Identification and characterization of tsunami deposits off southeast coast of India from the 2004 Indian Ocean tsunami: Rock magnetic and geochemical approach

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The December 2004 Indian Ocean Tsunami (IOT) had a major impact on the geomorphology and sedimentology of the east coast of India. Estimation of the magnitude of the tsunami from its deposits is a challenging topic to be developed in studies on tsunami hazard assessment. Two core sediments (C1 and C2) from Nagapattinam, southeast coast of India were subjected to textural, mineral, geochemical and rock-magnetic measurements. In both cores, three zones (zone I, II and III) have been distinguished based on mineralogical, geochemical and magnetic data. Zone II is featured by peculiar rock-magnetic, textural, mineralogical and geochemical signatures in both sediment cores that we interpret to correspond to the 2004 IOT deposit. Textural, mineralogical, geochemical and rock-magnetic investigations showed that the tsunami deposit is featured by relative enrichment in sand, quartz, feldspar, carbonate, SiO_2, TiO_2, K_2O and CaO and by a depletion in clay and iron oxides. These results point to a dilution of reworked ferromagnetic particles into a huge volume of paramagnetic materials, similar to what has been described in other nearshore tsunami deposits (Font *et al.* 2010). Correlation analysis elucidated the relationships among the textural, mineral, geochemical and magnetic parameters, and suggests that most of the quartz-rich coarse sediments have been transported offshore by the tsunami wave. These results agreed well with the previously published numerical model of tsunami induced sediment transport off southeast coast of India and can be used for future comparative studies on tsunami deposits.

1. Introduction

A tsunami is one of the most terrifying natural hazards known to humans and has been responsible for tremendous economic and human losses. Following the recent tsunamis in Indonesia (2004), Chile (2010) and Japan (2011), the risks associated with tsunamis have come into focus. Most tsunamis occur in the marine realm and are associated with large earthquakes (Kremer *et al.* 2012).

Keywords. Tsunami deposit; texture size; mineral; geochemistry; rock-magnetism.

Since the Indian Ocean Tsunami (IOT) in 2004, by far the biggest natural catastrophe in human history, the worldwide scientific community has conducted numerous investigations of tsunami deposits to assess tsunami impact. The 26 December 2004 tsunami event devastated several major coastlines in South Asia, including the Tamil Nadu coast, India. The IOT was generated by one of the largest earthquakes in the past 100 years, and its epicentre was located near 3.3°N and 95.95°E with a magnitude of 9.0 and focal depth of 10 km (Lay *et al.* 2005). On the Indian coast, the tsunami involved three waves that arrived at 5 minute intervals. The first wave reached the coast approximately at 9.25 am (Indian local time), some 3 hours after the initial earthquake. In many places, waves ripped large trees out of the ground by the roots and traditional wooden and modern brick and mortar structures off of their pilings or foundations and moved tens to hundreds of meters away from the coast. Tsunami waves have sufficiently high velocities and bed shear stresses to suspend and transport large quantities of sediment (Srinivasalu *et al.* 2007). Modern studies of tsunamis are often hampered by the lack of information on the frequency and magnitude of past events. In many cases, the unique information that can be used consists of historical records. Therefore, it is often difficult to provide a quantitative assessment of tsunami risks since historical datasets typically cover only a relatively short period of time. Identification of past tsunamis is crucial for risk assessment studies, especially in areas where the historical record is limited or missing (Kortekaas and Dawson 2007). When a tsunami occurs, the momentum of the water flow varies during shuttle movement (landwards and seawards). It is maximal during the main phase of the up-rush and it quickly decreases concomitantly to the reduction of the depth of the flooding water. After a slack phase in the remote areas of the flooding, the backwash begins. Then, the topographically controlled backflow increases. Finally, the backflow decreases as the result of the arrival of the next tsunami wave, and the next cycle begins. Related sedimentary accumulations mainly occur during the up-rush, the slack and beginning of the backwash (if nonerosive) phases. The topography controls the sedimentation of tsunami deposits with the best preservation in depressions (Wassmer *et al.* 2010). Various aspects of the 2004 IOT onshore deposits on the east and west coasts of India were reported by several researchers (Altaff *et al.* 2005; Earnest *et al.* 2005; Jayakumar *et al.* 2005, 2008; Kumaraguru *et al.* 2005; Nagendra *et al.* 2005; Neetu *et al.* 2005; Narayan *et al.* 2005; Srinivasalu *et al.* 2009; Anilkumar *et al.* 2006; Chaudhary *et al.* 2006; Hussain *et al.* 2006, 2010; Mascarenhas 2006; Shanmugam 2006, 2012; Yeh *et al.* 2006; Babu *et al.* 2007; Bahlburg and Weiss 2007; Mascarenhas and Jayakumar 2008; Pari *et al.* 2008; Vijayalakshmi *et al.* 2010; Jayakumar 2012). However, studies on offshore tsunami deposits in India are limited (Srinivasalu *et al.* 2010; Jonathan *et al.* 2012) and many case studies are necessary to develop a depositional model. Though, tsunami events are rare in nature, scientific documentation helps in coastal management and mitigation measures for the future.

Researchers have used many proxies including geomorphological, stratigraphical, sedimentological, archaeological, anthropological, palynological, numerical model, geochemical, mineralogical, anisotropic magnetic susceptibility, rock magnetic properties, macro- and micropalaeontological evidence to identify historical and palaeotsunami deposits (Goff *et al.* 2006, 2012; Sawai *et al.* 2008; Chague-Goff 2010; Font *et al.* 2010, 2013; Paris *et al.* 2010; Wassmer *et al.* 2010; Chague-Goff *et al.* 2011; Jonathan *et al.* 2012; Ramirez-Herrera *et al.* 2012; Smedile *et al.* 2012; Cuven *et al.* 2013; Goguitchaichvili *et al.* 2013; Sugawara *et al.* 2013). Ranjan *et al.* (2008) and Srinivasalu *et al.* (2008) evaluated the metal enrichments from the 26 December 2004 tsunami sediments along the SE coast of India. Srinivasalu *et al.* (2010) have studied the pre- and post-tsunami shallow deposits off SE coast of India from the 2004 IOT using the geochemical approach. In India, magnetism has been used in environmental studies with strong implications in anthropogenic pollution monitoring (Alagarsamy 2009; Sangode *et al.* 2010; Venkatachalapathy *et al.* 2010, 2011a, b, 2013; Blaha *et al.* 2011; Sandeep *et al.* 2011), climatic variations and depositional mechanisms (Shankar *et al.* 1994a, b, 1996; Sangode *et al.* 2001, 2007; Chauhan *et al.* 2004; Kumar *et al.* 2005; Kumaran *et al.* 2005; Rao *et al.* 2008; Dessai *et al.* 2009; Dewangan *et al.* 2013). However, until now, a magnetic approach to detect tsunami-induced deposits has never been tested in India. Karlin and Abella (1992), used rock magnetic measurements to study the paleoseismic record. The rock magnetic technique has been shown to be a promising tool to identify tsunami deposits in a beach environment (Font *et al.* 2010) but has never been tested in the case of offshore deposits. In this study, the cost effective rock magnetic techniques are used to identify the magnetic and mineralogical signatures of the 2004 IOT.

This study is the first report on the rock magnetic aspects of tsunami deposits in the continental shelf region of SE coast of India. The aims of the present work are to study (1) the textural, mineralogical and depositional nature of sediments and (2) rock magnetic and geochemical properties of tsunami induced deposits in the offshore region. This will help to compare and study the rock magnetic and geochemical nature of sediments of the 2004 tsunami deposits as well as paleo-tsunami deposits near the coastal/lagoon regions along the SE coast of India. Moreover, in Nagapattinam town (the study area), the inundation by tsunami waves was up to ∼800 m compared to the other parts of the coastal areas (Yeh *et al.* 2006) and the maximum damage (in Tamil Nadu state) in terms of economic and human losses were reported from this region (Srinivasalu *et al.* 2010).

2. Study area

The Nagapattinam coastal segment studied here is located north of Point Calimere region, Bay of Bengal, India. The near-shore bathymetry of this region is relatively steep, straight and parallel to the coast. The tides in this region are semi-diurnal with an average spring range of 0.67 m and neap range of 0.19 m (Sanilkumar *et al.* 2003). The rivers Nandalar, Puravandayanar, Vettar, Uppanar (tributaries of river Cauvery) pass through the granitic terrain and agricultural belt of the Tamil Nadu state before draining into the Bay of Bengal. The coastal stretch is affected by the seasonal monsoon (every year) in the latter half of the year (October–December) (Sarma *et al.* 1990). The geology around the study area indicates different types of rocks which include alluvium, charnockite, khondalite, garnet-sillimanaite gneiss, pink/grey granite, amphibolites, pyroxenites, and biotite schists, which lie in the southern part of the study area (figure 1a). In addition, the southern part of Cauvery basin (part of Nagapattinam and Karaikal Town) in the peninsular shield is underlain by rocks of Archean age and the coastal tract is covered by younger alluvium and coastal sands (Mohanachandran and Subramanian 1990).

At Nagapattinam, the tsunami overtopped and shattered the sea wall of the fishing harbour; trawlers were tossed ashore; a communication tower crashed, and oil storage tanks suffered erosive damage (Mascarenhas and Jayakumar 2008). The inundation limit and run-up of the study area are illustrated in figure 1(b). This shows more vulnerability in the southern part of Tamil Nadu coast (including the study area) due to its flat topography than the northern part. Backwash flow occurred following the maximum landward inundation of individual tsunami waves as water receded seaward. The study area also witnessed maximum backwash of sediments from land during/after the three major tsunami waves that struck the coastal region (Srinivasalu *et al.* 2009).

3. Materials and methods

3.1 *Sampling*

Several core samples were collected using a gravity core sampler (1.8 m length and 6 cm diameter) with the help of a fishing trawler boat off Nagapattinam, during October 2008. Two core samples referred here as C1 and C2 (from 5 m and 10 m water depths) were selected for the present study (figure 2). The water depths and geological coordinates (latitude and longitude) of the sampling points were identified using a single-beam echo-sounder (Odom Hydrotrack) with a Differential Global Positioning System (DGPS – Trimble) housed in a fishing trawler boat along with heave sensor (HS-50). The collected core sediments were sectioned into each 2 cm slices. Representative samples from each sediment core were stored in labelled self-seal plastic bags and then frozen at −4°C immediately onboard until further analysis.

3.2 *Analytical methods*

The sediment texture such as sand, silt, and clay were measured following the procedure of Ingram (1970). The samples were oven-dried (∼100°), powdered in an agate mortar and analysed for major elements such as SiO_2, Al_2O_3, TiO_2, Fe_2O_3, Na_2O, K_2O, CaO, MgO, P_2O_5, and MnO on powdered and pressed pellets with a Thermo Scientific X-ray fluorescence spectrometer. Mineralogical composition was obtained by Fourier transform infrared spectrometry (FTIR). For FTIR analysis, samples were placed in a KBr disc, which ensures that Lambert-Beer's law is valid. A quantitative determination of the mineral content from various blends was performed by making multi-component analysis of the experimental spectrum using the spectra of each component in the mixture (Bertaux *et al.* 1998; Veerasingam *et al.* 2014a). Discrete 2 cm sediment slices were air-dried at less than 40°C, gently disaggregated, and then packed in 10 ml polystyrene pots before being subjected to the rock magnetic measurements. The mass of each sample (without the mass of the polystyrene pots) was measured for normalization. Magnetic susceptibility (χ) measurements were carried out using a Bartington MS-2 magnetic susceptibility meter (with alternating current magnetic field amplitude of 80 A/m) linked to an MS2B dual-frequency sensor (0.47 and 4.7 kHz). The average of five measurements is presented as mass specific values in 10^{-8} m^3kg^{-1} (Dearing 1999). The frequency dependent of susceptibility ($\chi_{\rm fd}$) is calculated using the following formula.

$$\chi_{\rm fd}\% = \left(\frac{(\chi_{lf} - \chi_{hf})}{\chi_{lf}}\right) \times 100,$$

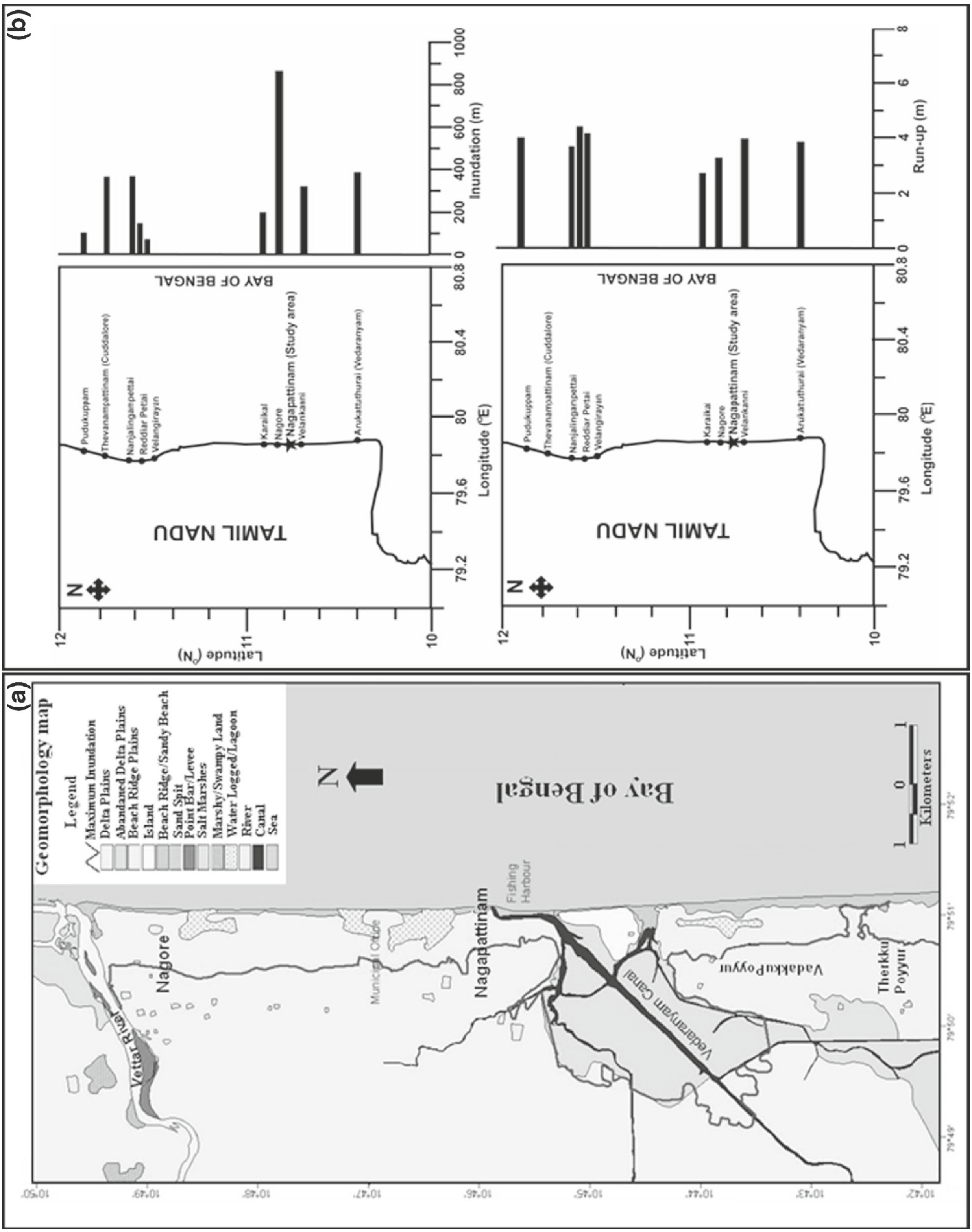

Figure 1. **(a)** Geomorphology of Nagapattinam taluk in the southeast coast of India and **(b)** inundation limits and run-up heights of southern Tamil Nadu coast (redrawn from Ramanamurthy *et al.* 2012 and Jayakumar *et al.* 2005).

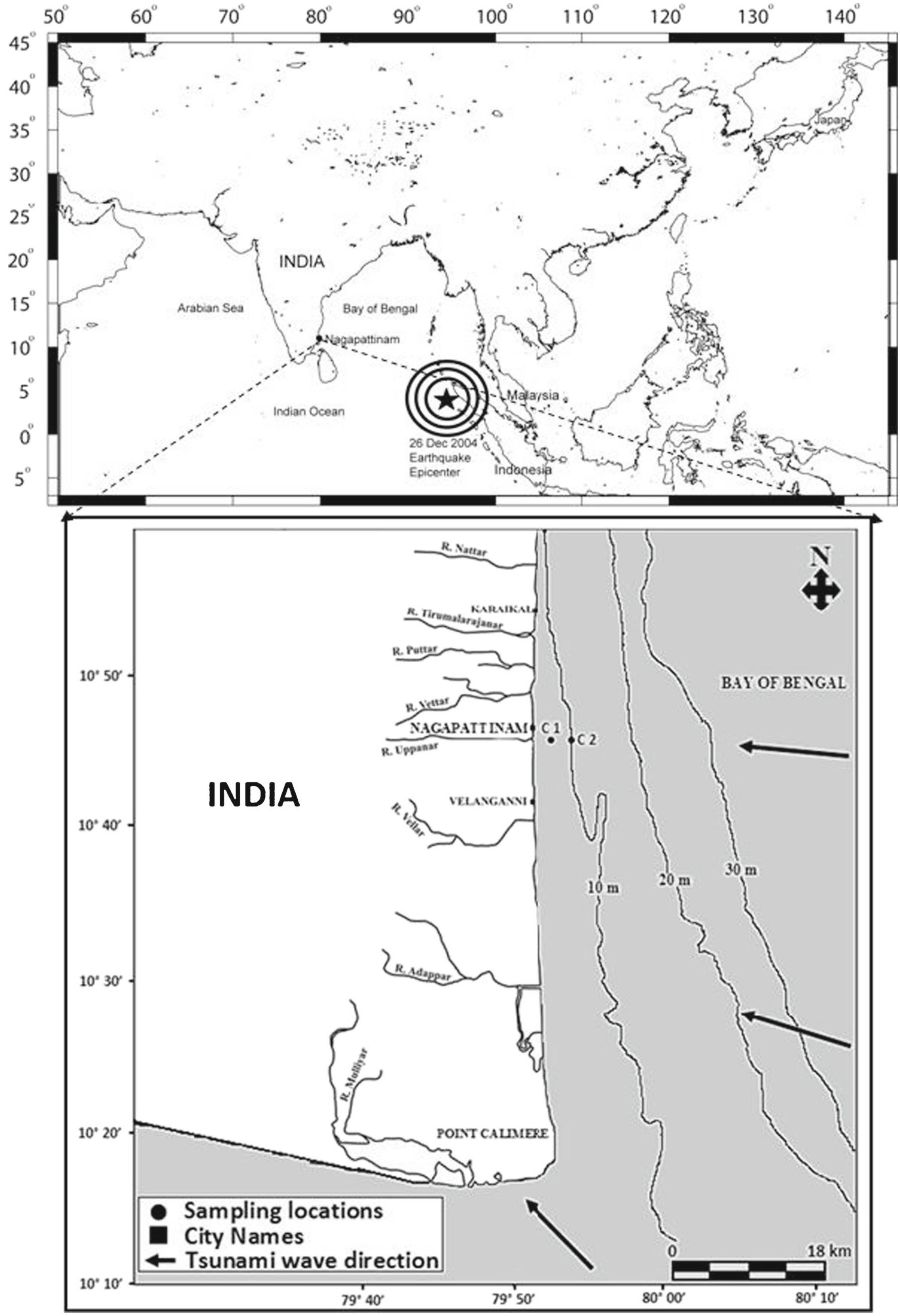

Figure 2. The study area and core sediment locations off southeast coast of India.

where, χ_{lf} and χ_{hf} are the low and high frequency mass specific magnetic susceptibilities. Anhysteretic remanent magnetization (ARM) was imparted in a steady 0.05 mT field superimposed over a decreasing, alternating field (AF) up to 100 mT using a Molspin alternating-field demagnetizer. ARMs are expressed here as anhysteretic susceptibility (χ_{ARM} = ARM/strength of the biasing field). All remanent magnetization of the ARMs and IRMs was measured using a Molspin fluxgate spinner magnetometer. Isothermal Remanent Magnetization (IRM) is the remanent magnetization acquired by a sample after exposure to, and removal from, a steady (DC) magnetic field(Walden *et al.* 1999). IRM was measured for forward fields of 20 mT, 1 T and 2 T and a reverse field of 20, 30, 40, 60, 80, 100 and 300 mT. IRM_{2T} is hereafter, referred to as the Saturation Isothermal Remanent Magnetization (SIRM). IRM was imparted with an MMPM9 pulse magnetizer. χ_{ARM}/SIRM, χ_{ARM}/χ, SIRM/χ, Soft IRM (= SIRM–$\text{IRM}_{-30\text{mT}}$) and Hard IRM (= SIRM–$\text{IRM}_{-300\text{mT}}$) were measured using forward DC fields. S-ratio (= IRM_{-300}/SIRM, being IRM_{-300} the acquired IRM at a backfield of 300 mT) are also calculated from IRM measurement, using backfield once the SIRM was reached (Thompson and Oldfield 1986). All magnetic measurements are normalized by mass of the sample. The correlation and cluster analyses were carried out to find the relationships among the sediment texture, mineral, geochemical, and rock-magnetic parameters in sediments using Statistical Package for the Social Sciences (SPSS) and Minitab softwares, respectively.

4. Results and discussion

4.1 *Sediment texture and mineralogical distribution*

The results of texture size parameters of sediment cores C1 and C2 are presented in figure 3. The average values of sand, silt, and clay contents in C1 core are 62.43%, 8.9% and 28.7%, while in C2 core are 59.6%, 13.5%, and 26.9%, respectively. Texture size analysis of both sediment cores indicates three zones namely I, II and III. The mean sand content in the C1 and C2 cores in the zone II are 82.3% and 78.4%, respectively. Likewise, the mean silt contents are 4.4% and 8.9%, where as the mean clay contents are 13.3% and 12.75%, respectively. Sediment texture size analysis and interpretation of various grain size parameters provide valuable information for both the sources of sediment and hydrodynamic interpretation of the tsunami deposits. The video clips, which were taken during the tsunami that struck Tamil Nadu coast, were first seen to have a direct understanding of the flow process that took place during the event. This video footage showed great plumes of turbid water moving offshore, suggesting that tsunami backwash flow velocities can be remarkably high (Dawson and Stewart 2007). Therefore, the sandy nature of the zone II revealed that the tsunami waves struck the coast and part of the coarse grained fraction was eroded due to returning sea water and deposited in this part. Numerical simulation model (using DHI-MIKE software) results for sediment transport during tsunami, showed the total load transport is higher towards the offshore region of Tamil Nadu coast (Jayakumar 2012). The similarity in depositional event in the land area of Nagapattinam as reported by Srinivasalu *et al.* (2009) and Devi *et al.* (2013) can be correlated with the sample in the offshore region, which is due to the return flow of tsunami wave, and the distinct subsequent layers (Goff *et al.* 2004). The recent study of Elakkiya *et al.* (2013) also describes the assemblage of foraminifera, ostracoda, and their distribution (species including *Ammonia beccarii, Globigerina bulloides, Quinqueloculina* sp., *Spiroloculina orbis, Propontocypris bengalensis, Propontocypris crocata* and *Phlyctenophora orientalis*) in the study area (Nagapattinam), suggesting that these species have been brought by the high energy tsunami waves (2004 IOT deposit). The previous studies (Srinivasalu *et al.* 2010; Jonathan *et al.* 2012) provide the supporting evidences of the source of sand deposits in zone II. The zones I and III indicate the domination of clay and silt as compared to zone II, suggesting suspension/deposition of finer particles and reworking of modern process in the near shore environment before and after the major event.

The study of clay mineralogy in marine sediments is closely related to the geology and hydrography of the adjacent land areas (Veerasingam *et al.* 2014b). The vertical distribution of quartz, feldspar and carbonate in C1 and C2 sediment cores is shown in figure 3. Zone II contains high amount of quartz (C1: 19–23.5%; C2: 19–22.5%), feldspar (C1: 17–21%; C2: 17.5–20.5%) and carbonate (C1: 8.4–9.6%; C2: 12.3–13%). Zone I and III of sediment cores are characterised by relatively lower mineral content than zone II, indicating the strong influence of detrital input from the continent. The high concentrations of carbonate in zone II suggest a high-energy environment, where the input of calcareous shells from the land/beach is due to the tsunami return flow (Salem 2009). In the case of the 1755 tsunami deposit of the Boca do Rio estuary, Portugal, textural and mineralogical characteristics between the base and the top of the tsunami

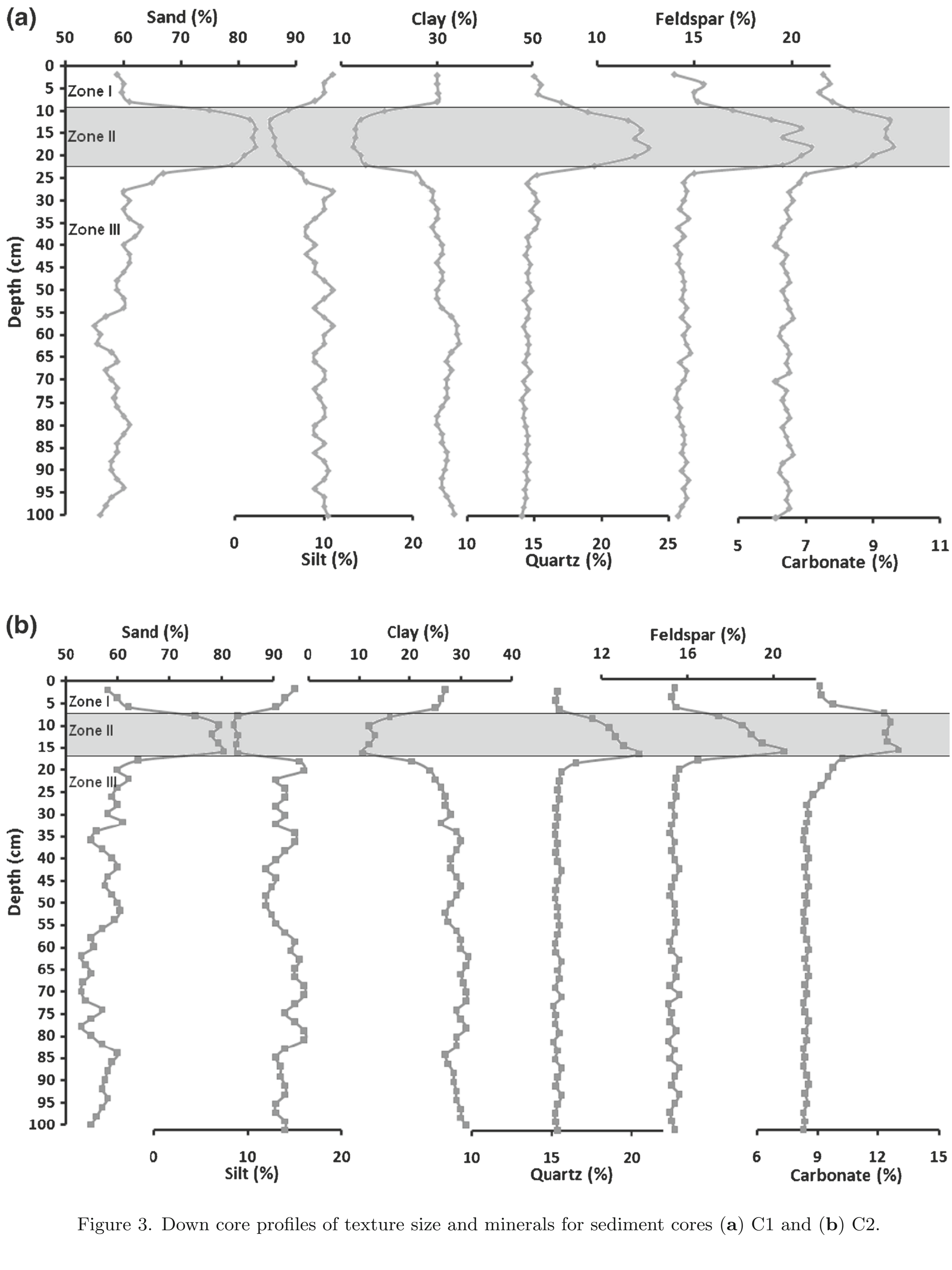

Figure 3. Down core profiles of texture size and minerals for sediment cores (**a**) C1 and (**b**) C2.

layer suggest the imprint of run-up and backwash currents derived from a unique wave (Font *et al.* 2013). Based on the India Meteorological Department (IMD) dataset, there were no catastrophic events such as tsunami and storms between January 2005 (after 2004 IOT) and October 2008 (sampling date) occurring in this region. According to the numerical model (Jayakumar 2012) and IMD data, the prevalence of allochthonous elements including sand and quartz in zone II, might be derived from an adjoining source area during the tsunami backwash.

4.2 *Geochemical elements*

The geochemical process in the coastal region and the effect of tsunami waves on the overall distribution process is evaluated using vertical distribution of geochemical elements. The vertical distribution of major geochemical elements in sediment cores is given in figure 4. Zones I and III present similar geochemical values while zone II is characterised by an abrupt shift in geochemical composition of both sediment cores. Geochemical analyses indicate that the zone II has lower amount of Al rich silt/clay than the zones I and III. These differences could reflect changes in the source energy of the depositional environment or transport mechanisms. The higher amount of Ti, Si, Fe, K, and Ca in zone II compared with the underlying and overlying clayey silt can be partly attributed to the higher occurrence of sand content as opposed to slit and clay content. The enrichment of TiO_2, SiO_2, Fe_2O_3, K_2O, and CaO and depletion of Al_2O_3, Na_2O, MgO, P_2O_5, and MnO in zone II might be attributed to the tsunami event. Al_2O_3 shows a negative correlation with SiO_2 and CaO in zone II, which is explained by the dilution of terrigenous material (clays) within huge volumes of nearshore sand brought by the tsunami wave (Srinivasalu *et al.* 2010; Font *et al.* 2013). Ca reflects the amount of carbonates, which is mainly produced under marine conditions, whereas Ti is enriched in tropical soils and is relatively inert against diagenetic processes (Ramirez-Herrera *et al.* 2012). The previous geochemical studies on Nagapattinam beach sediments (Seralathan *et al.* 2006; Sujatha *et al.* 2008), exhibit the same set of geochemical compositions and similar concentrations, which support the fact that the sands found in the tsunami deposit come from nearshore.

4.3 *Magnetic concentration dependent parameters*

Magnetic susceptibility (χ) measurements generally reflect physical changes in the depositional environment in relation to climate and environmental changes. χ is directly proportional to the quantity and grain size of ferromagnetic and/or ferrimagnetic minerals in a sample (Thompson and Oldfield 1986; Verosub and Roberts 1995), which is sensitive to diamagnetic and paramagnetic signals when ferrimagnetic concentrations are low (Robertson *et al.* 2003). Saturation Isothermal Remanent Magnetisation (SIRM) mainly reflects the combined concentration of ferrimagnetick (i.e., magnetite and maghemite) and imperfect anti-ferromagnetic (i.e., hematite and goethite) minerals. SIRM responds primarily to the concentration of ferrimagnetic mineral, but unlike χ it is not affected by diamagnetic and paramagnetic minerals (Rao *et al.* 2008). χ_{ARM} is particularly sensitive to the concentration of stable single domain ferrimagnetic grains (Oldfield 1991). Data of concentration dependent magnetic parameters (χ, SIRM, and χ_{ARM}) for C1 and C2 are shown in figure 5(a and b). The ranges of magnetic susceptibility for C1 and C2 sediment cores are 31.8–55.8 $\times$ 10^{-8} m^3 kg^{-1} (average 46.77 $\times$ 10^{-8} m^3 kg^{-1}) and 30.8–49.7 $\times$ 10^{-8} m^3 kg^{-1} (average 42.41 $\times$ 10^{-8} m^3 kg^{-1}), respectively. Values of SIRM vary between 290–488.09 $\times$ 10^{-5} Am^2 kg^{-1} (average 355.35 $\times$ 10^{-5} Am^2 kg^{-1}) and 256.52–361.94 $\times$ 10^{-5} Am^2 kg^{-1} (average 318.19 $\times$ 10^{-5} Am^2 kg^{-1}), respectively. Likewise, χ_{ARM} values for C1 and C2 sediment cores varied from 0.41–0.64 $\times$ 10^{-5} m^3kg^{-1} (average 0.56 $\times$ 10^{-5} m^3kg^{-1}) and 0.43–0.69 $\times$ 10^{-5} m^3kg^{-1} (average 0.54 $\times$ 10^{-5} m^3kg^{-1}), respectively. Zone I and III show similar χ, SIRM, and χ_{ARM} values while the tsunami deposit (zone II) is characterised by a sudden decrease of χ (C1: $\sim$32.7 $\times$ 10^{-8} m^3 kg^{-1}, C2: $\sim$31.9 $\times$ 10^{-8} m^3 kg^{-1}), SIRM (C1: $\sim$297.8 $\times$ 10^{-5} Am^2 kg^{-1}, C2: $\sim$263.7 $\times$ 10^{-5} Am^2 kg^{-1}) and χ_{ARM} (C1: $\sim$0.47 $\times$ 10^{-5} m^3kg^{-1}, C2: $\sim$0.45 $\times$ 10^{-5} m^3kg^{-1}) indicative of a very low contribution of ferrimagnetic minerals or the high contribution of paramagnetic/diamagnetic minerals into the sediment matrix. In zone II, the measured susceptibility of weak ferrimagnetic samples, in which calcium carbonate and silica or quartz are abundant, is reduced by diamagnetism. Depletion of magnetic susceptibility in zone II, matches the low values of magnetic susceptibility associated with quartz rich sand contents observed recently by Devi *et al.* (2013) in the Nagapattinam coast. The magnetic susceptibility values in Nagapattinam beach sediments (Devi *et al.* 2013), exhibit the same set of minerals and in similar concentrations. Thus, paramagnetic minerals (transfer of these minerals from the beach area had taken place during the backwash of huge tsunami waves) have contributed significantly to the magnetic susceptibility in zone II sediment samples.

4.4 *Magnetic grain size distribution*

The magnetic grain sizes (domain structures) are classified into four: stable single domain (SSD), pseudo-single domain (PSD), multi-domain (MD) and super-paramagnetic (SP). The domain structure plays an important role in the magnetic properties of ferro- or ferrimagnetic minerals (Dearing *et al.* 1996). The values of magnetic grain size dependent parameters ($\chi_{\mathrm{fd}}\%$, χ_{ARM}/χ, χ_{ARM}/SIRM and SIRM/χ) for sediment cores C1 and C2 are shown in figure 5(a and b). Frequency

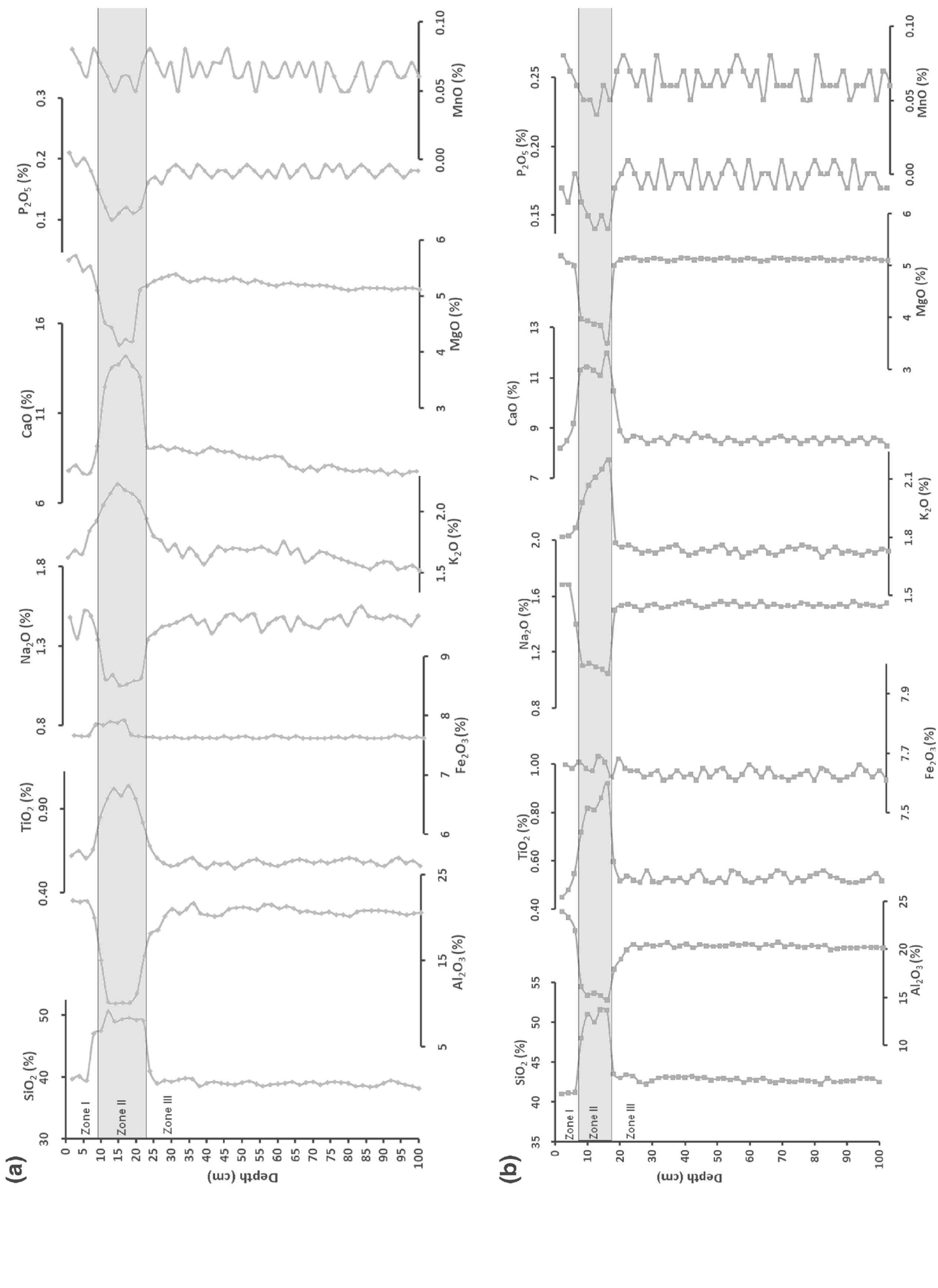

Figure 4. Vertical distribution of major geochemical elements in sediment cores (**a**) C1 and (**b**) C2.

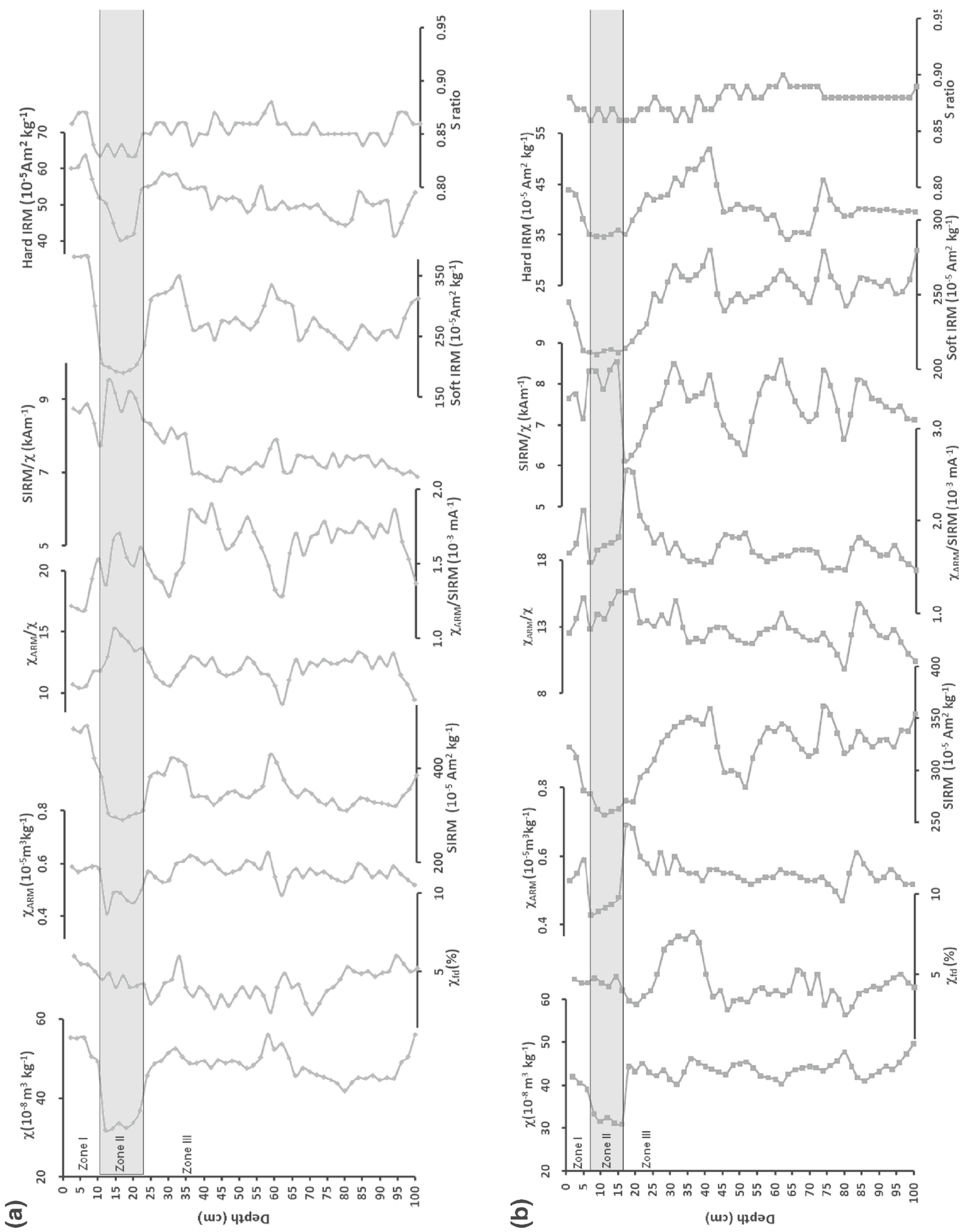

Figure 5. Vertical distribution of rock magnetic parameters in sediment cores (**a**) C1 and (**b**) C2.

dependent susceptibility is an indicator of the presence of very fine SP ferromagnetic grains. As coarse magnetic particles, such as MD and SSD grains, are frequency independent, they show similar susceptibility values at low and high frequencies. χfd% < 4% means no SP and dominant MD and SSD grains in sediment while, χfd% > 10% reflects high content of pedogenic SP grains (Dearing 1999). Mean values of χ_{fd}% of zones I, II and III are lesser than 10% and therefore indicate that superparamagnetic minerals are not dominant in these samples. χ_{ARM} is particularly sensitive to the presence of small grains (SD and small PSD grains), whereas χ and SIRM are relatively more sensitive to the presence of larger grains (large PSD and MD grains) (Evans and Heller 2003). Thus, the ratio χ_{ARM}/χ is used to assess the relative variations in the amount of fine *versus* coarse magnetic grains in geological materials (Verosub and Roberts 1995). Peters and Dekkers (2003) also pointed out that χ_{ARM}/χ values decrease with increasing magnetite grains sizes. Higher χ_{ARM}/SIRM values reflect a larger fraction of fine SD-PSD grains that respond more effectively to χ_{ARM} than SIRM (Maher 1988). χ_{ARM}/χ and SIRM/χ are sensitive to the finer magnetic grain sizes (above the threshold for stable SD behaviour), while χ_{ARM}/SIRM is sensitive to the coarser (PSD to MD) grain sizes (King *et al.* 1982). A χ_{ARM}/SIRM value of $<20 \times 10^{-5}$ Am^{-1} indicates MD + PSD grains. Values between 20 and 90×10^{-5} Am^{-1} suggest coarse MD grains (Dearing *et al.* 1997). All grain size parameters show continuous and smooth variations along the entire stratigraphic sequences except for zone II, which might be due to the significant contribution of coarse grained mixture of MD and SSD particles.

4.5 *Mineralogy dependent parameters*

Magnetic mineralogy parameters such as Soft IRM, Hard IRM and S ratio are shown in figure 5(a and b). Minerals with low coercivity values are termed magnetically 'soft' while those with high values are 'hard'. Ferromagnetic and ferrimagnetic minerals have lower coercivity values than anti-ferromagnetic minerals (Kruiver and Passier 2001). The soft IRM parameter is a measure of concentration of soft magnetic minerals (e.g., magnetite) while hard IRM reflects hard magnetic minerals (e.g., hematite and goethite). The S-ratio is a useful parameter for distinguishing magnetic mineral type. S ratio values close to one indicate the preponderance of the soft magnetic minerals, whereas values close to zero indicate the abundance of the hard magnetic minerals. The profiles of S ratio in both sediment cores reveal more or less uniform distribution throughout the length. All mineralogy dependent parameters indicate the abundance of ferromagnetic minerals with minor amount of canted anti-ferromagnetic minerals in zones I and III.

4.6 *Provenance of tsunami deposits*

Rock magnetic analysis is a useful tool in studies dealing with sediment provenance. The minor or trace magnetic components can carry key environmental information because their characteristics, or magnetic signature, vary according to their source and depositional history (Maher *et al.* 2009; Holden *et al.* 2011). Moreover, sensitive magnetic measurements can be

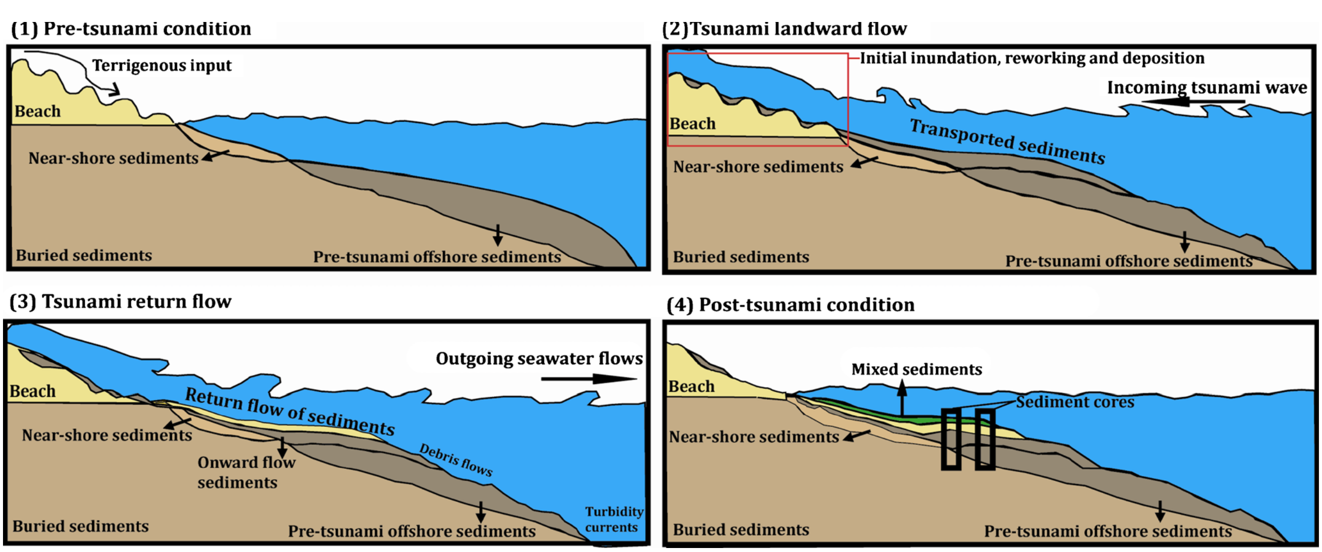

Figure 6. Depositional sequence of sediments (during the 2004 Indian Ocean Tsunami) indicating their characters in sediment cores collected off Nagapattinam, SE coast of India.

made relatively cheaply and rapidly compared with other mineralogical, geochemical and foraminiferal analyses. Based on tsunami video clippings, numerical model, textural, geochemical, mineralogical and magnetic results in core sediments, depositional data were generated for Nagapattinam coast (figure 6). This deposition model showed four progressive steps including pre-tsunami stage, tsunami stage (wave propagation landward and inundation), depositional stage (backwash flows and related gravity driven processes seaward) and post-tsunami stage. This model also showed that the backwash current has transported and deposited sediments from a landward source during the tsunami event.

Results of the Pearson's correlation coefficient matrix for the overall sediment textural, mineralogical, geochemical and rock-magnetic parameters of both C1 and C2 sediment cores are given in table 1. In order to compare and interpret the tsunami deposits zone with the other zones, we performed the Pearson's correlation coefficient analysis for textural, mineralogical, geochemical, and rock-magnetic parameters. The results of correlation coefficients of all measured parameters with respect to magnetic susceptibility have been illustrated in figure 7. Magnetic susceptibility is negatively correlated with sand contents of all three zones of both sediment cores, whereas a positive correlation is observed between magnetic susceptibility and silt and clay contents. It confirms that iron oxides in zone II are essentially contained in the detrital fraction (clay and silt) and dilution of huge volume of dia- to paramagnetic sands.

Magnetic susceptibility positively correlated with SIRM, Soft IRM, Hard IRM, and S-ratio

Table 1. *Pearson correlation coefficient matrix of textural, mineralogical, geochemical and rock-magnetic parameters in sediment cores C1 and C2.*

	χ	χ_{fd}%	χ_{ARM}	SIRM	χ_{ARM}/χ	χ_{ARM}/ SIRM	SIRM/χ	Soft IRM	Hard IRM	S ratio
Sediment core C1										
Sand	−0.36	−0.15	0.25	−0.07	0.42	0.20	0.33	−0.08	0.30	−0.28
Silt	0.29	0.22	−0.27	0.21	−0.40	−0.33	−0.02	0.24	−0.05	0.23
Clay	0.33	0.08	−0.19	−0.01	−0.36	−0.10	−0.42	−0.01	−0.37	0.25
SiO_2	−0.09	−0.24	0.14	0.23	0.15	−0.11	0.48	0.21	0.25	−0.10
Al_2O_3	0.31	0.03	0.17	0.02	−0.13	0.08	−0.37	−0.06	−0.11	0.06
TiO_2	−0.44	−0.06	−0.01	−0.14	0.34	0.10	0.32	−0.14	−0.16	−0.14
Fe_2O_3	0.37	−0.43	0.24	0.54	−0.17	−0.32	0.42	0.53	0.69	0.19
Na_2O	−0.12	0.41	0.05	−0.26	0.14	0.24	−0.28	−0.36	−0.25	−0.28
K_2O	0.21	−0.45	0.03	0.44	−0.17	−0.37	0.46	0.47	0.47	0.09
CaO	0.43	−0.44	0.31	0.54	−0.17	−0.28	0.34	0.49	0.65	0.21
MgO	0.46	−0.35	0.33	0.48	−0.19	−0.22	0.19	0.46	0.67	0.18
P_2O_5	0.00	0.27	0.09	−0.13	0.07	0.16	−0.22	−0.17	−0.12	−0.18
MnO	0.11	−0.32	0.08	0.15	−0.04	−0.09	0.13	0.15	0.28	−0.02
Quartz	0.15	−0.09	0.10	0.42	−0.08	−0.29	0.48	0.34	0.63	−0.18
Feldspar	0.10	−0.02	−0.08	0.34	−0.14	−0.35	0.43	0.32	0.08	0.17
Carbonate	−0.16	−0.02	−0.11	0.19	0.03	−0.24	0.51	0.23	0.20	0.03
Sediment core C2										
Sand	−0.14	−0.04	0.64	−0.50	0.54	0.67	−0.34	−0.41	0.29	−0.60
Silt	0.06	0.00	−0.03	0.05	−0.05	−0.01	0.01	−0.15	−0.45	0.08
Clay	0.14	0.05	−0.77	0.60	−0.64	−0.82	0.42	0.59	−0.10	0.70
SiO_2	0.01	0.06	0.37	−0.22	0.27	0.37	−0.19	−0.28	0.27	−0.42
Al_2O_3	−0.07	0.25	−0.72	0.48	−0.51	−0.76	0.43	0.52	0.23	0.44
TiO_2	0.17	−0.18	0.25	−0.22	0.10	0.28	−0.28	−0.38	−0.24	−0.16
Fe_2O_3	0.07	−0.21	0.29	−0.34	0.17	0.39	−0.32	−0.47	−0.21	−0.24
Na_2O	0.22	−0.05	−0.33	0.22	−0.34	−0.31	0.07	0.28	0.14	0.20
K_2O	0.05	−0.03	0.44	−0.21	0.31	0.41	−0.20	−0.22	0.00	−0.26
CaO	0.00	−0.12	0.62	−0.45	0.45	0.67	−0.38	−0.51	−0.16	−0.40
MgO	0.02	0.06	−0.49	0.12	−0.37	−0.40	0.09	0.19	0.21	0.27
P_2O_5	−0.08	−0.09	0.06	−0.03	0.09	0.04	0.02	−0.06	0.03	−0.04
MnO	0.00	−0.07	0.12	−0.34	0.08	0.27	−0.28	−0.27	−0.15	−0.09
Quartz	−0.01	−0.06	0.41	−0.45	0.30	0.52	−0.37	−0.47	−0.29	−0.13
Feldspar	−0.05	−0.19	0.56	−0.39	0.44	0.60	−0.30	−0.39	−0.20	−0.32
Carbonate	−0.05	−0.19	0.73	−0.63	0.56	0.84	−0.50	−0.74	−0.20	−0.50

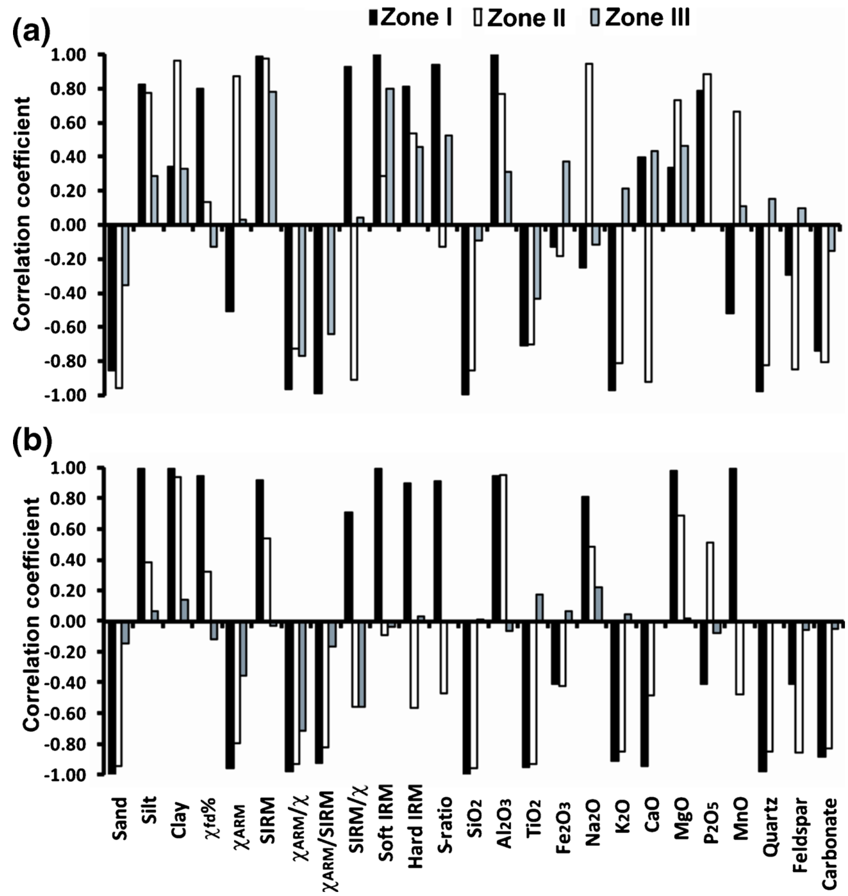

Figure 7. Pearson correlation coefficients of magnetic susceptibility *versus* a set of textural, mineralogical, geochemical and rock-magnetic parameters in sediment cores (**a**) C1 and (**b**) C2.

indicates that the variation of χ is mainly governed by the presence of ferrimagnetic minerals (Venkatachalapathy *et al.* 2010). Magnetic susceptibility (χ) show a negative correlation with χ_{ARM}/χ, χ_{ARM}/SIRM, and SIRM/χ suggesting that magnetic susceptibility may correspond to a change in magnetic particle content (Venkatachalapathy *et al.* 2011a, b). Magnetic susceptibility showed a positive correlation with χ_{fd} in core C1 and a negative correlation in core C2. This suggests that χ_{fd} measurements are unreliable due to the low signal to noise ratio that results from the weak magnetic susceptibility values (Mohamed *et al.* 2011).

χ positively correlated with Al_2O_3, Na_2O, MgO, P_2O_5 and MnO, but negatively correlated with SiO_2, TiO_2, Fe_2O_3, K_2O and CaO, revealed that the transfer of minerals from the beach area had taken place during the backwash of huge tsunami waves (Srinivasalu *et al.* 2010). The correlation results also showed that the deposition of magnetic minerals, geochemical and texture size of sediments in zone II is due to the erosion and transportation of sandy sediments from the backwash of the tsunami wave and the finer particles are being washed away to deeper regions.

5. Conclusion

The 2004 Indian Ocean tsunami has left significant sand deposits along the coastal, near-shore, and offshore regions of Tamil Nadu. The study of these deposits provides a better understanding of the effects of the tsunami on offshore region. The offshore region has the potential to preserve tsunami deposits in shallow coastal regions depending on the local topographical conditions. The textural, mineral, geochemical, and rock-magnetic results of sediment cores collected off Nagapattinam, on the southeast coast of India were effectively used to identify the depositional sequence in areas affected by the tsunami. In the two studied cores, the textural, mineralogical, and geochemical results of the zone II sediments, assumed here to represent the 2004 IOT, indicate enrichment in quartz, which is interpreted to result from the erosion and transportation of the inland area and beach by the tsunami wave. This interpretation is compatible with the previous numerical model for tsunami induced sediment transport off the southeast coast of India. The rock magnetic properties of zone II show low values of magnetic susceptibility interpreted to result in the dilution of iron oxides from rework terrestrial sediment (silt and clay) into huge volume of dia- to paramagnetic materials (sand and shell fragments). Such an interpretation is comforted by our correlation analysis. This work confirms that the rock magnetic techniques, being fast and cost effective, can be used as a promising tool to identify the tsunami induced deposits in offshore regions.

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