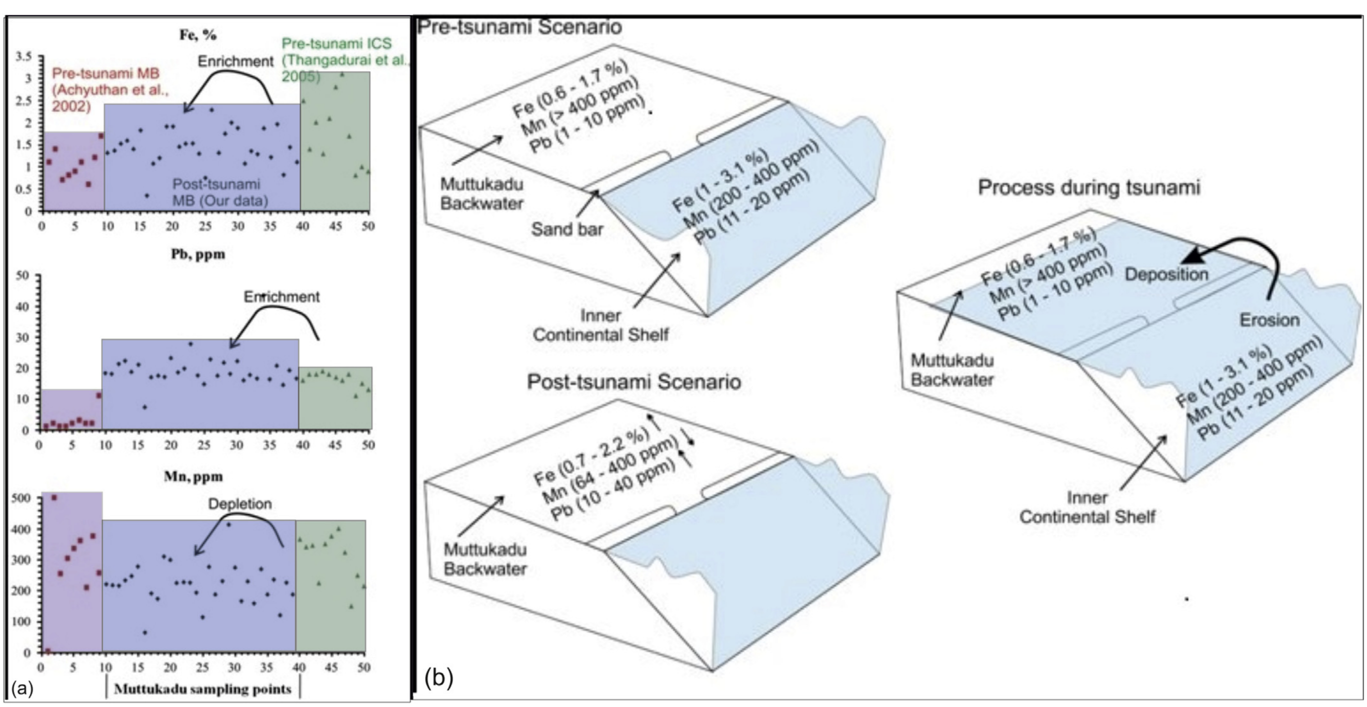

Fig. 3. (a) Enrichment and depletion of Fe, Pb and Mn concentrations in post-tsunami Muttukadu sediments compared to previous pre-tsunami data (Achyuthan et al., 2002; Thangadurai et al., 2005). (b) Sketch model depicting pre-tsunami and post-tsunami elemental changes inferring processes during a tsunami wave propagation.

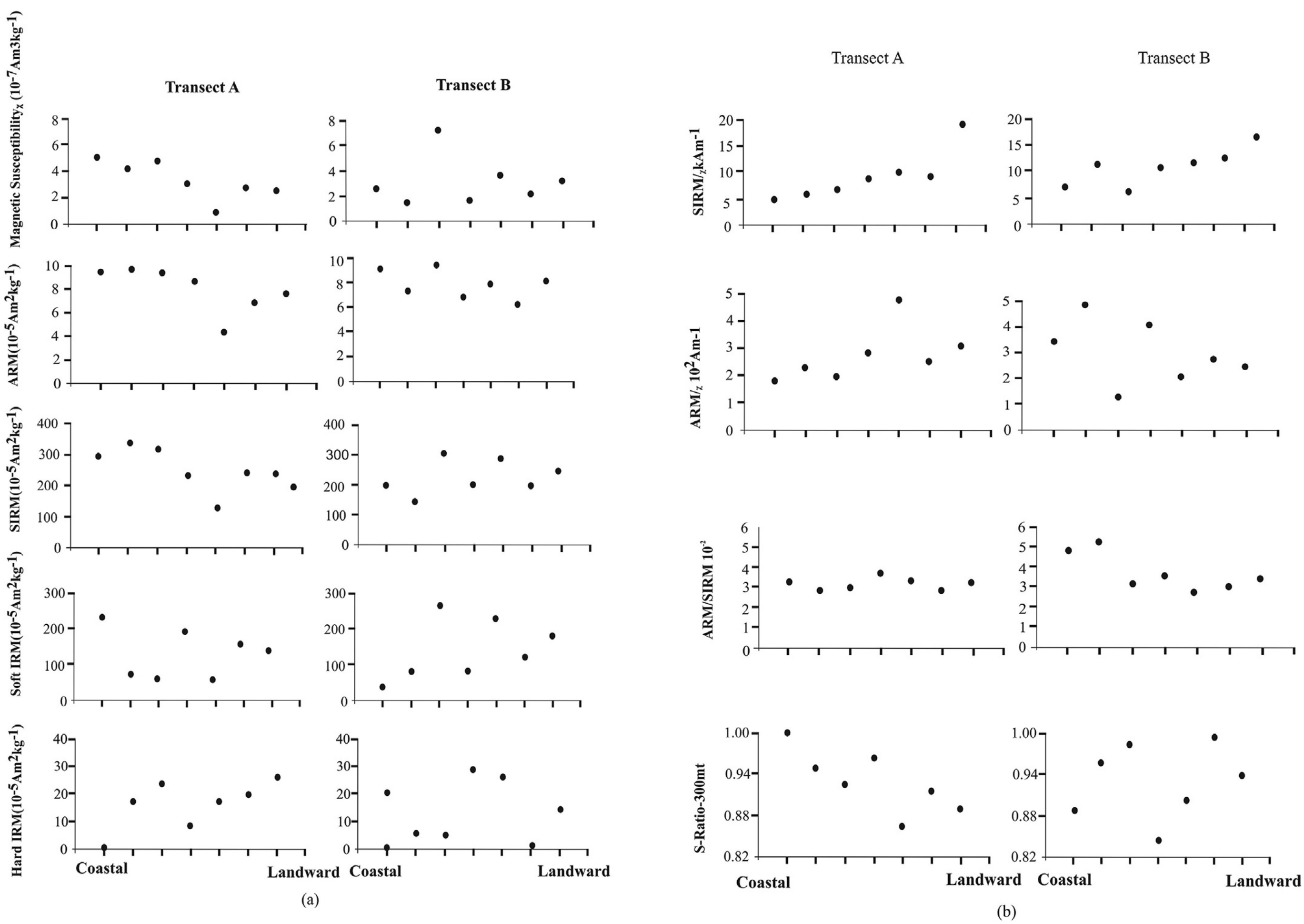

Fig. 4. Mineral magnetic records for post-tsunami Muttukadu backwater sediments showing variation in magnetic concentration, grain-size and mineral composition: (a) Magnetic concentration records of χ, ARM, SIRM, Soft IRM and Hard IRM. (b) Magnetic grain-size records of SIRM/χ, ARM/χ, ARM/SIRM and magnetomineralogical S-Ratio.

minerals (quartz and ilmenite) show lower χ, ARM, SIRM and Soft IRM values, indicating lower ferrimagnetic Fe–Ti oxides. The latter also shows higher coercivity ('harder') components associated to antiferromagnetic contents (e.g. titanohematite - composition between hematite (Fe_2O_3) and ilmenite ($FeTiO_3$)), reflected by high Hard IRM values (Fig. 4a). Also, the process of dilution in χ is clearly evident in the behavior of elemental Si variation at different sampling points in the region affected by tsunami (Fig. 2). Babu et al. (2007) and Vijayalakshmi et al. (2010) indicated that the high intensity of tsunami wave action caused severe deformation of ilmenite using scanning electron microscope (SEM) studies.

The curves of magnetic grain-size SIRM/χ average $12.9 \times 10^3 Am^{-1}$, ARM/χ average $3.1 \times 10^2 Am^{-1}$ and ARM/SIRM $\times 10^{-2}$, in contrast to the magnetic concentration-dependent χ, ARM, and SIRM curves, are inverted (Fig. 4b). Part of the explanation for the inverted form of magnetic grain-size curves is that a large quantity of tsunami material with coarser-grained lower coercivity ferrimagnetic Fe–Ti oxides, namely magnetite and titanomagnetite mixed with antiferromagnetic minerals, namely hematite and titanohematite transported into the backwaters. On the other hand, it appears that the deposition of fine-grained ferrimagnetic and antiferromagnetic Fe–Ti oxides is reflected in overall higher values of ARM/χ and ARM/SIRM (Fig. 4b, Table 1). This behavior in magnetic grain-size indices is consistent with the finer grain-size of the magnetic minerals present at all the observation points due to weakening hydrodynamics after the tsunami retreat. It may be interpreted that the fine-grained magnetic minerals transported away by the push of tsunami waves seem to have been recovered by the backwash flows into estuarine Muttukadu backwater region.

Font et al. (2010) reported distinct shifts in magnetic susceptibility values due to marked changes in detrital input in case of a tsunami rather than variations in magnetic properties in continuous stratigraphic sequence. Here it is interpreted that the magnetic mineralogical data are highly influence by detrital high-energy marine sources. The observed wavy magnetic behavior appears to be confirmed by the global signatures of extreme wave events associated with the tsunamic deposit of chaotic nature that consists of massive structureless detrital sediment ranging from sandy conglomerate to muddy sand (e.g. Dawson et al., 1995; Sawai et al., 2009). These analyses suggest that the magnetic mineral characteristics of backwater sediments are combined with results of magnetic coarse-grains transported from marine sources of the high wave energy regime and fine-grained magnetic particles from nearshore hydrodynamic conditions which are non-linearly correlated with each other.

The magnetic properties of 2004 IOT also serve as a database for identifying palaeotsunami deposits of Late Holocene period from the SE coastline of India. This, however, holds valid only to sites which are not affected by post-tsunami mixing of sediments. The SE Indian coastline has been host for several settlements and known for maritime trade during the Late Holocene period. The reoccurrence of tsunami event along the Java Sumatra has been computed to be 550 years from Andaman coast of Thailand and 363-434 years from Sri Lankan coastline (Prendergast et al., 2012; Jackson et al., 2014). This raises the possibility of SE coastline of India to have experienced multiple tsunami events during last 3000 years. Our database would serve as additional proxy in the toolkit of palaeotsunami identification criteria.

4.4. Sources and depositional processes of tsunami backwater sediments

The sediment deposits record the tsunami inundation for coastal settings, rivers and backwaters. Tsunami sediments were recognized by their grain gradation into clay towards land. Srinivasalu et al. (2009) reported ~50% reworked foraminiferal specimens in the tsunami deposits of the northern Tamil Nadu coast, indicating that the tsunami sediments were derived from a palaeo-strandline. Rashi et al. (2011) found the post-tsunami sediment texture was predominantly coarser. Granulometric analysis indicated a shift from a well-sorted, coarse skewed and platykurtic nature during the pre-tsunami season to moderately sorted, fine skewed and leptokurtic behavior after the tsunami.

For the identification of tsunami deposits from Muttukadu backwaters, three main sediment properties of elemental (Figs. 2 and 3), magnetic (Fig. 4) and textural (Table 1) parameters are used. Episode of high-energy hydrodynamic conditions is accompanied by the input of sandy-silt and coarse sediments, as was observed by Dawson et al. (1995) in Portugal Algarve sediments. As backwaters are silent water bodies and Muttukadu cuts and connects with the Bay of Bengal seasonally, the deposition of newer sediments is less and hence forms an excellent source for tsunami mixed sedimentary facies since the 2004 IOT. In the present study area of Muttukadu backwater, the coarser sediments with Si content (Fig. 2) dominate the sand composition varying from 40.5% to 85.7% with an average of 65.3%, coarse silt ranges from 21% to 30% with minor clay (Table 1). The distribution of particle-size suggests for mixed depositional environments, implying the effect of tsunami at all observation points with abundant sandy material. Similar observation was reported from the SE coast of India, where alike textural results indicate the source of sediments to an extreme wave action (Vijayalakshmi et al., 2010).

The 2004 tsunami produced onshore sand sheets not just near the tsunami's source (Moore et al., 2006) but also on shores more than 500 km distant in India (Chadha et al., 2005; Nagendra et al., 2005; Singarasubramanian et al., 2006), Sri Lanka (Goff et al., 2006), Malaysia and Thailand (e.g. Szczucinski et al., 2005, 2006; Hawkes et al., 2007). The tsunami event has left significant geological signatures with changes in coastal geomorphology and deposition of sediments along the coast, derived from the waves (Narayana et al., 2007; Mascarenhas and Jayakumar, 2008; Pari et al., 2008). Nevertheless, the majority of described tsunami deposits are sandy (Bourgeois, 2009) and vented sediments typically consist of sand but can contain sediment particle sizes from silt to pebbles (Obermeier, 1996). Studies along Mexico's Pacific coast have used the presence of sand layers in sediments to identify marine intrusions from tsunamis (Ramirez-Herrera et al., 2016).

4.5. Hydrodynamic tsunami depositional model

Generally, backwaters display slow sedimentation with newer sediments continuously washed out into offshore. The pre-tsunami phase of Muttukadu backwater shows deposition of fine clayey-silt with less coarser sand supporting the reported dominant clayey-silt than coarser sand in the sediment core samples from continental shelf region of SE coast of India (Srinivasalu et al., 2010). The depositional environment of Muttukadu backwater holds finer sediments due to reworking of earlier deposits, and less transport of newer sediments from offshore as the backwater is seasonally cut-off from the Bay of Bengal during May–September.

The high-energy nature of the tsunami waves is evidenced from the transport of sea floor sediments, from source areas ~100 m deep and several km away (Uchida et al., 2010). During 2004 IOT event, high energy waves carried blanket of coarser materials and deposited in the backwaters, as illustrated by coarser sand which dominates with fine silty-clay (Table 1). Accordingly, the post-tsunami condition depicts a thick accumulation of sediments with coarser and finer magnetic particles along with the newer deposits and pollutants.

Therefore, the collected tsunami sediment samples point to an admixture of mainly coarser and finer sediments indicating the post-tsunami scenario, which could be final facies or settling of sediments at different hydrodynamic cycles (Jonathan et al., 2012). Switzer et al. (2012) reported an extensive sand sheet deposited on the coastal plain of SE India and the sedimentary bedding in the sand sheet provided evidence of variable energy conditions and flow during inundation of the coast. Sawai et al. (2009) showed that turbulent tsunami currents caused rapid entrainment of a mixture of freshwater species, eroded soil and benthic marine species within a mass of coastal sand.

5. Conclusion

We compared the results of pre-tsunami sediments from onshore and offshore with our post-tsunami sand dominated sediments from Muttukadu backwater. We found enrichment and dilution of specific elements (Fe, Mn, Pb) which are found in the offshore regions. Our results highlight the process of tsunami wave propagation, its mechanism of erosion of the offshore sediments and their deposition on onshore. The study also generated a database of mineral magnetic properties of 2004 IOT deposits from Chennai coast. It is concluded that when used in combination with textural and geochemical analyses, mineral magnetic technique can serve to be a promising additional proxy tool in recognizing tsunami-induced deposits by the rapid and random change in magnetic concentration, mineral composition and magnetic grain-size. These results suggested that low χ, ARM and SIRM along with high ARM/χ, SIRM/χ and ARM/SIRM as magnetic proxies to help identify tsunamigenic deposits in the coastal backwater environments of SE coast of India.

The present study may provide a step forward to develop access to new proxy approaches following the line of thought described in the 'tsunami toolkit' of Chagué-Goff et al. (2011) in order to examine the tsunami backwater sediments after the 2004 IOT flow dynamics. The study would be immensely useful for expanding the proxy toolkit for hunting palaeotsunami deposits that would have affected not only the past human settlements along SE coastline of India but also destroyed coastal environments.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2018.10.038.

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