

Distribution and dispersal of surface sediments on the continental margins of India

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Abstract

The vast area, varying climate regimes, diverse source terrain lithology of the mainland India generate complex weathering and erosional patterns and leads to diverse sediment distribution and dispersal on the surrounding continental margins of India. Thus, to delineate the sources, distribution and sediment dispersal pathways around India, 254 sediment cores from the eastern and western continental margins of India were investigated for physical properties using non-destructive, whole core logging technique combined with grain-size analyses. The distribution of magnetic susceptibility, gamma ray density and grain-size traces the sources in the Indian landmass which contribute sediments to the margins and demarcates their extent of influence. The results from the magnetic susceptibility distribution indicate that the dominant influx of modern high susceptibility sediment into the margins of India originates from the weathering of Deccan Basalts and its subsequent transportation by Narmada and Tapti Rivers in the west coast and Krishna and Godavari Rivers in the east coast. Though the Himalayan sources are the second largest supplier of magnetic minerals to the shelf, their contribution, when compared to the Deccan sediments is not significant. The lack of present-day sedimentation in the outer shelf regions of margins of India is evident from the gamma ray density distribution and is confirmed by the discrete sample grain-size analysis. Gamma ray density variations in the margins follow the same pattern as the grain size variations and demarcate the boundary between inner shelf modern clayey sediments and the outer shelf relict carbonate sands. Regional distribution maps of physical properties and grain-size for both the margins of India are presented and geographical limits of each provenance are defined, thus providing a comprehensive picture of sediment distribution and dispersal patterns in the area and highlights the use of magnetic susceptibility as a powerful tool in deciphering the source to sink pathways of sediments.

Keywords: Continental margin, India, Environmental magnetism, Magnetic susceptibility, Physical properties, Gamma ray density, Grain Size, Sediment dispersal

1. Introduction

Though the continental margins cover less than 20% of the surface area of world oceans (Walsh, 1991), they are the main interface between terrestrial sediment sources and deep-sea depositional systems and act as either a capacitor or a conveyor for sediments (eg: Covault and Fildani, 2014). The role of continental margins in the sediment distribution and global biogeochemical cycles is well documented. They also act as the archives of climate, sea level and sedimentation changes, record the terrestrial input (Hebbeln and Berner, 1993) and are a major carbon sink (eg: Muller-Karger, 2005).

The Atlantic type passive continental margins of India evolved through a large geological period starting from Early Mesozoic as a result of rifting and drifting of the Indian subcontinent from Antarctica, Australia, Madagascar and Seychelles. These margins on both sides of India are generally termed as the Eastern continental margin of India (ECMI) and Western continental margin of India (WCMI). The margins cover an area of 440,000 km² and measure about 6027 km in its coastal length. Factors such as particle size, rate of sediment supply, oceanographic parameters (waves, tides and currents), topography and gradient of the continental margins and coast influence the sediment dispersal and transport pattern in the continental margins (Dias et al., 2002; Brooks et al., 2003; Rao et al., 2005). Deciphering the natural dispersal patterns is useful both for offshore development activities and to assess the pathways that pollutants may take when introduced into the sea. Various academic and the oil industry scientific communities have identified turbidite and slope instabilities at passive margins as high priority targets that need to be studied. There were a number of studies to understand the sources and distribution of the sediments in the continental margin of India (Subba Rao, 1964; Siddiquie, 1967; Goldberg and Griffin, 1970; Kolla et al., 1976, 1981; Nair et al., 1982b; Shankar et al., 1987; Rao and Rao, 1995; Kessarkar et al., 2003; Kurian et al., 2013 and others). But most of them were restricted either to WCMI or to the ECMI using different tools in each case. In this study, we intend to delineate the sources, sedimentary processes and the dispersal pathways using the non-destructive, whole core physical properties and grain-size analysis of sectioned sediments using a large number (254) of sediment cores representing a single-most study covering both the margins. With the large number of sediment cores studied here, the provenance of sediments, the natural dispersal pathways of sediments and the geographic limits of influence of each source on the Indian margins have been assessed. In addition, first regional distribution maps of density, magnetic susceptibility and the grain size for both the margins around India are presented which will have the utility in offshore developmental activity and also to assess the pathways the pollutants may follow.

2. Geological setting and oceanography of the study area

2.1. Physiography

. The east coast of India has a length of 2686 km while the west coast has a length of 3341km (<http://iomervis.nic.in>). The western continental shelf covers an area of about $0.31 \times 10^6 \text{ km}^2$ and is characterized by a wide continental shelf with a NNW-SSE trend (Chauhan and Gujar, 1996). The width of the continental shelf narrows down southward from a maximum of 350 km in Gulf of Cambay (GoC) to a minimum of 60 km off Cochin with shelf break occurring at approximately 130 m water depth (Manjunatha and Shankar, 1992). The eastern continental shelf covers an area of about $0.13 \times 10^6 \text{ km}^2$ and its width varies from a maximum of 210 km off the Ganges to a minimum of 16 km off Karaikal. The Eastern continental margin is aligned in a NE-SW trend. The shelf break is highly variable and generally occurs between 70 - 220 m water depths (Murthy et al., 1993). The Eastern coastal plain (ECP) separating the Eastern Ghats from the Bay of Bengal is wider (100-130 km) than the Western Coastal plain (WCP) (50 km width) between the Western Ghats and Arabian Sea (**Fig.1**). The rivers on the East coast are long and delta-forming type compared with the short rivers on the west coast that hardly form deltas. The steep gradient of Western Ghats, shorter river lengths and the narrow coastal plain prevents the formation of deltas in the west coast. There are a number of large and small estuaries present along the vast coastline of India. While most of the larger estuaries are present in the east coast, there are many smaller estuaries present along the west coast.

2.2. Oceanography and hydrodynamics

The northern Indian Ocean is characterized by seasonally reversing currents due to the reversal in the wind direction. The winds generally blow from southwest during the summer monsoon (May - September) and from the northeast during winter monsoon (November - February). The West India coastal current (WICC) and East India coastal current (EICC) are the major surface currents that affect the coastal hydrodynamics around India (Shankar et al., 2002). Longshore sediment transport directions in Indian coasts are highly variable. In the West Coast, though the drift is bi-directional and season dependent, the long term net littoral drift is southwards (Paula et al., 2001). In the East Coast, longshore sediment transport direction is northerly from April to September, southerly from November to February, and variable in March and October with the annual net transport towards north (Chandramohan and Nayak, 1991; Kumar et al., 2006).

2.3. Sediments on the continental margins of India

The major source of sediments in the continental margins of India is the fluvial discharge from the rivers. The annual sediment load of Indian rivers to the adjacent oceans is approximately 1.2 billion tonnes, which is about 10% of the global sediment flux. Out of this, Bay of Bengal receives about 1 billion tonnes of sediment annually (Subramanian, 1993). WCMI receives its sediments mainly from the terrestrial sources delivered by Indus, Narmada, Tapti and many other smaller rivers. The drainage area of these rivers differs in their lithology, weathering pattern and climate. The Indus River flows through the Precambrian metamorphic rocks of Himalayas and the recent alluvial soils (Krishnan, 1982) and brings the physical weathering products compared to Narmada and Tapti rivers which carry the chemical weathering products. The major lithology in the Narmada Basin is the Deccan basalts followed by the sedimentary rocks of Vindhyan and Gondwana Super Groups (Gupta and Chakrapani, 2005). Tapti River initially flows through basaltic terrains of the Deccan Traps and then through alluvial deposits before entering the Gulf of Cambay (Sharma et al., 2010). In the south, smaller rivers such as Periyar, Sharavati, Bharathapuzha, etc drain the Precambrian gneissic rocks, charnockites and schists of Western Ghats (**Fig. 2**). The Arabian Sea also receives a considerable supply of dust from Thar and Arabian deserts through eolian transport (Sirocko and Lange, 1991; Schnetger et al., 2000).

The sediments of WCMI can be broadly classified into two types based on their grain-size, carbonate and organic matter contents, and radiocarbon ages (Manjunatha and Shankar, 1992). The inner shelf contains modern sediments - mainly silt and clay - with high organic carbon content and the outer shelf is composed of relict, sandy carbonate sediments formed as a result of reef growth, progradation and wave activity during the Late Quaternary sea level low stands (Rao and Wagle, 1997). The continental slope in WCMI is covered by silty clays (Borole, 1988). The inner continental shelf was further subdivided by Rao and Rao, (1995) into three zones based on the clay mineral composition; 1) region north of Gulf of Kutch (GoK) with abundance of illite, chlorite, smectite and kaolinite in decreasing order, 2) Saurashtra - Goa region with dominance of smectite, 3) Goa - Cochin shelf with kaolinite and smectite dominance. The geochemical studies of sediments from the western continental margin of India have shown a distinct north-south provinciality, with the source signatures pointing at Deccan basalt for sediments in the north (from Dwaraka to Goa) and gneisses and granulites of South India in the south (Kurian et al., 2013).

The sediments of ECMI are mainly derived from Himalayan and Peninsular Indian sources. The Ganges - Brahmaputra River system brings the sediments derived from the glacial weathering of Himalayas, while the peninsular rivers Mahanadi, Krishna, Godavari, etc drain peninsular India.

Among these, Ganges is the major contributor of sediments and forms Bengal fan, the largest deep-sea fan in the world. Some of the peninsular Indian rivers (eg: Krishna and Godavari) also drain the Deccan Volcanic province. In the southern part of ECMI, rivers such as Cauvery and Vaigai drain through the Precambrian formations of South India comprising the schistose rocks of Dharwar system, Peninsular granite gneiss, charnockite and Closepet granite (Krishnan, 1982) (**Fig. 2**). In the East Coast, the inner shelf and the continental slope are covered by fine-grained clastic sediments (Rao, 1985). The outer shelf in the east coast is also made up of relict carbonate (mainly oolitic in nature) sediments (Alagarsamy, 2009). The clay mineralogy of the ECMI sediments indicates that the sediments derived from the Himalaya are characterized by abundant illite followed by chlorite, and the Deccan Trap derived sediments contain abundant smectite. The sediments derived from Eastern Ghats (composed of khondalites, leptynites, charnockites, pegmatites and calcgranulites) are dominated by illite and kaolinite in the north and by smectite and illite in the south (Raman et al., 1995).

3. Materials and methods

3.1. Sampling

Two hundred fifty four sediment cores (among them 36 are gravity cores and 218 are shorter spade cores) were collected from the continental margins of India from 2012 to 2015 (**Fig. 2**). These samples were collected during the oceanographic expeditions SSK 35, 40, 50, 59, 71, 73 and 80 on RV Sindhu Sankalp and SSD 03 on RV Sindhu Sadhana. Among this, 94 cores were collected from the ECMI and 160 were raised from the WCMI. The water depths at the sampling sites varied from 15 m to 1711 m and sampling in further shallower waters was not possible using the research vessels. Many of these cores were collected in depth-wise transects to get a better picture of sediment distribution and dispersal. The core samples were packed in PVC liners and kept at 4°C in cold storage until analysis.

3.2. Multi-Sensor Core Logging

The physical properties of marine sediments are an important source of information regarding the provenance, composition, microstructure and environmental conditions during and after their deposition (Breitzke, 2006). They reflect the changes in grain-size distribution (Bassinot, 1993; Weber et al., 1997), calcium carbonate content (Mayer, 1980), depositional history, anthropogenic pollution (Petrovsky and Ellwood, 1999), atmospheric dust supply (Larrasoana et al., 2008), post-depositional diagenesis (Karlin, 1990) etc. The advancement of automated logging techniques such as Multi sensor core logger (MSCL) replaced the time consuming, expensive and sometimes sample

destructive laboratory analysis procedures for the determination of physical properties of sediments. In this study, gamma-ray attenuation and magnetic susceptibility of sediments were measured at 1 cm intervals on whole cores at CSIR - National Institute of Oceanography, Goa, India using an MSCL - X (Geotek Ltd., UK) (**Fig. 3**). The sediment cores stored in the cold storage were taken out to bring them to room temperatures before the logging began to avoid the influence of changing temperatures on the measurements.

3.2.1. Gamma ray density

Gamma-ray density (GRD) is a term used for the bulk density measured using gamma-ray attenuation technique by passing gamma photons through sediments. In unconsolidated upper seafloor sediments, GRD is often an indicator of the variations of mean grain size (Kim et al., 2012). Coarse-grained sediments have higher densities due to their lower porosity, lower water content and their grain to grain contact (Weber et al., 1997). In order to measure the GRD, Cesium-137 with an energy of 0.662 MeV was used as the gamma-ray source and the beam was collimated into the samples through a 5 mm collimator. The gamma photons attenuated by Compton scattering by the electrons in the core were then measured with the help of a gamma detector which counts the number of transmitted photons that have the same principal energy of the source (0.662 MeV) and calculates the gamma ray attenuation. It was then converted into gamma densities using the Geotek MSCL software.

The calibration of gamma density measurements was done using a calibration section which consists of a cylindrical piece of aluminum of varying thickness surrounded completely by distilled water in a sealed core liner (For detailed method, refer Best and Gunn, 1999). Gamma counts were measured through the calibration sample at different thicknesses each for a time of 100s. The average density (ρ_{av}) at each thickness was calculated using the equation,

$$\rho_{av} = [(d_i / D) * \rho_{Al}] + [(D - d_i)/D * \rho_{water}]$$

Where D = total thickness

d_i = thickness of Al section

ρ_{Al} = density of Al

The product of average density (ρ_{av}) value and the total thickness of the liner were plotted against the natural log of measured counts per second (CPS). A polynomial equation $y=Ax^2+Bx+C$

was fitted to the graph (**Fig. 4**) in order to find the coefficients A, B and C. These parameters were then entered into the gamma density processing panel to get the calibration.

3.2.2. Magnetic Susceptibility

Magnetic susceptibility of marine sediments is often used as a proxy to characterize the terrigenous sediment sources and their mixing patterns in differing depositional environments provided that the post-depositional alterations does not affect the magnetic signals (Thompson and Oldfield, 1986; Horng and Huh, 2011). The major contributors to the magnetic susceptibility of sediments include detrital iron oxides, authigenic iron oxides and other weakly paramagnetic silicate minerals. In the continental margins of India, magnetite, titanomagnetite and hematite are the major contributors to the surface susceptibility signals (Kulkarni et al., 2014). The measurement of magnetic susceptibility was carried out in whole cores using a Bartington loop sensor (MS2C). Since the core liners in this study were having an external diameter of 130 mm, a loop sensor of 150 mm internal diameter was used to measure the susceptibility. The oscillator circuit in the loop sensor produces a low intensity, non-saturating, alternating magnetic field. When the sediment-filled cores pass through the sensor, the magnetic minerals present in it causes changes in oscillator frequency. The MSCL system converts it into volume specific magnetic susceptibility values (SI Units). The calibration of MS2C loop sensor was done using the standard sample of a stable iron oxide provided with MSCL system, which has been tested and analyzed by the manufacturer (Bartington Instruments Ltd).

In order to map the variation of gamma density and magnetic susceptibility around India, surface values were extracted from the whole core data. Data from the top 6 cm of the cores were discarded to account for the core compaction and to avoid the errors due to the presence of core caps. The average of the next 10 cm readings was taken as the surface value at that location.

3.3. Grain-size analysis

In order to study the sediment distribution pattern in the margins and validate the MSCL measurements, grain-size analysis was carried out on surface sediments from 218 locations. While collecting the sediment cores in the oceanographic cruises itself, surface samples (top 2 cm) were also collected from the box corer. These were used for the grain-size measurements. Most of these locations were the same as the core locations used in the study although 19 additional samples were also used to improve the data resolution in the areas where sampling resolution was poor such as the shelf regions off Ganges-Brahmaputra and Nellore-Visakhapatnam. The bulk sediment samples were sieved through 63-micron mesh to separate the sand fraction. The <63 μ m fraction was then treated

with acetic acid and hydrogen peroxide to make them free of calcium carbonate and organic matter. This lithogenic silt-clay fraction was analyzed using Malvern Laser Particle size analyzer (LPSA, Master sizer 2000) available at CSIR - National Institute of Oceanography, Goa. Sediment grain-size was determined according to the classification of Shepard (1954) based on the relative abundance (wt. %) of sand, silt and clay fractions.

4. Results

4.1. Gamma ray density

The gamma density values along the continental margin of India range from 1.11g/cm³ to 2.42 g/cm³. In most of the areas, GRD values vary narrowly between 1.5-1.75 g/cm³. GRD values show a southward increase in the west coast, with comparatively higher values in the Kerala coast in the southwest (**Fig.5**). The values also increase seaward on the west coast, resulting in increased density in the outer shelf compared to the inner shelf. A higher GRD value was also observed in the Gulf of Kutch area.

In the east coast of India, GRD values are higher in the inner shelf regions except at the mouths of Mahanadi - Brahmini, Krishna - Godavari and Rushikulya Rivers (Fig. 5). The inner shelves of Tamil Nadu, some parts of Andhra Pradesh and the mouth of Hooghly River in Bengal shelf region show higher density values. A high-density zone is observed between the north of Bhubaneswar to Visakhapatnam in the central part. The sediments off rivers draining Southern Granulite province and Dharwar Craton (Cauvery, Penner, Palar, etc) show higher density values while those derived from Deccan traps and alluvial sequences (rivers Krishna, Godavari, Vamsamdharma etc) have lower density values.

4.2. Magnetic Susceptibility-

The magnetic susceptibility values of Indian continental margin sediments show a large variability (**Fig. 6**). They are as low as 0.6×10^{-5} , which increase to values as high as 965×10^{-5} SI units. In general, highest values of susceptibility are observed at two areas- the Gulf of Cambay shelf off Gujarat on the west coast and the Krishna - Godavari shelf off Andhra Pradesh in the east suggesting input of sediments with high magnetic mineral content. Maximum value (965×10^{-5} SI units) is seen in the Gulf of Cambay shelf where Narmada and Tapti rivers debouch their sediments. Susceptibility decreases southward in west coast reaching to values below 25×10^{-5} SI units in Goa - Kerala region. The susceptibility values also decrease north of Gulf of Cambay, where Indus River sedimentation is dominant suggesting reduced magnetic mineral content in the sediments reflecting a different provenance.

In the east coast, susceptibility show maximum values (as high as 400×10^{-5} SI units) off Krishna - Godavari River mouth. The susceptibility values are less than 100×10^{-5} SI units in all other parts of the east coast. With increasing water depth, the susceptibility values show a decrease. The river mouths and inner shelf area, which receive more terrigenous input, show higher values compared to the outer shelf in both the coasts. Thus, the distributional trends in the magnetic susceptibility indicate the variations in provenance and dispersal pathways of sediments.

4.3. Grain Size

The grain-size variation of sediments in the continental margin of India is presented in **Fig. 7** following the grain size-class nomenclature of Shepard (1954). The triangular plot of sand-silt-clay reveals that most of the sediments fall under silty-clay and clayey-silt category. The sand content in the sediments varies from 0% to 96%. The silty-clay or clayey-silt size sediments are dominant in the entire inner shelf, except south of Mangalore, in the west coast. Sand content shows an increasing trend from the inner to outer shelf in west Coast with increasing water depths (greater than 100 m off Gulf of Kutch and 50 m off Mangalore). It also varies in the north-south direction, with higher sand content in the inner shelf of Mangalore - Quilon region compared to the north. The inner shelf sediments south of Mangalore are composed of more than 70% sand at even 30 m water depth. In the East coast, sand content shows a decreasing trend in the outer shelf compared to inner shelf areas except in areas of Krishna - Godavari, Mahanadi - Brahmini and off Bengal.

5. Discussion

The results of the physical properties and the grain-size characteristics of sediments, presented above, have helped us in tracing the sediment sources and assessing their dispersal pattern in the continental margins of India

5.1. Sources and distribution of sediments in WCMI

The grain-size distribution map divides the western continental margin into three zones, 1) inner shelf with fine-grained sediments; 2) outer shelf with coarse-grained sediments and 3) continental slope with fine to medium grained sediments (**Fig. 7**). The GRD data also records these three zones; inner shelf with low GRD, outer shelf with high GRD and continental slope with low GRD (**Fig. 5**). Sediments with silty clay texture are seen in the inner shelf region between Gulf of Kutch to Saurashtra and south off Mumbai, whereas in other areas, the grain-size is clayey silt (**Fig. 7**). The inner shelf clays are limited to <25 m water depth in Mangalore - Cochin shelf (Rao and Wagle, 1997) and are not seen in our map due to the absence of samples in very shallow water depths. The results from our study show coarse-grained sediments (silty sand - sandy size) in the

deeper areas of inner and outer shelf here. The GRD data also reflect this coarse grain-size with high values in the inner and outer shelves of Mangalore - Cochin coast. These coarse-grained sediments are mainly carbonate sands and are relics of the past corresponding to a once lowered sea level (Nair and Pylee, 1968). The large number of estuaries present in this area, relative to other areas in north, restricts the amount of modern sediments reaching the shelf and thereby limiting the fine-grained clay zone to shallow water depths (Nair and Hashimi, 1986). These estuaries are fed by smaller rivers, compared to others, which carry lesser sediment loads.

The outer shelf of WCMI shows coarse grain-size and high gamma density. The outer shelf between Saurashtra and Mangalore is composed of sandy sediments while the outer shelf off Gulf of Kutch is silty in nature (**Fig. 7**). Previous workers have established that the outer shelf of WCMI is made up of relict carbonate sands of Holocene age (Hashimi et al., 1982; Nair and Pylee, 1968). The results from the grain-size and gamma density measurements reaffirm the coarse nature of outer shelf sediments. The gamma density values and grain-size data have helped us to map the geographic extent of relict sediment patch which extends from Saurashtra to Quilon in WCMI (**Fig. 5**). The continental slope, in most of the areas, is an admixture of sand, silt and clay and exhibit a coarser nature compared to the inner shelf. Based on the physical properties and grain-size, the inner shelf of WCMI can be classified into three zones; 1) Shelf north of Gulf of Kutch, 2) Saurashtra - Goa shelf and 3) Goa - Kerala shelf.

5.1.1. Shelf north of Gulf of Kutch

The inner shelf sediments north of GoK are characterized by relatively higher GRD values with a silty clay to clayey silt texture. The major source of sediments to this shelf is river Indus. The silt content is high in the Indus River mouth region. The annual sediment discharge of Indus has been estimated to ~291million tonnes (Hovius, 1998). Most of this sediment is stored in the Indus delta while some of it is bypassed to deeper depths through the canyon and turbidity currents (Prins et al., 2000). A portion of the Indus sediment load reaches the GoK region through longshore sediment transport. Previous workers have found that illite, derived from the physical weathering of felsic Higher Himalayan Crystalline Series and Lesser Himalayan Series source rocks (Huyghe et al., 2011) is the major clay mineral present in the Gulf of Kutch (Ramaswamy et al., 2007) and ascertained the Indus provenance of GoK shelf sediments (Rao and Rao, 1995).

The differences in grain-size and physical properties reveal that the influence of Indus derived sedimentation is limited to the GoK and the sediments from Indus are not transported further southwards to the inner shelf regions of Saurashtra. The magnetic susceptibility values in the GoK

shelf sediments are much lower (average - 35.9×10^{-5} SI units) than those in the Gulf of Cambay shelf (average - 378.6×10^{-5} SI units). The average GRD value of GoK sediments with water depths shallower than 50 m is 1.87 g/cm^3 while in GoC, it is 1.74 g/cm^3 . The drastic changes in the susceptibility, GRD and grain-size in these adjacent shelves results from the presence of high-velocity tidal streams in the macrotidal Gulf of Kutch which prevent the mixing of sediments from Indus and peninsular rivers. This tidal streams prevent the longshore sediment transport across the mouth of the gulf and cause the Indus sediments to get funneled through the Gulf and thrown into deeper depths by ebb tides and thereby leading to the dominance of Indus sediments off Gulf of Kutch and dominance of peninsular sediments off Saurashtra (Nair et al., 1982a). Although the influence of Indus is absent in the inner shelf sediments south of Saurashtra, Indus-derived sediments were found to be transported southward through the deeper depths in the outer shelf and slope regions in the WCMI (Ramaswamy and Nair, 1989; Rao et al., 1995; Rao and Rao, 1995).

5.1.2. Saurashtra - Goa Shelf

The susceptibility, GRD and grain-size data divides the Saurashtra - Goa shelf into two regions viz., the Gulf of Cambay shelf and the Mumbai - Goa shelf. The gamma density values and sand content vary considerably in the inner shelf area of GoC, with the sand content varying between 0 and 40% within the 25 m isobath itself. This may be due to the presence of bedforms like sand ridges, shoals, mudflats and sand bars generated from sediment dynamics (Kunte, 2008). The sediments in the northern and southern flanks of GoC are different in their grain-size and physical properties. The sediments in the Saurashtra shelf of the Gulf shows coarse-grained nature and relatively high GRD and susceptibility values (average - 1.83 g/cm^3 , 532×10^{-5} SI), while the shoreward side of the shelf shows finer grain-size and low values of GRD and susceptibility (average - 1.51 g/cm^3 , 256×10^{-5} SI). This is in agreement with the previous remote sensing observations in the GoC, which showed a muddy mainland coast, while the Saurashtra coast is muddy in the north and sandy to rocky in the south (Kunte, 2008). The tidal propagation in the macrotidal Gulf is responsible for these variations by transporting the fine-grained sediments to the inner shelf and sandy sediments to south-westwards and outwards of GoC (Kunte, 2008).

The decrease in gamma density values and a drastic increase in magnetic susceptibility values in the inner shelf south of Saurashtra compared to the GoK shelf indicate the difference in sediment provenance. The highest values of magnetic susceptibility in the continental margins of India are seen in GoC shelf (maximum = 954×10^{-5} SI units, average = 378×10^{-5} SI units) (**Fig. 6**). The reason for the very high content of magnetic minerals in this shelf lies in the Deccan Trap provenance of sediments here. The chemical weathering of titanomagnetite rich Deccan Volcanic Province and its

transport by the Narmada and Tapi Rivers bring magnetic mineral-rich sediments to the shelf of Saurashtra through GoC. This is in agreement with the previous studies based on clay mineralogy (Nair et al., 1982b; Rao and Rao, 1995) and the geochemistry (Kurian et al., 2013). The GRD values range between 1.75-1.5 g/cm³ in this shelf.

The inner shelf between Mumbai and Goa is composed of silty clay and clayey silt sediments. A clay-rich zone is observed off Mumbai. The grain-size of the sediments coarsens southwards with an increase from silty clay to clayey silt in the inner shelf off Goa. The magnetic susceptibility, on the other hand, decreases southwards implying the reducing influence of Deccan provenance.

5.1.3. Goa - Kerala Shelf

The sediments in the inner and outer shelf between Goa and Kerala are mostly sandy in nature (**Fig. 7**). In the Goa- Mangalore shelf, the inner shelf sediments are comparatively finer (silty sand and clayey sand) compared to the outer shelf sands. A number of estuaries present in the Kerala coast covering large area of (~2420 km²) and length (~325 km out of 580 km coastline) act as regional filters and restrict the amount of modern sediments reaching the shelf and thereby limiting the fine-grained clay zone to shallow water depths by trapping the coarse-grained sediments in the estuaries. The sudden fall in the river velocities and the cyclic variations in the coastal water salinity due to the presence of monsoons has been interpreted as the possible reasons for this trapping (Nair and Hashimi, 1986).

The low magnetic susceptibility value (average - 12.4×10^{-5} SI units) in the sediments south of Goa marks the end of Deccan basalt provenance and the beginning of gneissic provenance. This is consistent with the earlier finding of north-south provinciality in provenance using the sediment geochemistry data (Kurian et al., 2013). The sediments here owe their provenance to the weathering of Western Ghats (Kessarkar et al., 2003). The intense chemical weathering of Precambrian gneissic rocks, charnockites and schists of Western Ghats due to high rainfall (>2500 mm) and humid tropical climate is the major contributor of sediments to the western continental margin through smaller rivers like Mandovi, Periyar, etc. (Kessarkar et al., 2003).

5.1.4. Relict sediments in the outer shelf of WCMI

The outer shelf sediments on the WCMI have coarser grain size (mainly silty sand and sandy) and high GRD values (**Figs. 5 & 7**). The GRD values of the outer shelf relict sediments are high (1.75-2.25 g/cm³) compared to the inner shelf terrigenous clays and the slope sediments (1.25-1.75g/cm³). The outer shelf sediments of West Coast of India are composed of medium to coarse grained carbonate-rich relict sediments, containing shells and skeletal fragments of various

organisms and a variety of limestones (Wagle et al., 1994). The outer shelf sediments between Saurashtra and Ratnagiri show very low values of magnetic susceptibility indicating that the sediments from Narmada and Tapi rivers do not reach the outer shelf region. It is due to the presence of a relict carbonate platform known as fifty fathom flat (FFF) in the outer shelf which occurs below the 70 m isobath. The karstic topography and the occurrence of beach rock in the area has been interpreted (Nair, 1971) that the Fifty Fathom Flat stood at sea-level, probably during the Pleistocene and is now submerged due to eustatic and/or tectonic causes. The huge siliciclastic sediment load carried by the Narmada and Tapi rivers settles down in the inner shelf itself and does not reach FFF despite its close proximity. The high energy conditions in the FFF and its bathymetric elevation is attributed as the reason for the absence of late Holocene sediments on this platform (Rao and Wagle, 1997).

5.2. Sources and distribution of sediments in ECMI

The distribution of grain-size and physical properties in the ECMI is complex compared to the WCMI owing to the narrow shelf width and the presence of major rivers. The gamma density values show high values in the shelves off Ganges-Hooghly, Puri - Visakhapatnam, Nellore - Nagapattinam regions (**Fig. 5**). The values are low in the shelves off Mahanadi and Krishna - Godavari river systems. The grain-size data also shows a similar pattern with sandy sediments in the shelves off Ganges-Hooghly, Puri - Visakhapatnam, Nellore - Nagapattinam and clay-rich sediments in the Mahanadi and Krishna-Godavari shelves. Although the grain size shows fining from inner shelf to outer shelf in ECMI, the difference is not as marked as in WCMI. Based on the grain-size and physical properties, five sediment zones can be identified in ECMI and they are; 1) the Ganges - Hooghly shelf, 2) Mahanadi - Brahmini shelf, 3) Puri - Visakhapatnam shelf, 4) Krishna - Godavari shelf and 5) Nellore - Nagapattinam shelf. While coarser grain size and GRD is observed in the shelves off Ganges - Hooghly, Puri – Visakhapatnam and Nellore - Nagapattinam, low GRD and clayey sediments are present in Mahanadi - Brahmini and Krishna - Godavari shelves. The magnetic susceptibility shows high values in the Krishna – Godavari shelf, intermediate values in Ganges - Hooghly, Mahanadi - Brahmini and Nellore - Nagapattinam shelves and low values in Puri - Visakhapatnam shelf.

5.2.1. Ganges -Hooghly Shelf

The Ganges - Hooghly shelf receives an abundant supply of sediments from GB river system, which is the largest contributor of sediments to the Bay of Bengal. The high energy conditions in the shelf due to the tides and storm surges control the distribution of these sediments. The grain-size data

reveals that the sediments in the G-H shelf are clayey silt in the inner shelf and silty clay in the outer shelf (**Fig. 7**). The seaward fining of the sediments is also displayed in the gamma density data where the GRD values are higher in the inner shelf and decrease offshore in a similar way as the grain size (**Fig. 5**). Kuehl et al., (1989) attributed the seaward transport of sediments during high energy conditions through the submarine canyon 'Swatch of No Ground' which intercepts the mid-shelf mud deposits and acts as a major conduit for modern river sediment supply to the Bengal fan, as responsible for the fining of sediments in this direction.

Clay mineralogical studies by previous workers have found illite, which is derived from the physical weathering of Himalayas, as the dominant mineral (70-80%) in this shelf (Murty and Shrivastava, 1979; Rao, 1991a). The eastern and western sides of the Ganges - Hooghly shelf differ in their grain-size and physical properties. The sediments near the mouth of Hooghly River are rich in silt and clay content (> 94% on average) while on the western side of the shelf, the sand content is more (average ~65 %). Gamma density also shows a higher value on the western side compared to the Hooghly river mouth sediments. The magnetic susceptibility values in the shelf vary between 10 and 40×10^{-5} SI units (average - 26×10^{-5}) and are higher in the eastern side (**Fig. 6**). The variation in the grain-size and physical properties between the western and eastern sides of the Ganges - Hooghly shelf indicates the possible influence of sediments from the peninsular sources on the western side. Mallik, (1976) studied the shelf sediments of the Ganges Delta for heavy minerals to understand their dispersal pathways. The results indicated that the heavy mineral suite consisted of hornblende, tremolite/actinolite, opaques, zircon, ortho and clinopyroxenes, garnet, sillimanite, chlorite, muscovite, biotite, epidote, monazite, kyanite, staurolite, riebeckite, carbonates and glauconite originated from two distinct sources. While G-B and its tributaries drain the crystalline and Precambrian complex of the Himalayas and the peninsular shield, Dhamra and other east flowing peninsular Indian rivers drain the khondalites, charnockites, gneisses and Cenozoic sediments in the Eastern Ghats and coastal areas of Orissa (Mallik, 1976). While, the dominant minerals in sediments with Hooghly River provenance were hornblende, tremolite/actinolite, epidote and garnet, the sediments with Dhamra provenance were characterized by high content of opaques, sillimanite and orthopyroxene (Mallik, 1976).

Segall and Kuehl, (1992) studied the clay mineralogy of surface sediments of Bengal shelf and suggested that much of the sediment delivered to the shelf during the high discharge season bypasses the inner shelf through the submarine canyon named 'Swatch of no ground' and forms thicker deposits seaward. These sediments are reported to reach as far as 8°S covering a distance of 3000 km (Nath et al., 1989). The sediments collected on a transect in the western side of Swatch of

No Ground confirms this bypassing by showing a comparatively coarser texture in the continental slope (clayey silt) than the outer shelf sediments (**Fig. 7**). The longshore sediment transport in the shelf is limited by this canyon and the west of the canyon is dominated by a Ganges source, whereas in the east, both the Ganges and Brahmaputra rivers contribute sediments (Kuehl et al., 1989; Segall and Kuehl, 1992). The sediment samples used in the present study are collected from west of the canyon and are derived from the Ganges.

Although the Subarnarekha River is a small river (395 km length) compared to the nearby rivers the Ganges, Mahanadi and Brahmini, the sediments off Subarnarekha River in the western part of Bengal shelf exhibit marked differences in texture, gamma density and magnetic susceptibility values from Hooghly shelf sediments and Mahanadi - Brahmini sediments. The inner shelf sediments are sandy in nature compared to the clayey silt and silty clay sediments of Ganges and Mahanadi. The magnetic susceptibility also shows decreased values in transect off Subarnarekha ($0-25 \times 10^{-5}$ SI units) compared to Ganges and Mahanadi ($25-50 \times 10^{-5}$ SI units). These changes indicate the reduced influence of Ganges source in the inner shelf off Subarnarekha. The sediments in this area are derived from the weathering of khondalites, charnockites, gneisses and Cenozoic sedimentary rocks in the Eastern Ghats and coastal areas of Orissa by rivers such as Dhamra and Subarnarekha. Subarnarekha River drains ultrabasic rocks, alluvial soils and granitic and gneissic rocks of Chhotanagpur province (Chatterjee et al., 2014).

5.2.2. Mahanadi - Brahmini Shelf

The Mahanadi - Brahmini shelf sediments are mainly composed of clays. The inner shelf sediments are clayey silts and the outer shelf sediments are silty clays (**Fig. 7**). The sediments also exhibit low values of gamma density in agreement with the grain-size data. The sand content in the sediments decreases from 39 % at 34 m water depth to 1 % at 96 m water depth. The average magnetic susceptibility value of the Mahanadi - Brahmini shelf sediments is 44×10^{-5} SI units. This is consistent with the source area geology and the previous studies on mineralogical studies in the area. Mahanadi and Brahmini Rivers mainly drain the Precambrian metamorphic rocks of the Eastern Ghats, limestones, sandstones and shales of the Gondwanas, and recent deltaic alluvium deposits (Chakrapani and Subramanian, 1990). Although illite is the dominant clay mineral in this shelf, it is less in content compared to Ganges province. Kaolinite content, on the other hand, is higher in these sediments (Rao, 1991a).

5.2.3. Puri - Visakhapatnam Shelf

The shelf between Puri and Visakhapatnam is sediment starved due to the absence of major rivers (Faruque et al., 2014). The smaller rivers Rushikulya, Nagavali, and Vamsadhara drain their sediments to this shelf. The sediments in this shelf show high values of gamma density except at the mouth of Vamsadhara and Nagavali Rivers. In contrast, magnetic susceptibility shows high values at these river mouths. The grain-size data reveals that the sediments in the Puri-Visakhapatnam shelf are mainly clayey and silty sands in nature. The high gamma density and sand content values in this area may be a result of the presence of relict sands as small units in the inner and outer shelf between Puri and Visakhapatnam (Banerjee and Sengupta, 1992).

5.2.4. Krishna - Godavari Shelf

The sediments in the Krishna - Godavari shelf are silty clays in nature. The gamma density values are low compared to the Puri - Visakhapatnam shelf sediments. The magnetic susceptibility of the shelf sediments with predominantly K-G provenance are distinctly higher than other areas in ECMI. The average magnetic susceptibility of K-G sediments is 210×10^{-5} SI units while the average value in the East Coast is 52.4×10^{-5} SI units. Similar to the sediments derived from Narmada - Tapi Rivers in WCMI, Krishna - Godavari river system also derives a part of its sediments from the weathering of Deccan Traps. Approximately 50% of the total basin area of Godavari River is represented by Deccan Volcanic Province (Kulkarni et al., 2014). Krishna River flows through Archaean and younger crystalline rocks in nearly 80% areas while the remaining 20% flows on Tertiary Deccan Traps and recent sediments. About 80% of Bhima River, a tributary of Krishna flows through Deccan Trap terrain (Ramesh and Subramanian, 1988). This clearly demonstrates that the high magnetic mineral content in the sediments is due to their sources in Deccan Traps. Smectite is the major clay mineral present in this region followed by kaolinite and illite. The weathering of Deccan Trap basalts is argued to be the reason for the high amount of smectite in the K-G sediments (Rao, 1991a).

5.2.5. Nellore - Nagapattinam Shelf

The shelf sediments south of Nellore are sandy in nature and show high GRD values (average - 1.77 g/cm^3). The major rivers that bring sediments into this shelf are Pennar, Palar and Vellar. These rivers drain the Precambrian formations of South India comprising the Dharwar system and southern granulite province. The sand content in the sediments increases at the mouths of Cauvery and Pennar. The outer shelf sediments are a mixture of sand, silt and clay. Magnetic susceptibility values in this shelf sediments range between 0 and 65×10^{-5} SI units (average - 35×10^{-5}) with higher

values in the Nellore shelf and a decrease towards the south (**Fig. 6**). The GRD show high values in the inner shelf (1.85 g/cm^3) and low values in the outer shelf (1.75 g/cm^3) indicating the seaward fining of sediments.

5.2.6. Outer shelf sediments in the east coast

The narrow continental shelf and the less number of sampling points in the deeper depths make it difficult to study the outer shelf sediments in the ECMI. Compared to WCMI, the outer shelf sediments of the East coast do not show a clear pattern in their grain-size or physical properties. The grain size of sediments decreases seawards in the ECMI except at Puri - Visakhapatnam region (**Fig. 7**). The inner shelf sediments are clayey sands while the outer shelf is made of sands and silty sands in this region. This may be due to the presence of relict carbonate sands in this region which are formed during the Pleistocene sea-level low stand (Subba Rao, 1964, Banerjee and Sengupta, 1992). Although the outer shelf of ECMI is made up of relict carbonate sands, they are covered by modern sediments in most of the areas, unlike the WCMI where modern sedimentation is limited to the inner shelf.

5.3. Dispersal pathways of sediments around India

The magnetic susceptibility distribution can provide the details about the sediment sources, distribution and dispersal patterns in depositional systems (Ellwood et al., 2006; Horng and Huh, 2011; Yu and Oldfield, 1993, 1989). The differences in source rock lithology and weathering patterns around India lead to different magnetic mineral assemblages in the continental margin sediments. The spatial distribution of magnetic susceptibility can thus provide information regarding the provenance and source to sink dispersal pathways in these sediments. The very high values of susceptibility in the Gulf of Cambay and Krishna - Godavari shelf implies that the Deccan Basalts are the major source of magnetic minerals in the East and West coast of India. The plot depicting the latitudinal distribution of magnetic susceptibility affirms this and demarcates their extent of influence in margins of India (**Fig. 8**). In the WCMI, Narmada and Tapti Rivers debouch the weathering products of Deccan Traps into the Gulf of Cambay while in ECMI, Krishna - Godavari Rivers bring them to the shelf. The spatial distribution of magnetic susceptibility in the WCMI indicates that the Narmada - Tapti sediments are transported southwards and are reaching up to the inner shelf regions of Ratnagiri. The N-T sediments are also carried northwards to the shelf of Saurashtra but do not reach the Gulf of Kutch due to the strong tidal currents there (**Fig. 6**). This is also supported by the differences in the physical properties of sediments in the north and south of GoK. The map also shows that the modern sediments of N-T are not transported into deeper depths in WCMI due to the

high energy conditions in the fifty fathom flat. The magnetic susceptibility south of Goa is almost constant and does not show much variation except at two locations off Murudeshwar where slightly higher values are observed. The lack of deposition of recent sediments in the outer shelf area and the presence of fine-grained clays in the continental slope has been explained differently in the past by different workers. Some of them (Kolla et al., 1976; Ramaswamy and Nair, 1989) argued that the outer shelf clays are derived from Indus River discharge while others favored the cross-shelf transport model (Nair et al., 1982b; Rao, 1991b; Rao et al., 1983; Rao and Rao, 1995). However, from the susceptibility and GRD distribution maps of WCMI, it is evident that the modern sediments are confined to the inner shelf regions and most of it does not reach the outer shelf area through cross-shelf transport thus supporting the conclusions by Kolla et al., (1976).

In the ECMI, the magnetic susceptibility distribution map shows a more complex sediment dispersal pattern. Susceptibility shows highest values in the K-G shelf sediments and its distribution indicate that these sediments are carried both towards northern and southern sides. This may be due to the influence of seasonally reversing currents of Indian coasts (Shankar et al., 2002). In the south, the low susceptibility zone off Chennai - Nagapattinam Shelf marks the end of K-G provenance and the beginning of peninsular provenance which derive its sediments from the Precambrian formations of South India. In the north, the K-G provenance extends up to Visakhapatnam. The sediment starved shelf between Visakhapatnam and Puri show low susceptibility values north of Kalingapatnam. Comparatively higher values of susceptibility are observed in the mouths of Vamsadhara and Nagavali Rivers. The inner shelf sediments of Hooghly - Ganges and Mahanadi - Brahmini show higher susceptibility values ($25-100 \times 10^{-5}$ SI units). The lowest values of susceptibility in the inner shelf of ECMI are observed at Subarnarekha shelf and Pennar shelf. The low values of susceptibility off Subarnarekha River compared to the Ganges - Hooghly shelf and Mahanadi -Brahmini shelf separates their provenances. A map depicting the inferred sediment dispersal pathways in the continental margins of India based on the grain-size and physical properties generated for this work is presented in Figure 9, which to our knowledge is the first of its kind.

6. Conclusions

The regional distribution maps of grain-size, magnetic susceptibility and gamma-ray density of surface sediments in the continental margins of India presented in this work trace the sources, distribution and dispersal pathways of sediments around India. The GRD distribution and grain-size data follows a close correspondence with each other and demarcates the boundary between the fine-grained inner shelf sediments and the coarse-grained outer shelf relict sediments in the margins. The distribution maps illustrate that the modern sediments on the west coast are restricted to the inner

shelf regions. The magnetic susceptibility distribution indicates that the Deccan Basalt weathering and its subsequent transportation by Narmada, Tapti, Krishna and Godavari Rivers are the major contributors of modern high susceptibility sediment into the margins of India. Though, the Ganges-Brahmaputra rivers supply huge sediment loads to the Bay of Bengal, they bear a low susceptibility.

The magnetic susceptibility, density and particle grain-size data helped us 1) delineate the extent of influence of river Narmada - Tapti sediments and the role of prevailing strong tidal currents in Gulf of Kutch in controlling the sediment dispersal, 2) confirm the lack of cross-shelf transport in western shelf; 3) delineate the boundary that separates the Ganges - Mahanadi provenance on eastern shelf, 4) define the boundary of relict sediment zone on both the shelves, define the extent of influence of each of these sources on the margins around India and construct the sediment dispersal pattern (Fig. 9). The detailed regional maps of the grain-size, density and the characteristic magnetic susceptibility presented for each source, are first of their kind, which can help in deciphering the depositional history and understand the change in provenance with time.

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Figure Captions

Fig. 1: Topographic and bathymetric map of India with names of major rivers and places. Schematic representation of the surface currents in the margins is also shown. The dashed lines represent the current directions during summer monsoon while the solid lines represent their winter monsoon directions. Tidal current directions in Gulf of Kutch and Gulf of Cambay are also drawn in the map.

Fig. 2: Map showing the geological provinces of India with sampling locations modified from the map of Geological Society of India (GSI, 2000). Different symbols are given for each oceanographic cruise in which the core was collected. SSK - RV Sindhu Sankalp and SSD - RV Sindhu Sadhana indicate the names of the research vessels in which the cruises were conducted.

Fig. 3: Schematic diagram of Multi-Sensor Core Logger (MSCL)

Fig. 4: Graph showing the calibration of MSCL for GRD measurements

Fig. 5: Map showing the distribution of gamma-ray density (GRD) of sediments along the continental margins of India

Fig. 6: Map showing the distribution of whole-core magnetic susceptibility of sediments along the continental margins of India

Fig. 7: Map showing the variations in the sediment grain-size in the continental margins of India. The triangular plot of Shepard (1954) based on relative percentages of sand, silt, and clay is also shown.

Fig. 8: Plot showing the latitudinal distribution of magnetic susceptibility highlighting the Deccan source of high susceptibility sediments and their extent of latitudinal distribution.

Fig. 9: Map showing the possible sediment dispersal pathways and limits of each provenance in the continental margins of India interpreted from grain-size and physical properties. The geological formations are similar as in figure 2.

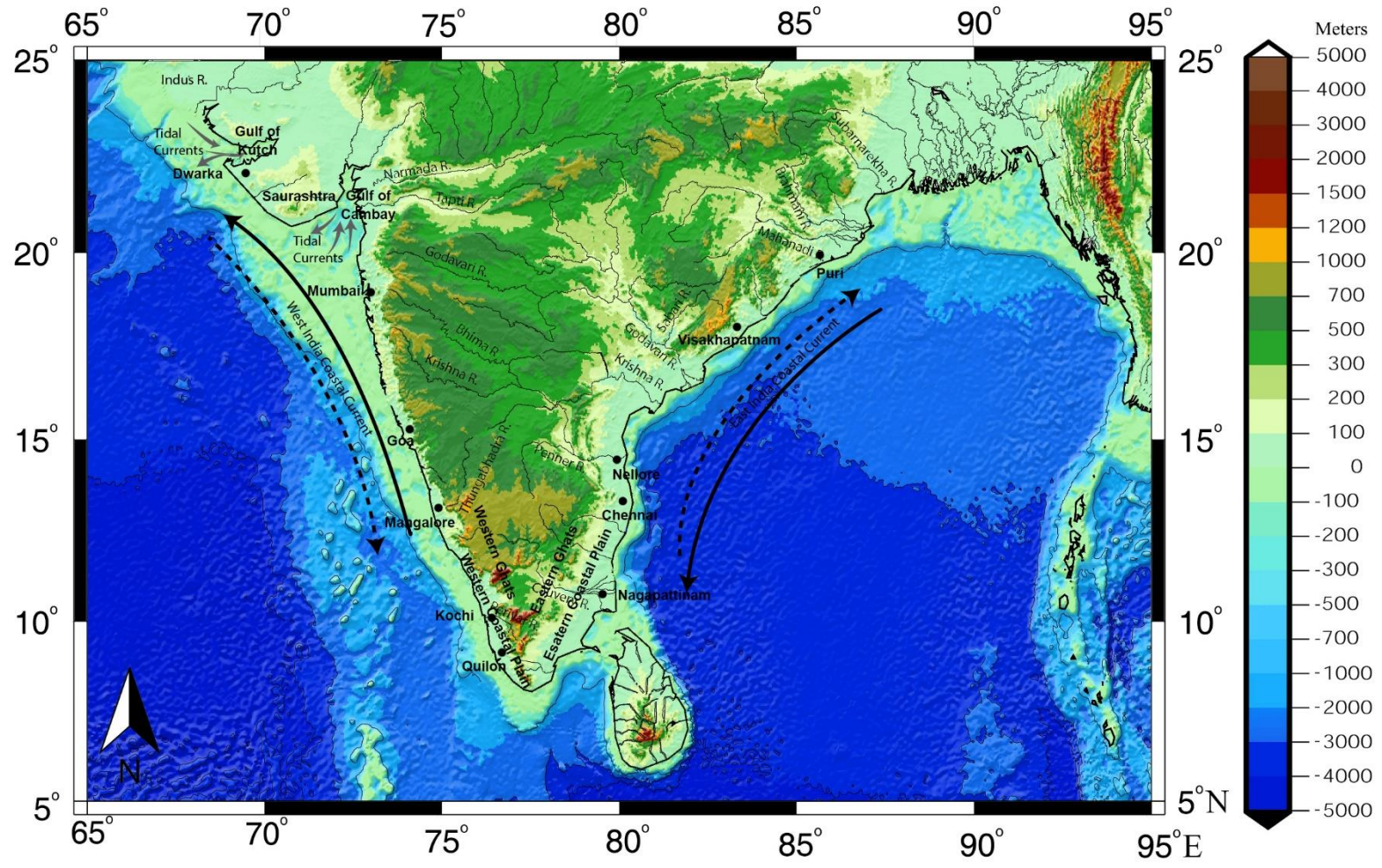


Figure 1

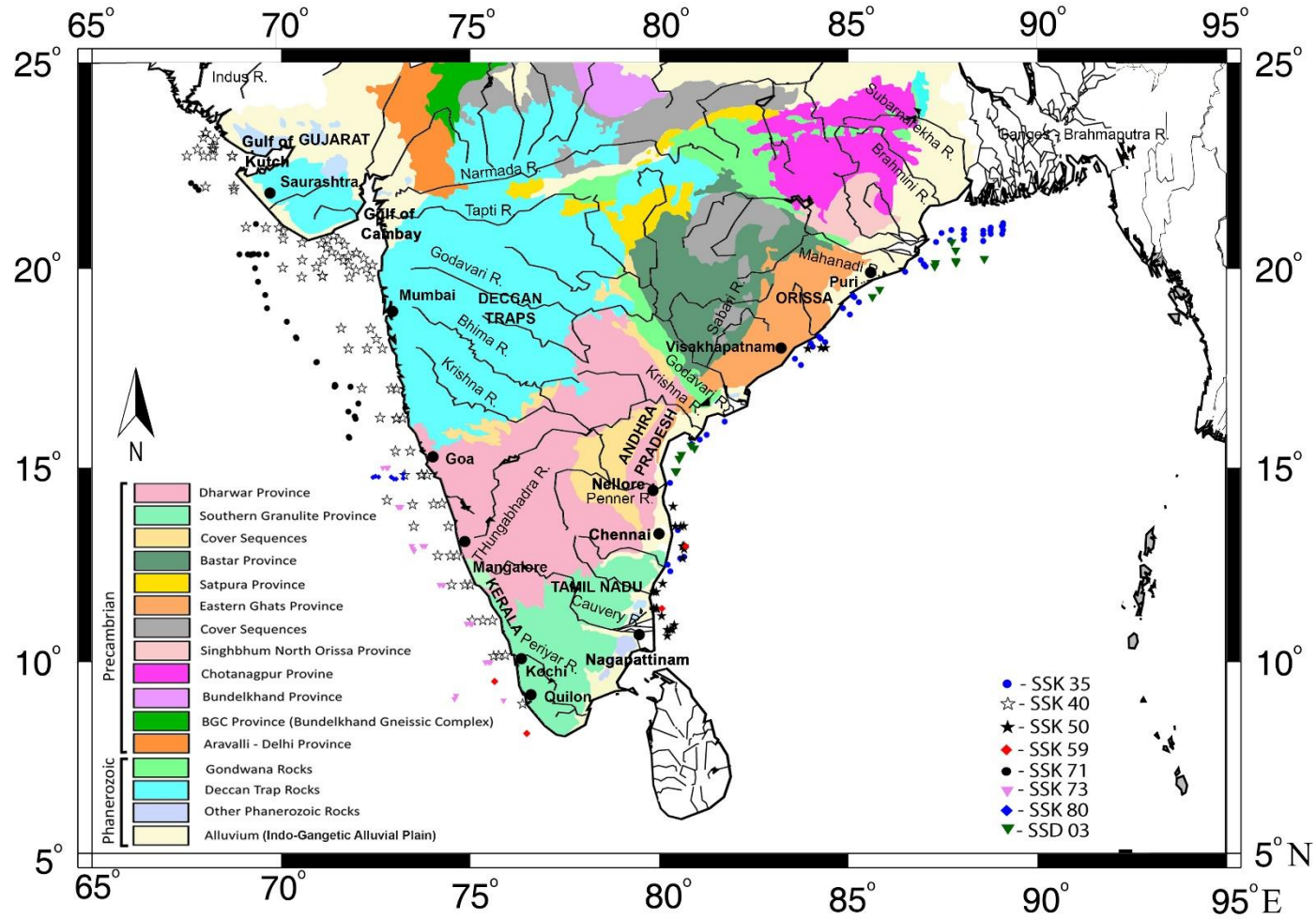


Figure 2

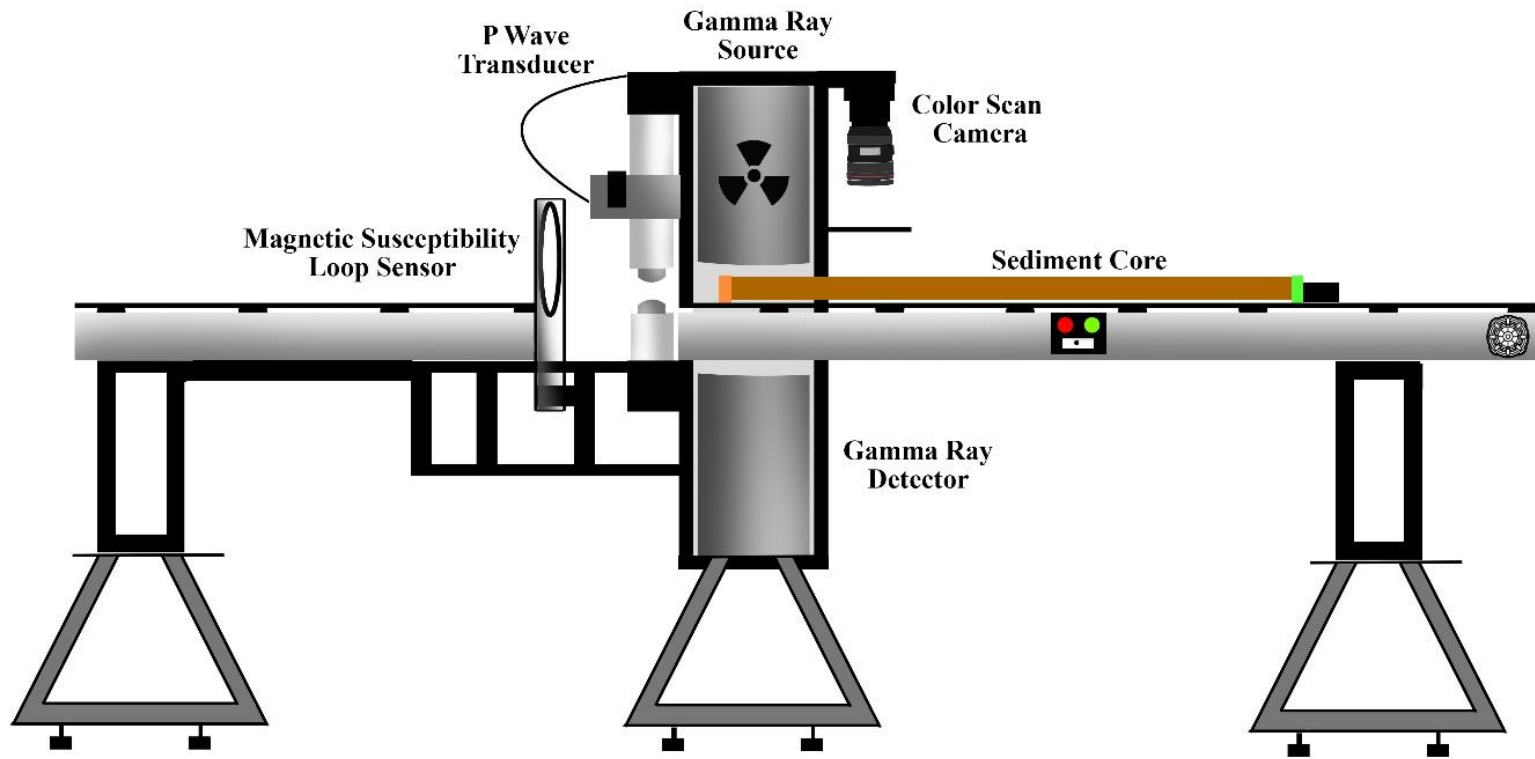
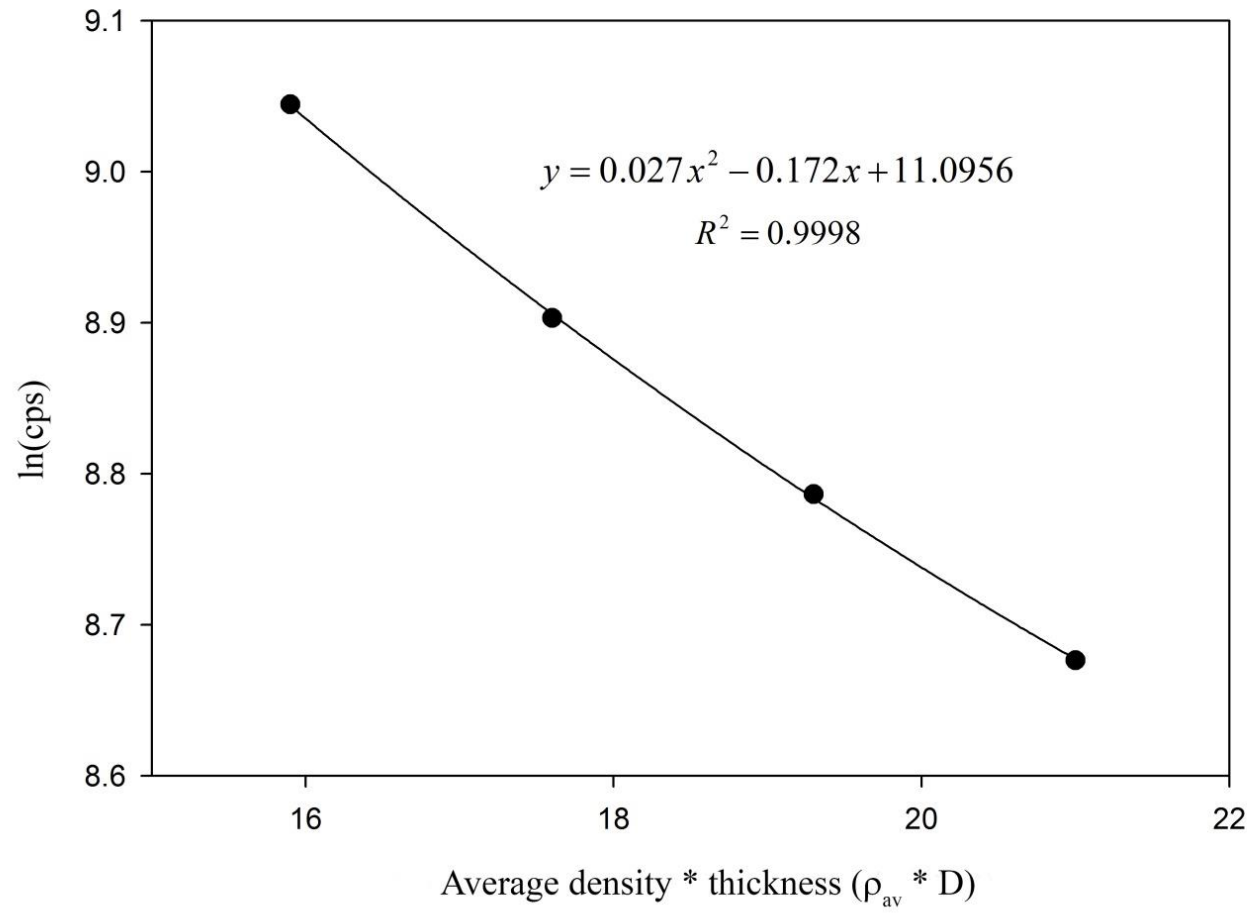


Figure 3

**Figure 4**

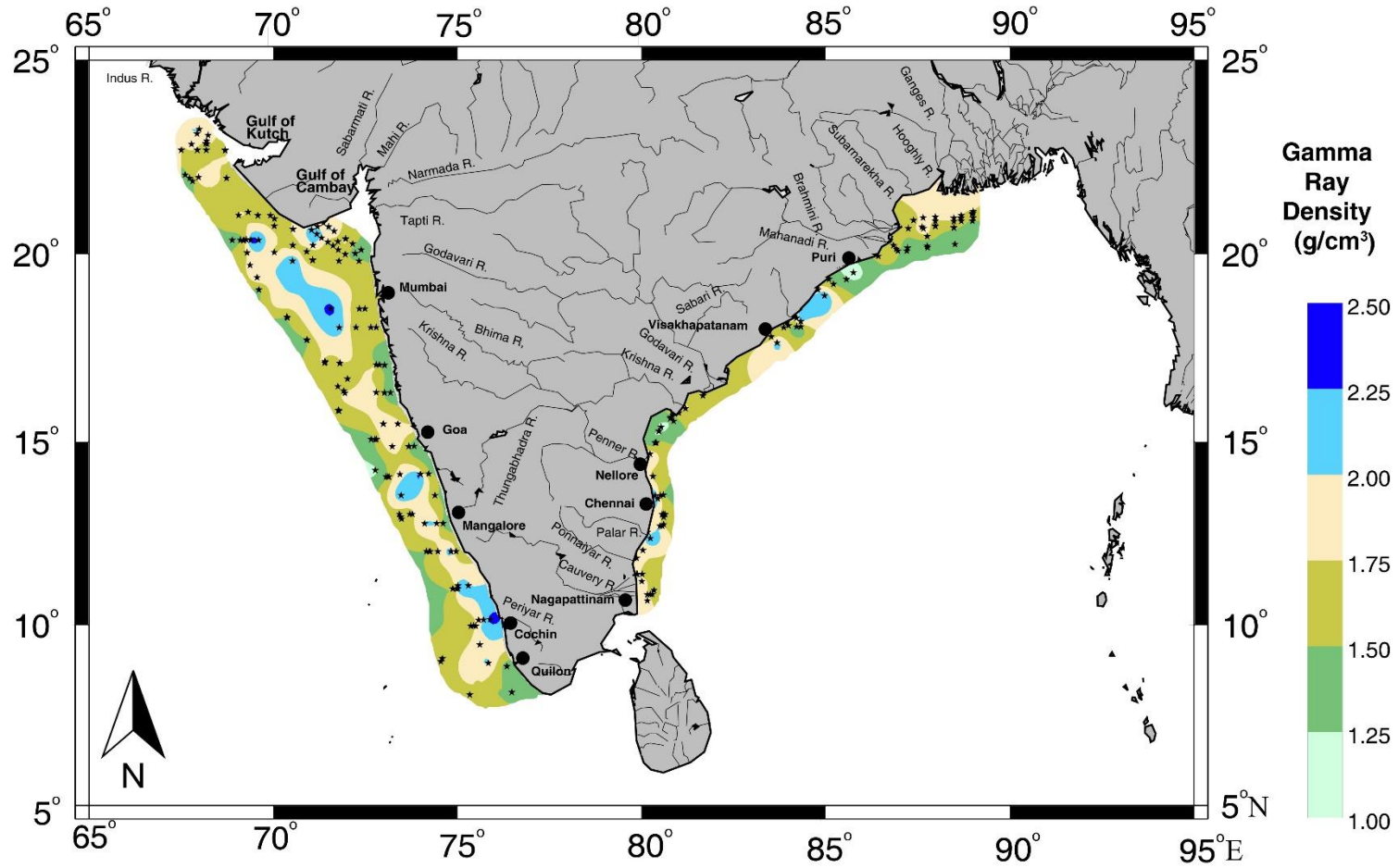


Figure 5

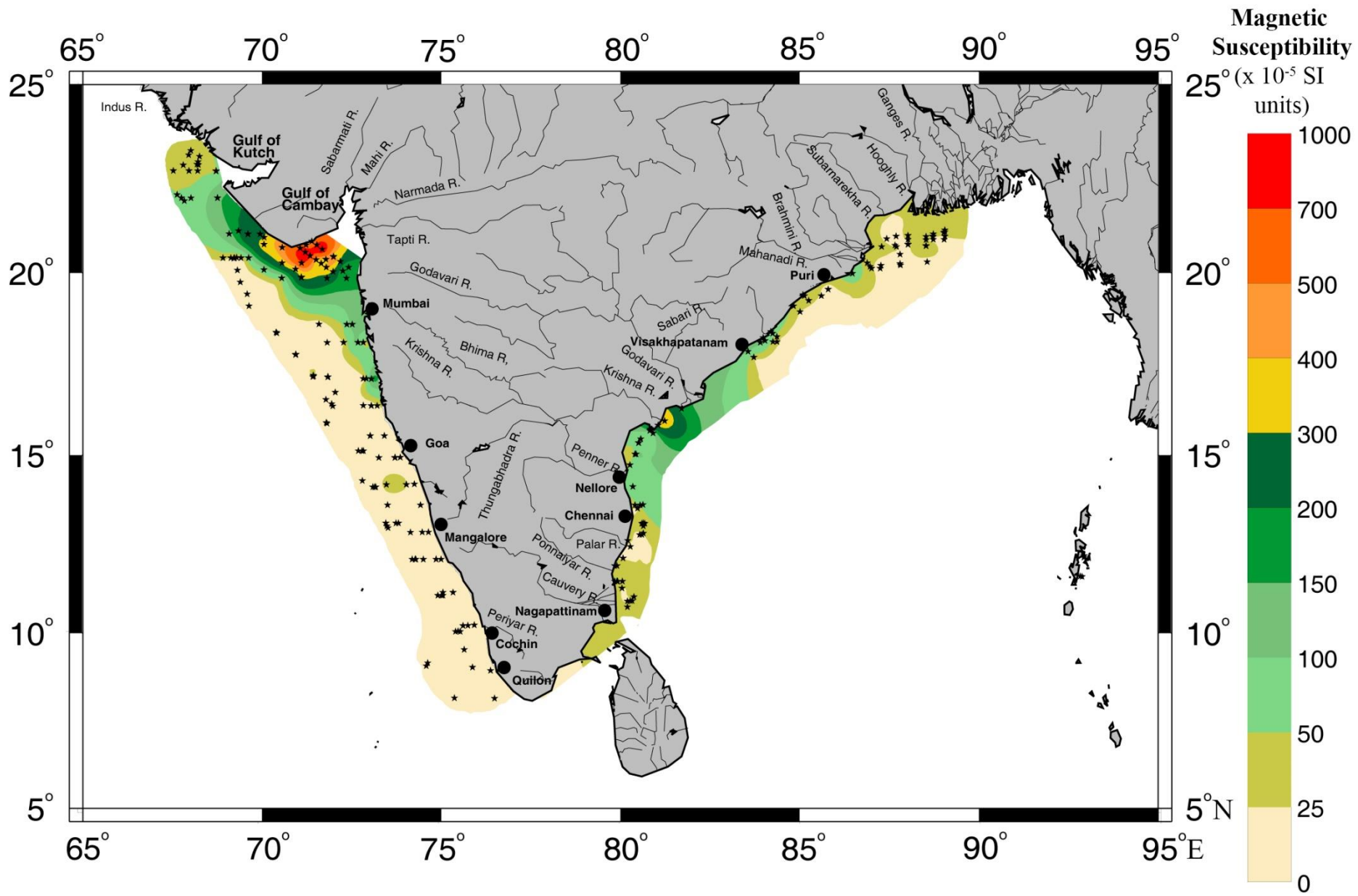


Figure 6

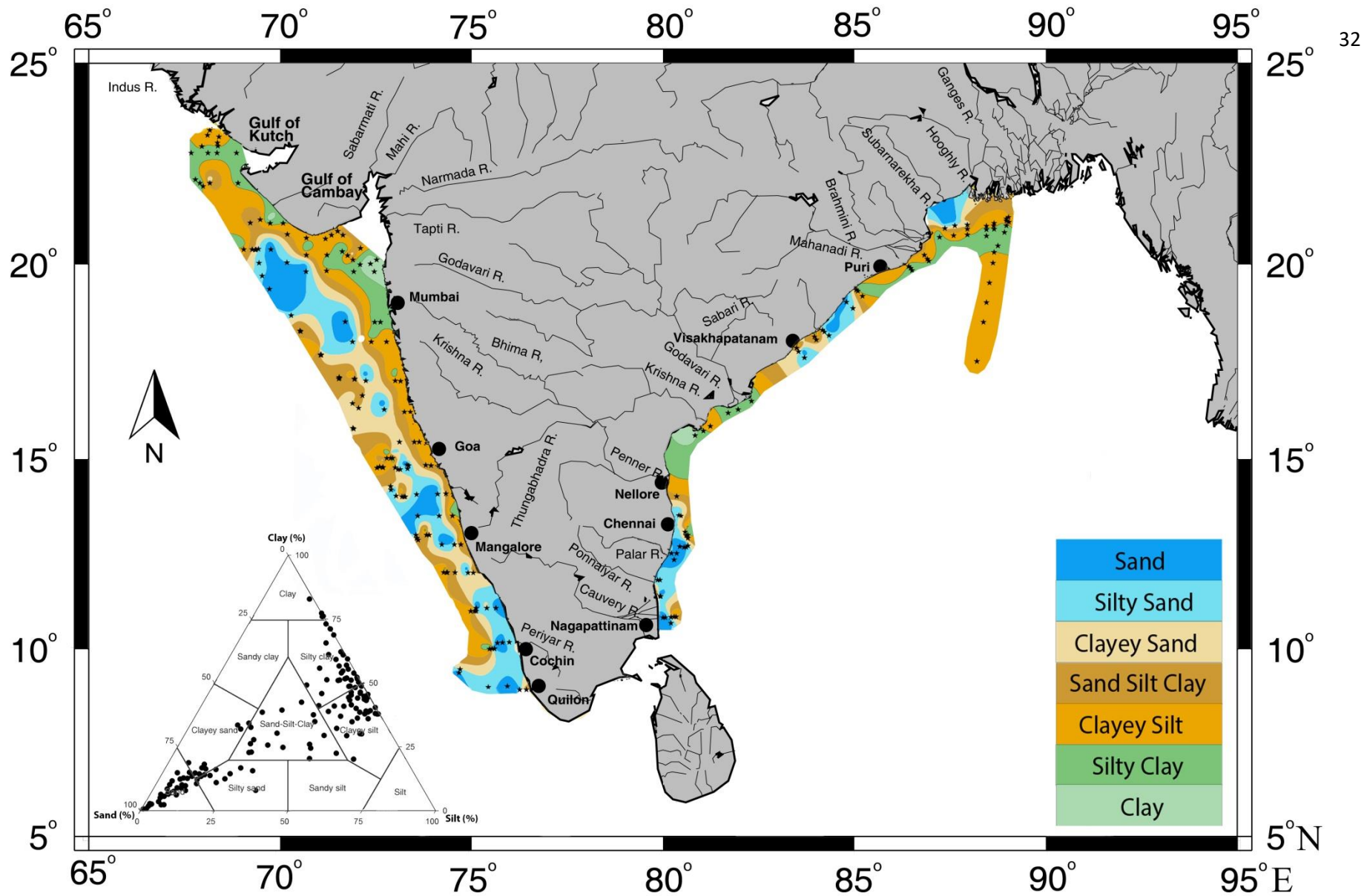


Figure 7

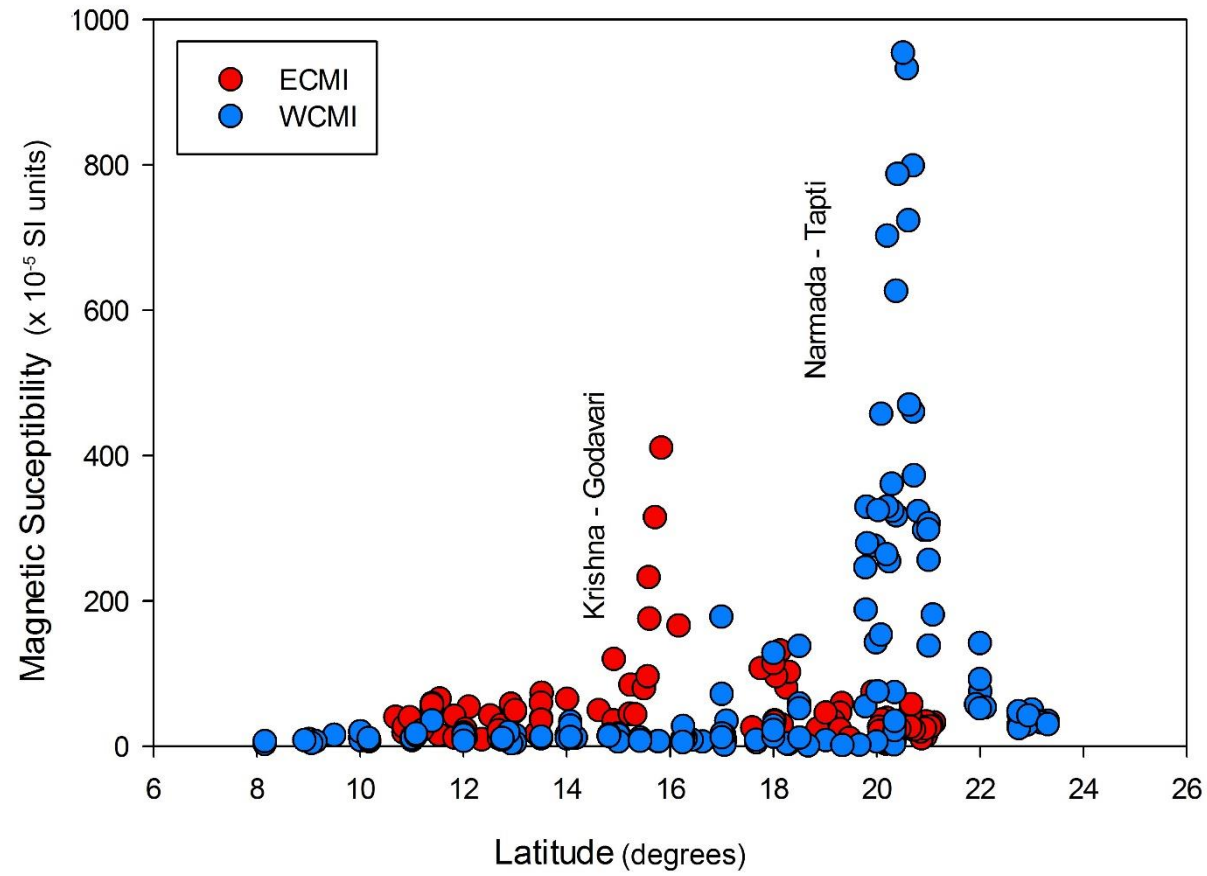


Figure 8

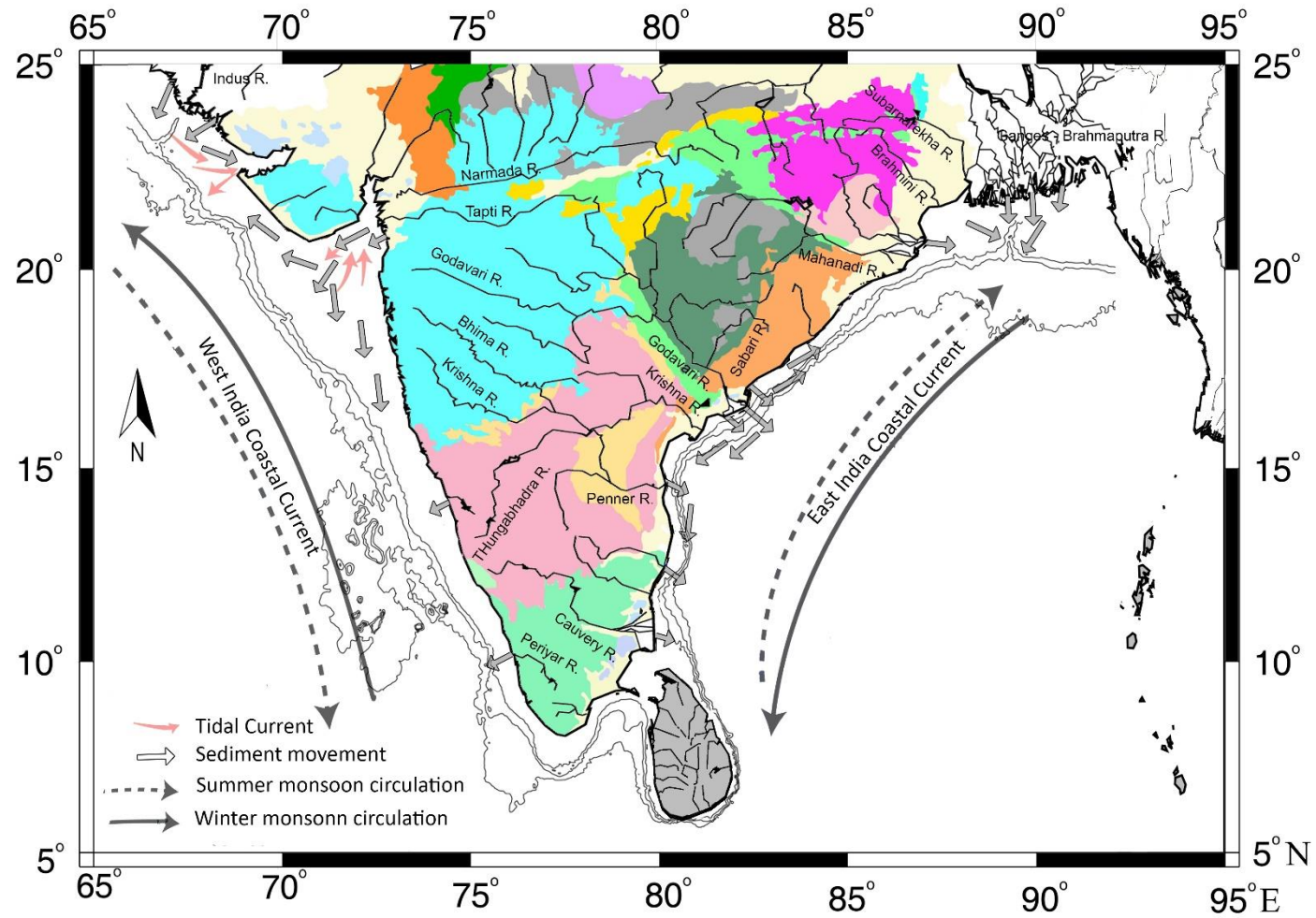


Figure 9