

Controls of contrasting provenance and fractionation on the sediment magnetic records from the Bay of Bengal

F.Badesab^{1*}, V.Gaikwad^{1,2}, B.Nagender Nath¹, M.Venkateshwarlu³, P.V.Aiswarya¹, A.Tyagi¹, K.Salunke¹, W. Fernandes¹, N. Kadam^{1,2}, S. J. Sangode⁴, A. Sardar¹, G. Prabhu¹

¹CSIR- National Institute of Oceanography, Dona Paula, Goa, 403004, India

²School of Earth Ocean and Atmospheric Sciences, Goa University, 403206, Goa, India

³CSIR–National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India

⁴Department of Geology, Savitribai Phule Pune University, Pune, Maharashtra, India

*Corresponding Author: Dr. Firoz Badesab (firoz@nio.org)

Abstract

We present the results of rock magnetic, granulometric, microscopy and mineralogical analyses of shelf sediments off Krishna, Godavari, and Mahanadi Rivers, Bay of Bengal. The aim of the study was to assess the influence of contrasting lithologies and hydrodynamic controlled grain size fractionation processes on the magnetic properties of shelf sediments. Sediment magnetic mineralogy mainly consist of ferrimagnetic titanomagnetite grains of detrital origin with variable concentrations and grain sizes. A clear trend of alongshore (SE - NW directed) decrease in magnetite concentration followed by fining of magnetic grain size can be attributed to the enhanced change in magnetic contribution from Deccan basaltic (mafic) to granitic (felsic) gneissic dominated sediment province coupled with differential sediment fluxes at each site. Bivariate plot of magnetic and grain size parameters clearly records such shift in sediment provenance and differential transport mechanism of magnetic particles at the studied sites. Magnetogranulometric ratio (ARM/IRM) positively correlates with the magnetite content in majority of the studied samples. Higher magnetic susceptibilities were found associated with coarser magnetic particles. Granulometry of the magnetic fraction showed that magnetic grain size is independent of physical grain size above > 40 μm . The non-monotonous relationship between the magnetic and physical grain size can be explained by the fact that few individual finer particles occurred as magnetic inclusions protected within host (coarser silt and sand) fractions. Rockmagnetic and granulometry based approach presented in this study bears high potential for efficient tracking of sediment provenance and fractionation mechanism of magnetic particles in the shelf system, where contrasting sediment sources and complex transport dynamics create a large variability in magnetite content and grain size.

Keywords: Rock Magnetism, Shelf Sediments, Magnetic Mineralogy, Magnetogranulometry, Krishna-Godavari-Mahanadi Basin.

Key Highlights:

- Variations in concentration and grain size of titanomagnetite between basins is mainly linked with the shift in provenance (mafic – felsic) and differential sediment fluxes.
- Sediment magnetism is mainly carried by detrital magnetic particles occurring as discrete as well as inclusions in silicate grains.
- Magnetogranulometry approach can efficiently track the effect of provenance and grain-size based fractionation on the bulk sediment magnetic signal.

1. Introduction

Magnetic minerals are widespread and potential recorders of geological processes including provenance, weathering/erosion, climatic conditions, depositional processes and diagenetic changes in marine sedimentary environment (Oldfield et al., 1985; Thompson and Oldfield, 1986). Mixing, sorting, and transport of magnetic particles in littoral and shelf environment, are greatly controlled by the composition and amount of transported material, river inflow, tide-wave interactions, and regional hydrodynamics (Liu et al., 2003; Gallaway et al., 2012; Hatfield, 2014). Hence the magnetic minerals have been increasingly used as a potential marker to track sediment provenance and transport pathways (Oldfield et al., 1985; Evans and Heller, 2003; Booth et al., 2005; Maher et al., 2009; Hatfield and Maher, 2009; Sebastian et al., 2019a), paleoenvironment reconstruction (Geiss and Banerjee, 1997; Colin et al., 1998; Evans and Heller, 2003; Rao et al., 2010; Kessarkar et al., 2013; Kissel et al., 2016), weathering and erosional processes in the source regions (Oldfield, 1991; Sebastian et al., 2019b), heavy metal pollution (Foster et al., 1991), diagenesis (Dewangan et al., 2013; Roberts, 2015; Badesab et al., 2019; Amiel et al., 2020), and also in assessing hydrothermal alteration (Nath et al., 2008).

The eastern continental margin of India (ECMI) receives a large amount of magnetite-rich sediment load from the Himalayan and Peninsular region through the major river systems including Ganga, Brahmaputra, Mahanadi, Godavari, Krishna and Cauvery. Contrasting lithology including heterogeneity of sub-catchment geologies and time-varying monsoonal conditions in the Indian peninsular provides high compositional diversity in magnetic mineral assemblages which gets well-recorded in the sediments deposited along the continental margins (Ramesh and Subramanian, 1988; Sangode et al., 2001, 2007). Previous studies documented the control of provenance and paleoceanographic changes on the sedimentation off Krishna, Godavari and Mahanadi (K-G-M) basins. For instance, Sr-Nd isotope, elemental, and clay mineralogical investigations on the sediment cores off K-G-M basin revealed that the compositional heterogeneity between K-G-M basin sediments is mainly constrained by differential sediment contributions from Deccan Basalts (DcB) and Archean- Proterozoic Gneissic Complexes (APGC) due to variable weathering and erosional regime in response to changing monsoonal patterns (Sangode et al., 2001, 2007; Kulkarni et al., 2014, 2015; Mazumdar et al., 2015; Peketi et al., 2020). Based on the regional distribution map of magnetic susceptibility, density and grain size of surface sediments, Sebastian et al. (2019a) successfully delineated the provenance, distribution and transport pathways of the magnetic particles along the ECMI. They reported that magnetic susceptibility variations in surface sediments off K-G and Mahanadi basin were mainly sourced from weathering of DcB and APGC and its subsequent

transportation by K-G-M river systems respectively. Rock magnetic study on topmost sediments of spatially distributed seventy three gravity cores off K-G basin by Usapkar et al. (2014) established the linkage between variability in magnetic parameters and differential sediment sorting mechanisms in slope basin and channel system. However, a dedicated magnetic study evaluating the control of provenance and sedimentary processes on the magnetic properties of shelf sediments along ECMI was still lacking.

Bulk sediment magnetic signal mainly reflects the total average contribution exhibited by the different clastic size fractions representing range of lithologies. Sediment magnetism has shown a strong particle size dependence (Oldfield and Yu, 1994; Hatfield and Maher, 2008, 2009; Hatfield et al., 2017). Composition of magnetic minerals in the shelf sediments is highly controlled by multiple grain-size sorting processes throughout source-to-sink transport and can mislead the provenance tracking studies which solely rely on interpretation of bulk sediment magnetic signals (Komar, 2007; Hatfield, 2014). Continental shelf sediments off Krishna, Godavari and Mahanadi rivers originate from various terrestrial sources and each carry a specific magnetic signature. Geological setting dominated by igneous, metamorphic and sedimentary rocks in the hinterland and well-developed K-G-M river systems assures high supply of magnetic minerals from these terrains to the ECMI. Three sediment (gravity) cores (SSK-50/GC-10, SSK-35/GC-18, SSK-35/GC-04) retrieved from the shelf off Krishna, Godavari and Mahanadi rivers preserve an excellent record and are well-suited for studying source-sink related processes. For the first time, rock magnetic, magnetogranulometry, grain size, and mineralogy of the shelf sediments represented by geologically distinct sediment provinces and hydrodynamic conditions off K-G-M Rivers are being jointly investigated. The present study sets out to address two key questions:

- (a) How efficiently can magnetic fingerprinting technique elucidate the provenance of the magnetic minerals and their contributions derived from relatively large and lithologically complex sub-catchments experiencing changing monsoonal patterns?
- (b) How do magnetogranulometry estimates evaluate provenance vs fractionation effects on the bulk sediment magnetism?

2. Study area, catchment geology and river systems

The Krishna-Godavari basin (K-G basin) is a proven petroliferous basin situated in the central part of the eastern continental margin of India (ECMI) (Fig. 1). The basin covers an area of about 28,000 km² onshore and 145,000 km² offshore (Rao, 2001). A sediment thickness of 3 –5 km in the onshore and about 8 km in the offshore region has been reported (Prabhakar and Zutshi, 1993;

Bastia, 2007). The sediments of ECMI are mainly derived from Himalayan and Peninsular Indian sources. Indian south-west (SW) and northeast (NE) monsoons controls the weathering and erosional processes in the drainage basinal areas of K-G-M river systems (Biksham and Subramanian, 1980; Kulkarni et al., 2015; Bejugam and Nayak, 2017). The Krishna and Godavari are the major rivers which drain through Late Cretaceous DcB and APGC and deliver the sediments to the K-G basin. The Krishna River originates in the Western Ghats and delivers the sediments to the K-G basin. The total catchment area of the Krishna River covers about 258,948 km² and the annual sediment load is 67.72 x 10⁶ ton yr⁻¹ (Ramesh and Subramanian, 1988). The lithology of drainage area comprised of Tertiary Deccan traps (basalt), late Archaean and early Proterozoic crystalline rocks, and recent sediments. The catchment area of Godavari River covers an area of 313,147 km². The lithology of the drainage basin is dominated by Deccan trap basalts, late Archaean/early Proterozoic granites, recent alluvial cover and Precambrian and Gondwana sedimentary rocks (Biksham and Subramanian, 1988; Mukhopadhyay et al., 2010).

Mahanadi basin is a passive pericratonic rift and a potential petroliferous basin located along the ECMI. The basin covers an area of about 260,000 km² and the geology of the basin is mainly dominated by Precambrian rocks of the Eastern Ghats consisting of khondalites, chnockites, leptynites, granites gneisses, rocks associated with the Gondwana supercontinent such as limestone, shales and sandstones and recent littoral deposits (Chakrapani and Subramanian, 1993a,b; Singh, 2008). Majority of the detrital material is delivered by the Mahanadi River and its tributaries including Shaonath, Jonk, Harado, Mand, Ib, Tel and Ong. Mahanadi river drainage basin covers an area of about 1.42 x 10⁵ km² (Rao, 1975). The catchment geology comprised of Late Archaean and early Proterozoic granite batholiths, tonalite-trondjhemite gneisses (TTGs), and chnockites and khondalites of the Eastern Ghats of the catchment area. Sedimentary rocks (limestone, shale and sandstone) of Gondwana age and recent alluvium/littoral deposits constitute the catchment area (Mukhopadhyay et al., 2010; Meert et al., 2010).

3. Materials and methods

3.1. Sediment sampling

Three gravity cores retrieved off the shelf Krishna (SSK-35/GC-18), Godavari (SSK-50/GC-10) and Mahanadi (SSK-35/GC-04) rivers were sub-sampled at an interval of 1 cm (Fig. 1). More details regarding the location, water depth, recovered length of sediments cores are provided in Table. 01. For magnetic analyses, six hundred and thirty seven sub-samples were dried, weighed, and packed in a 25-mm cylindrical plastic sample bottles. Magnetic susceptibility and remanence

measurements were carried out at the paleomagnetic laboratory of CSIR-National Institute of Oceanography (CSIR-NIO), Goa, India. Specialized rock magnetic measurements including thermomagnetic and hysteresis loop were conducted at the Paleomagnetic Laboratory of CSIR-National Geophysical Research Institute (NGRI), Hyderabad, India.

3.2. Rock magnetic measurements

Low field magnetic susceptibility (χ) measurements were carried out using a Bartington Instruments MS2B dual frequency susceptibility meter. The susceptibility was measured at two different frequencies $\chi_{lf} = 0.47$ kHz and $\chi_{hf} = 4.7$ kHz. Anhysteretic remanent magnetization (ARM) was applied using a 100-mT alternating field (AF) field with a superimposed fixed direct current (DC) bias field of 50 μ T on a Molspin alternating field demagnetizer with pARM attachment. The remanence was measured using an AGICO JR-6A automatic spinner magnetometer. An isothermal remanent magnetization (IRM) was applied in an inducing field of +1 T in the forward direction and was demagnetized by DC backfields at -20 mT, -30 mT, -100 mT, and -300 mT using a MPM10 pulse magnetizer. The corresponding remanences were measured using AGICO JR-6A automatic spinner magnetometer. As the bulk magnetic mineralogy of sediments is dominated by ferrimagnetic minerals (Dewangan et al. 2013; Badesab et al. 2017), we have therefore considered the mass-normalized IRM acquired at a peak field of +1T as the saturation isothermal remanent magnetization (SIRM). S-ratio is calculated following the Bloemendal et al. (1992) formulae: $S_{-0.3T} = (IRM_{-300mT}/IRM_{1T})$. Temperature-dependent magnetization curves and the hysteresis loop analyses were carried out using Advanced Variable Field Translation Balance (AVFTB). Magnetite concentration refers to magnetite content within bulk sediment sample. The sediment magnetite content was derived by dividing bulk magnetic mass susceptibility (χ) by the mineral-specific value for pure multidomain magnetite $\chi_{Mag} \sim 660 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$ given by Maher (1988).

3.3. Wet-sieving and magnetic granulometry

A suite of fifteen bulk samples representing the sediment intervals with high and low magnetite content as well as fine and coarse grained magnetic particles in these three sediment cores were selected for wet-sieving. Five representative bulk sediment samples from each sediment core were used for granulometric analyses. Bulk sediment samples of about 15 g were dried, weighed, and wet-sieved for 20 min with an automated sieve shaker (Fritsch Analysette) creating five sieved fractions including $> 63 \mu\text{m}$, $40\text{--}63 \mu\text{m}$, $20\text{--}40 \mu\text{m}$. The fractions $4\text{--}20 \mu\text{m}$ and $< 4 \mu\text{m}$ were created by separately sieving the residual sediments $< 20 \mu\text{m}$ using the $4 \mu\text{m}$ sieve. Each fraction was dried,

weighed, and packed in the 25-mm cylindrical plastic sample bottles and further analyzed for rock magnetic measurements.

3.4. Extraction of magnetic particles, scanning electron microscope (SEM-EDS), and x-ray diffraction (XRD) analyses

The magnetic particles were extracted from the bulk sediment following the procedure of Petersen et al. (1986). Images of the magnetic particles were captured using a scanning electron microscope (JEOL JSM-5800 LV) in a secondary electron (SE) imaging mode (Energy levels: 5 and 20 keV). Energy dispersive X-ray spectroscopy (EDS) probe attached to the microscope was used to determine the elemental composition. Optical microscopy on separated $> 63\mu\text{m}$ fraction was conducted on OLYMPUS (BX41). Magnetic mineralogy in bulk sediment samples representing different depth intervals of three cores was identified using a Rigaku X-Ray Diffractometer (Ultima IV). The samples were run from 20° to 65° 2θ at $1^\circ/\text{min}$ scan speed using Cu $K\alpha$ radiation ($\lambda = 1.5414 \text{ \AA}$). Magnetic minerals were identified from the XRD data following the Crystallography open database (COD). The software used for processing was Match-Phase analysis using powder diffraction (<http://www.crystalimpact.com/match/>).

4. Results

4.1. Down-core variations in rock magnetic properties of bulk sediments in cores from shelf off Krishna, Godavari and Mahanadi rivers

Magnetic susceptibility (χ_{lf}) and SIRM are sensitive to concentration of magnetic minerals (Thompson and Oldfield, 1986). A systematic SE-NW trend of alongshore decrease in magnetite content in shelf off Krishna to shelf off Mahanadi river mouth is seen (Fig. 2). Highest magnetite concentrations were found in shelf off Krishna and lowest off Mahanadi River. Downcore changes in the rock magnetic properties of sediment cores from shelf off Krishna (Fig. 3a-3e), off Godavari (Fig. 3f-3j), and off Mahanadi river (Fig. 3k-3o) are displayed. In general, χ_{lf} profile of core off Krishna River showed a cyclic pattern and exhibit large variability in the concentration of magnetic particles (Fig. 3a). Magnetite content in this core ranges between 1.84 – 6.43 % (Table.1). Four distinct sediment intervals (K1– K4) of elevated χ_{lf} and SIRM values at 39 cmbsf, 91 cmbsf, 138 cmbsf, and 164 cmbsf reflect the periods of increase in deposition of detrital magnetic particles (Fig. 3a,c). Magnetic grain size proxy (ARM/SIRM) showed good correlation with the χ_{lf} . Higher χ_{lf} in K1-K4 intervals are found to be associated with coarse-grained magnetite particles as seen through low ARM/SIRM values (Fig. 3a,d). Magnetic mineralogy diagnostic (S-ratio) proxy parameter

showed less variation and varies between 0.91 – 0.99 suggesting the predominance of ferrimagnetic minerals in this core (Fig. 3e).

Rock magnetic profile of Godavari core mimics the trend (in terms of χ_{lf}) observed in Krishna core, but with different concentrations (Fig. 3a,f; Table. 01). A cyclic variation in χ_{lf} is noticed in sediment cores in shelf off Krishna and Godavari river (Fig. 3a,f). High χ_{lf} peaks (G1 – G11) were found to be associated with coarse-grained magnetite particles as evident through low ARM/SIRM values and vice-versa (Fig. 3f,i). Two distinct intervals of low S-ratio between 50 – 61cbsf and 213 – 223 cbsf reflect either the periods of increased input of high coercivity magnetic minerals or intense diagenesis (Fig. 3j; Nowaczyk, 2011; Rodelli et al., 2019). In sediment core off Mahanadi, a gradual down-core decline in magnetite concentration is seen (Fig. 3k). Four peaks (M1 – M4) showed higher values of χ_{lf} and the remanence is carried by coarse-grained magnetite particles (Fig. 3k,n). A distinct shift in ARM/SIRM values is noticed at 113 cbsf (Fig. 3n). In the upper most sediment interval (0 – 110 cbsf), a gradual downcore increase in ARM/SIRM suggests the dominance of fine-grained magnetic particles (Fig. 3n). Relatively lower and consistent values of ARM/SIRM below 113 cbsf followed by downcore decrease in χ_{lf} suggest the loss of fine-grained magnetic fraction and a subsequent increase in magnetically weak coarse-grained magnetic particles (Fig. 3k,n). S-ratio varies between 0.86– 0.94 and is indicative of predominance of ferrimagnetic particles in this core (Fig. 3o).

4.2. Thermomagnetic curves and Day Plot

The thermomagnetic curves of all fifteen measured samples show very similar pattern (Fig. 4). The susceptibility values gradually decrease above 500°C, with sharp reduction between 533°C and 550°C indicates the presence of magnetite and titanomagnetite in the samples (Fig. 4a-4c; Dunlop and Özdemir, 1997). Day plot show variability in magnetic grain sizes (Fig. 4d). Sediments off Krishna and Godavari rivers possessed relatively higher values of M_{rs}/M_s compared to Mahanadi sediments (Fig. 4d; Day et al., 1977)

4.3. SEM-EDS and Mineralogical observations

We analyzed the representative magnetic particles separated from the bulk sediments that exhibited contrasting magnetic properties. Detrital titanomagnetites of various size and shapes are present in almost all sediment cores (Fig. 5, Fig. 6, Fig. 7). Magnetically high and low sediment intervals in core off Krishna river comprised of both fine and coarse-grained magnetic particles (Fig. 5a-5p). Diagenetically formed fine-grained iron sulfides were noticed at 30 cbsf in the sediment core off Krishna River. These intervals is also marked by low χ_{lf} and SIRM (Fig. 3a,c and Fig. 5f). In

sediment core off Godavari and Mahanadi rivers, abundant titanomagnetite grains of various size and shape were noticed (Fig. 6a-6m and Fig. 7a-7n). A well-developed pyrite framboid of diagenetic origin was noticed in the low χ_{lf} bearing sediment interval (161 cmbsf; Fig. 3f and 6j) in this core. Titanohematite is noticed in sediment interval (224 cmbsf; Fig. 6l) which is marked by low S-ratio (Fig. 3j). Some of the titanomagnetite grains show abrasion features, whereas others have sharp edges.

XRD curves of magnetic minerals from different sediment intervals of cores from three areas are shown in Fig. 8 and Figs. S1 – S3. XRD analyses reveal that titanomagnetite is the predominant ferrimagnetic mineral in the studied sediments in terms of its contribution towards the bulk sediment magnetic properties.

4.4. Relationship between rock magnetic and sediment grain size

A good relationship ($R^2 = 0.98$) between χ_{lf} and SIRM is observed in all analyzed cores, but with different gradients (Fig. 9a). Large variations in magnetite content and magnetic grain size were found. Samples from sediment cores off Krishna (avg $\chi_{lf} = 20.9947 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$) and Godavari (avg $\chi_{lf} = 17.4146 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$) rivers showed relatively higher values of χ_{lf} and SIRM in contrast with Mahanadi (avg $\chi_{lf} = 4.5125 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$) samples with distinctly lower values (Fig. 9a). A strong covariation between χ_{lf} and ARM/SIRM is seen more specifically in Krishna and Godavari sediment samples (Fig. 9b). Higher values of χ_{lf} are associated with coarse-grained magnetic particles and vice-versa. Comparatively, Mahanadi samples are dominated by low-concentration of fine-grained magnetic particles and showed less fluctuation in terms of magnetite concentration as seen through distinct grouping (Fig. 9b). In terms of magnetic mineralogy, Krishna and Godavari samples showed large variations in S-ratio (0.82 - 0.99) suggesting the presence of mixed-type magnetic (low and high coercive) mineral assemblages (Fig. 9c). The concentration (χ , SIRM, ARM), grain size (ARM/SIRM), and mineralogy (S-ratio) related magnetic parameters shows good covariation with the sand and clay fraction (Fig. 9d-i).

4.5. Magnetic Granulometry

Magnetic measurements on sieved fractions provided a robust understanding of fractionation and depositional processes compared to bulk sample measurements. The sediment magnetite content was derived from the bulk magnetic mass susceptibility (χ) following Maher (1988). Hence, the magnetic susceptibility is used as a proxy for magnetite concentration. Average magnetic susceptibility showed spatial variations in all clastic grain size fractions (Fig. 10). In general, magnetite concentration decreases with increasing particle size with highest values in clay ($< 4 \mu\text{m}$)

and fine silt (4 – 20 μm) fraction (Fig. 11). Elevated χ_{f} values in the clay and silt size fraction of Krishna and Godavari samples is consistent with previous findings of Badesab et al. (2017; 2019) which reported the dominance of silt and clay size magnetic particles in the bulk sediments from the K-G basin. These observations suggest that ferrimagnetic minerals preferentially reside in the silt and clay size fractions.

Relative contribution of each magnetic particle size fraction towards the bulk sediment magnetism (concentration, grain size) in Krishna, Godavari and Mahanadi samples are presented in Fig. 10. Magnetic susceptibility of the sieved fractions vary strongly and systematically with grain size (Fig. 11a). Higher magnetite content in clay and fine (FS) silt suggests that discrete magnetite particles are mainly contained within < 4 μm – 20 μm range (Fig. 11a). Mahanadi samples showed broad range in distribution of magnetic particles within clastic grain size fractions (i.e., clay, fine and coarse silt) (Fig. 11e). Magnetogranulometric proxy (ARM/SIRM) showed good variation with clastic grain size especially in Godavari and Mahanadi samples (Fig. 11d, f). The magnetic grain size decreases systematically with clastic grain size from 4 μm to 40 μm . We noticed that this relationship reverses above 40 μm wherein finer magnetite particles are found in coarser silt and sand fractions (Fig. 11d, f). This could be due to the occurrence of finer particles as magnetic inclusions within silicate grains (Hounslow and Maher, 1996). These observations suggest that 40 μm represent the size limit beyond which usage of magnetogranulometric ratio as a magnetic grain size proxy is constrained. Similarly, the 63 μm appears to be upper size limit in Krishna samples (Fig. 11b).

5. Discussion

5.1. Origin of magnetic minerals and plausible controls on its distribution and dispersal along ECMI.

In general, rock magnetic, SEM-EDS and XRD data revealed that titanomagnetite is the dominant ferrimagnetic mineral in the sediments in terms of contribution to the bulk magnetic properties (Fig. 2, Fig. 3, Fig. 4, Fig. 5-7, Fig. 8, and Fig. S1-S3). Rock magnetic records of the sediment cores from the shelf off Krishna, Godavari and Mahanadi display considerable variation mainly in terms of magnetite content and grain size (Fig. 2, Fig. 3, and Fig. 4d) which can be mainly attributed to the changing sediment provenance constrained by the contrasting lithology and climatic variations. The Krishna and Godavari rivers supply abundant of magnetite-rich sediment load to the basin which are primarily derived from late Cretaceous Deccan basalt (DcB) and late Archean-early Proterozoic peninsular gneissic complexes (APGC) (Sangode et al., 2001, 2007). In contrast, felsic rocks belonging to the late Archean-early Proterozoic peninsular gneissic complexes are the primary

source and deliver relatively weakly-concentrated magnetic particles to the nearshore and shelf region off Mahanadi River (Ramesh and Subramanian, 1988; Chakrapani and Subramanian, 1990; Sangode et al., 2001; Mukhopadhyay et al., 2010; Kulkarni et al., 2015; Mazumdar et al., 2015). Magnetite concentration in Krishna and Godavari sediments are relatively higher and varies between 0.68 – 6.43 wt% compared to Mahanadi sediments which constitute 0.29 – 1.43 wt % to the bulk magnetic susceptibility values (Table.1). Recent studies based on Sr-Nd isotopes, elemental and clay mineralogical data of sediment cores off Krishna, Godavari and Mahanadi (K-G-M) basins have shown the compositional differences between basinal sediments and are found to be largely controlled by the variability in the relative sediment contributions sourced from DcB and APGC (Mazumdar et al., 2015; Peketi et al., 2020). For example, elevated illite and lower Ti content derived from felsic rocks belonging to APGC were reported in the sediment cores off Mahanadi basin, while high smectite and Ti content is predominant in the Krishna and Godavari basin sediments (Mazumdar et al., 2015; Bejugam and Nayak, 2017; Prajith et al., 2018). Compositional differences in clay mineralogy in the offshore Mahanadi and K-G basins were also observed in surface sediments (Rao et al. 1988; Kolla and Rao, 1990). More recently, a dedicated mineralogy based study by Philips et al. (2014) on the long drilled sediment cores also reported the differences in clay and bulk mineralogy between the K-G and Mahanadi basins. Magnetomineralogical diagnostic ($\chi - T$) data coupled with SEM-EDS and XRD results confirmed the dominance of Fe-Ti bearing minerals in all three cores (Fig. 4, Fig. 5-7, Fig. 8, Fig. S1- S3). A clear trend of SE - NW (K – G – M) decrease in magnetite concentration accompanied by the fining of magnetic grain size can be attributed to enhanced change in magnetic mineral contribution from Deccan basalt to granitic gneissic dominated sediment province (Fig. 2, Fig. 3, Fig. 9a, b, and Table. 1).

Bivariate magnetic plots (Fig. 9a-c) showed clear distinction between Krishna, Godavari and Mahanadi sediments which can be very well linked with heterogeneity of the sub-catchment geology and changing riverine (river length, run off, gradients, annual flow, sediment load; Panda et al., 2011) conditions which seems to have generated compositional diversity in the studied sediments. Better grouping between Krishna and Godavari sediment in terms of their magnetite concentration and magnetic grain size reflects on the DcB provenance (Fig. 9a-c). Based on Sr-Nd isotopic record, Peketi et al. (2020) demonstrated that increased sediment contributions of DcB compared to granitic gneissic rocks was due to the higher susceptibility to weathering of basalts. Dominance of higher χ_{fr} associated with distinctly coarse-grained magnetic particles in the studied cores off Krishna and Godavari rivers support this interpretation (Fig. 2, Fig. 3, Fig. 4d, and Fig. 9b; Table. 1). Presence of magnetically weak fine-grained particles in the Mahanadi sediments can be directly attributed to

their granitic- gneissic provenance (Mazumdar et al., 2015). Intense monsoon precipitation coupled with heightened erosion of basalt and granitic gneissic rocks in peninsular region strongly contributed to the formation of sedimentary deposits along east coast of India (Peketi et al., 2020). It is interesting to note that sediment intervals showing peaks of increased susceptibility in sediment cores off Krishna (K1– K4), Godavari (G1– G11), and Mahanadi (M1– M4) basin corroborates well with the presence of coarser magnetic particles (as seen through lower ARM/SIRM values) (Fig. 3a,d,f,i,k,n). We hypothesize that these peaks of χ_{lf} magnetic susceptibility most likely corresponds to the time period of increased sedimentation events due to intensification of monsoon. Similar magnetite-rich bands formed as a result of high sedimentation events has been well-reported in continental slope sediments off K-G basin (Badesab et al., 2019; Joao et al., 2021). A plausible reason for the observed variations in magnetite concentration and grain size in shelf off Krishna and Godavari can be explained based on the possibility that stronger monsoon (Biksham and Subramanian, 1980; Bejugam and Nayak, 2017) in the hinterlands might have favoured the increased supply of Deccan sourced (more specifically coarse-grained magnetic particles) fluxes off Krishna and Godavari shelf compared to sediments off Mahanadi shelf which are predominantly derived from felsic sources.

Decline in vegetation cover, increase erosion in the source areas during periods of aridity could also increase the production and supply of highly coercive minerals (hematite, goethite) in the fluvial sediments (Hu et al., 2019; Phartiyal et al., 2003). Two distinct drops in S-ratio at 50 – 61 cmbsf and 213 – 223 cmbsf in the sediment core off Godavari shelf probably indicates the periods of increased input of high coercivity minerals relative to magnetite and represent the phases of intense arid condition in the source regions (Fig. 3j; Yang et al., 2016). The post-depositional processes including sediment diagenesis and authigenesis can also significantly alter the magnetic mineral assemblages (Karlin and Levi 1985; Dewangan et al. 2013; Roberts 2015). For instance, preferential diagenetic dissolution of ferrimagnetic minerals and preservation of higher coercivity minerals due to their higher resistance has been well-reported in marine sediments (Nowaczyk, 2011; Rodelli et al., 2019). It is quite possible that the low S-ratio intervals (Fig. 3j) in the sediment core off Godavari River might have been formed as a result of intense diagenesis which led to the dissolution of ferrimagnetic minerals. Consequently, the titanohematite grains in these intervals might have survived diagenesis because of its inherent property to resist the dissolution (Nowaczyk, 2011; Rodelli et al., 2019). The diagenetic factor is beyond the scope of present study. However a dedicated study in future involving geochemical proxies would provide vital insights into the diagenetic processes at these sites. In addition to provenance and hydrodynamics (fluvial, nearshore), several other factors including river

length, transport distance (i.e., distance between river mouth and core location) and catchment area can substantially affect the export of magnetic particles (derived from terrestrial sources) to the sea (Just et al., 2012). Several mineral magnetic studies made an attempt to evaluate the influence of these factors on the magnetic properties of the riverine, deltaic and nearshore sediments. For example, in estuarine and nearshore sediments off Bay of Plenty, New Zealand Badesab et al. (2017) reported a strong linkage between catchment area of each river system and magnetite concentrations and sediment grain size. Influence of varying sediment particle-size distribution supplied by different tributaries on the bulk magnetic properties of Red river and Delta sediments, Vietnam (Nguyen et al., 2016), and Pangani River Basin, Tanzania (Mzuza et al., 2017) has also been well-reported. In Mahanadi core samples, lack of covariation between average magnetite concentration and these parameters (Fig. 2) suggest that variability in the rock magnetic properties are predominantly due to change in sediment provenance (basaltic to granitic).

Magnetic grain size record showed that the sediment cores off Krishna and Godavari basin are dominated by mixture of fine and coarse grained magnetic particles (Fig. 3d, 3i, Fig. 4d). A close correlation between magnetite content and magnetic grain size is seen in Krishna and Godavari sediments, where higher susceptibility values are found to be associated within coarser magnetic particles and vice versa (Fig. 9b). We hypothesize that increased terrestrial (magnetite-rich) sediment export and homogeneity in source material generated such pattern. In contrast, Mahanadi sediments are mainly comprised of fine-grained magnetite in relatively low concentration (Fig. 3k,n, Fig. 4d, Fig. 9a-c). Two distinct trends in magnetic grain size variations are observed in the Mahanadi core (Fig. 3n). A systematic pattern of downcore fining of magnetic particles is seen upto 110 cmbsf, while slightly lower and consistent values of ARM/SIRM persist till the end of the core (Fig. 3n). The presence of fine and slightly coarse-grained magnetic particles are also well recorded as mixture in the Day plot (Fig. 4d). The modern trends in the sediment load of Krishna, Godavari, and Mahanadi Rivers are 9.0×10^6 t, 170×10^6 t, and 30.7×10^6 t respectively (Panda et al., 2011). We put forward following plausible reasons to explain the dominance of fine-grained (low concentrated) magnetite in the shelf sediments off Mahanadi river: (1) weaker fluvial export and hydrodynamic regime might have allowed the dispersal of sediment plume containing fine-grained sediments to the shelf, while coarser magnetic particles get preferentially retained within the catchment, estuarine or nearshore region. Bejugam et al. (2017) observed higher sand accumulation off Mahanadi river mouth and its concentration decrease with increasing water depth offshore. Increased sand content near Mahanadi river mouth was linked with the dominance of high energy environment prevailing closer to the coast. Alongshore decrease in sediment grain size from off Mahanadi River mouth to

off Pennar River mouth was attributed to NW-SE directed sediment transport along east coast of India (Bejugam et al., 2017). Furthermore, Chakrapani and Subramanian (1990) reported that nearly 80% of the annual sediment load of Mahanadi River is carried by the coarse-silt fraction. Magnetogranulometric data showed that higher magnetic susceptibilities were found in clay and coarse-silt size fractions (Fig. 11e). Hence, it is most likely that most of the coarse-grained magnetic particles supplied by Mahanadi river mostly remained confined to the nearshore region and predominantly gets transported alongshore from Mahanadi towards the mouth of Krishna and Godavari rivers due to SE directed littoral transport system, while finer (clay and coarse-silt size) magnetic particles gets frequently transported off Mahanadi river i.e., from nearshore to the shelf region, (2) distance between Mahanadi river mouth and core location is ~ 11.01 km as compared to Krishna (~ 12.85 km) and Godavari (~ 15 km) rivers (Fig. 2b). Due to proximity to the source area and shortest river length (Fig. 2a), we rather expected that sediment plume of the Mahanadi river would deliver abundant coarse and fine grained magnetite-rich load to nearshore and shelf region. This observation suggests that transport distance is not a vital factor, while dilution of fluvial (magnetite-rich) sediment by less magnetic fine-grained nearshore sediments off Mahanadi is also an important mechanism and cannot be ruled out. A multi-proxy record of sediment core off the Zambezi River, SE Africa (Just et al., 2014) revealed that climate induced sub-basin source area shift due to spatial varying rainfall intensities can strongly modify the composition of the sediments exported from different parts of the basin. Changing pattern and intensities of monsoon over peninsular India has been well-reported (Parthasarathy, 1984; Narkhedkar et al., 2015). Sr-Nd isotope and elemental data of the sediment cores retrieved off K-G basin provided record of change in sediment composition due to variability in monsoonal rainfall and contrasting lithologies (Peketi et al., 2020). It is highly likely that changes in rainfall intensities on a sub-basinal/catchment areas of Mahanadi River coupled with variable weathering conditions might be responsible for generating such fine-grained magnetic particles. Several studies established the linkage between increased chemical weathering and dominance of finer magnetic particles during wet and warmer climate, while dry and cold climate favoured the physical weathering of rocks resulting in the production of coarser magnetic particles (Colin et al., 1998; Kissel et al., 2003; Sebastian et al., 2019). The magnetic grain size record showed predominance of fine-grained magnetic particles (Fig. 3n). Based on the elemental and isotopic record of sediment core off K-G basin, Peketi et al. (2020) have shown that the contrasting rainfall distribution pattern and changing source rock compositions in peninsular India provides important constraints on the mineralogical and geochemical composition of the sediments deposited along the east coast of India. The dominance of fine-grained magnetic particles

in Mahanadi sediments may not be related to climate controlled chemical weathering and we provide following reasoning to explain this.

Magnetic susceptibility of Mahanadi sediments is relatively low compared to Krishna and Godavari samples and ferrimagnetic grains are mostly found to be enriched in clay fractions (Fig. 2, Fig. 10). Magnetogranulometric proxy (ARM/SIRM) showed good variation with clastic grain size in Mahanadi samples (Fig. 11d,f). The magnetic grain size decreases systematically with clastic grain size from 4 μm to 40 μm and this relationship reverses above 40 μm wherein finer magnetite particles are found in coarser silt and sand fractions (Fig. 11d,f). This suggests that magnetic grain size does not corroborate well with the physical grain size. More recently, Hatfield et al. (2017) conducted a detailed rock magnetic characterization on bulk sediments and sieved size fractions to discriminate the sources of ferrimagnetic minerals in Iceland and South Greenland terrestrial sediments. They attributed the presence of finer magnetic grain size to the rock formation processes. The coarser magnetic grains in Greenland sediments resulted from the granitic igneous intrusions that cooled down at low rates and for longer duration compared to the rapidly cooled basalt in the hinterland of Iceland. This process increased the production of fine and coarse magnetic particles in the bedrock. They further suggested that the mechanical weathering causes liberation of fine-grained clay and silt-size magnetic fractions from the parent rocks simultaneously. Catchment geology of Mahanadi basin is predominantly covered by Late Archaean and early Proterozoic granitic gneissic rocks (Mukhopadhyay et al., 2010; Meert et al., 2010). Magnetogranulometry data of Mahanadi samples revealed that fine-grained magnetite particles occur mainly in silt and clay size fractions (Fig. 10, and Fig. 11e). Similar to the mechanism reported by Hatfield et al. (2017), we hypothesize that analogous enhanced mechanical weathering of granitic gneiss rocks in the hinterlands covering Mahanadi basin might be a formative process which increased the liberation of fine-grained magnetite leaving them as discrete particles in the clay and silt-size fractions (Fig. 10).

5.2. Unravelling the provenance versus fractionation effects on the sediment magnetic record:

A magnetogranulometric approach

Complex hydrodynamic pattern on the continental shelves provides important constraints on the deposition and dispersal of magnetic particles (Wang et al., 2017). Hence, the influence of multiple fractionation processes from source-to-sink on the composition of the magnetic particles in the shelf sediments is of primary concern especially in provenance-related magnetic studies (Hatfield, 2014). Although, the studied sediment cores are retrieved off the river mouth, near-source fractionation is not a major issue as the present study does not directly compare the rock magnetic signatures of source rocks and sediments (Razik et al., 2015). Majority of bulk sediment samples from all three

sediment cores are dominated by ferrimagnetic (titanomagnetite) particles in varying concentration and grain size with ~ 90% of SIRM acquired in applied field below 300 mT which suggests that it originated from geological sources (Fig. 3, Fig. 4; Maher, 1998, Hatfield and Maher, 2008). Thermomagnetic curves (Fig. 4) and S-ratio (Fig. 3e,j,o) also suggest the predominance of detrital Fe-oxides minerals. In geological context, such unaltered sediment magnetic characteristics reflect mountainous origin and igneous source rock (DcB, APGC) lithology indicating primarily fluvial transport. SEM-EDS and XRD data further confirmed that detrital Fe-Ti rich magnetic particles in the studied cores are mainly derived from basaltic and granitic province (Fig. 5-7, Fig. 8, and Fig. S1- S3).

Magnetic particles of different size are the important component that drives the bulk sediment magnetic signal and reflect the characteristic catchment lithology and hydrodynamic conditions (Hatfield et al., 2014). We conducted magnetogranulometric analyses to examine the particle size dependency of magnetic properties which is important for improving the interpretation of the bulk sediment magnetic signals in Krishna, Godavari and Mahanadi sediments where contrasting sources and/or transport processes play a role. A general trend of systematic decrease in average magnetite concentration with increasing clastic grain size is noticed in all representative samples from sediments off Krishna, off Godavari and off Mahanadi rivers (Fig. 10). In Krishna and Godavari sediments, clay (< 4 μm) and fine silt (4 – 20 μm) fractions possessed higher magnetite concentration and contribute significantly to the bulk magnetic susceptibility (Fig. 11a, c). These could be due to strong non-coherence between changes in the proportion of fine grained silt and clay size magnetic particles and bulk magnetic signal. Comparatively, clay fraction showed highest magnetite enrichment in Mahanadi sediments (Fig. 11e). Such a heterogeneity in the distribution of magnetic particles between different grain size fractions is mainly due to varying contribution from multiple sources. Although the local sorting processes at river mouth can override the source-specific magnetic signal, magnetogranulometric data showed that sediment fractionation during transport and deposition had little impact on magnetic source characteristics.

Ferrimagnetic Fe-oxide particles in igneous, metamorphic, and volcanic rocks generally occur in different grain-sizes and are not larger than a few microns (Razik et al., 2015). Ferrimagnetic particles also occur as inclusions in silicate grains (Hatfield, 2014). Association of different size discrete and included magnetic grains with different sediment grain sizes potentially has important implications for the interpretation of source-to-sink related processes. A dedicated magnetic petrology study of equatorial Atlantic sediments by Franke et al. (2007) reported that the strong grain-size dependence of magnetic properties in marine sediments should not be expected as the

source specific magnetite grains size is least affected by the clastic grain size. Magneto-granulometry data of Godavari and Mahanadi samples showed that magnetic grain size is independent of physical grain size above $> 40 \mu\text{m}$ which could be mostly due to polycrystalline nature and explain the reason for occurrence of finer magnetic particles in the coarse silt and sand fraction as seen through high ARM/SIRM values (Fig. 11d,f Fig. 12; Hatfield et al., 2013). As already explained in section 5.1, non-monotonous relationship with $>40 \mu\text{m}$ is due to the fact that few individual magnetic particles might be occurring as inclusions within silicate grains (Hounslow and Maher, 1996). Several studies have demonstrated that magnetic inclusions within polycrystalline lithoclasts can decouple the magnetic grain size from physical grain size and can strongly affect the bulk sediment magnetic signal (Hounslow and Maher, 2009; Chang et al., 2016; Hatfield et al., 2013, 2017; Badesab et al., 2017). For example, the magnetic properties of sediments draining through contrasting lithologies (basaltic and granitic) will vary strongly with source and sediment grain size. As already highlighted, high χ_{lf} associated with finer magnetic particles in coarse silt and sand fractions in Krishna, Godavari and Mahanadi samples can be directly attributed to the presence of ferrimagnetic particles occurring as inclusion within non-magnetic silicate (host) grains (Fig. 10, Fig. 11a,c,e and Fig. 12; Hounslow and Maher, 1996), fine magnetite inclusions within larger polycrystalline clasts as observed in the Icelandic silt and sand fractions (Hatfield et.al., 2017), and inner shelf sediments off Burdekin River, NE Australia (Maher et al., 2009).

6. Conclusions

Combined rock magnetic, granulometric, microscopic and mineralogical investigations helped to evaluate the effect of provenance change and sedimentary processes on the magnetic properties of shelf sediments off Krishna, off Godavari, off Mahanadi Rivers in the Bay of Bengal. The findings are summarized below:

(1) Sediment magnetic mineralogy is dominated by titanomagnetite, which is the major magnetic mineral of detrital origin occurring in variable concentrations and grain sizes in addition to a minor amount of diagenetically formed pyrite. A clear trend of SE - NW directed decrease in magnetite concentration followed by fining of magnetic grain size is mainly linked to enhanced change in magnetic contribution from Deccan basaltic to granitic gneissic dominated sediment provenance.

(2) Granulometry of the magnetic fraction showed that magnetic grain size is basically independent of physical grain size above $> 40 \mu\text{m}$. The non-monotonous relationship between the magnetic and physical grain size can be explained by the fact that few individual finer magnetic particles was found to be occurring as inclusions within coarser silt and sand fractions.

(3) Diagenesis of magnetic minerals also affected the sediment magnetic record. Intense diagenetic dissolution of ferrimagnetic minerals and preservation of higher coercivity minerals due to their higher resistance was well-recorded by two low S-ratio intervals in the sediment core off Godavari river. The diagenetic factor is beyond the scope of present study. However a dedicated study in future involving geochemical proxies would provide vital insights into the diagenetic processes at these sites.

(4) We have demonstrated that magnetogranulometry approach can efficiently track the effect of provenance and grain-size based fractionation on the bulk sediment magnetic signal in complex sedimentary shelf systems.

Data availability

The data used in this study is available on CSIR-NIO repository. The link to access data online is <https://publication-data.nio.org/s/nxBWmGZY5rKzxaa>

Declaration of competing interest

None.

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Figure Caption:

Fig. 1: Geological map showing the lithology of Krishna, Godavari and Mahanadi river drainage basin and locations of the sediment cores in the Bay of Bengal.

Fig. 2: Plot showing relationship between (a) distance between river mouth and sediment core locations, river length, and (b) average magnetite content and catchment area.

Fig. 3: Downcore variation of rock-magnetic parameters of the sediment cores from the shelf (a–e) off Krishna (SSK-35/GC-18), (f–j) off Godavari (SSK-50/GC-10), and (k–o) off Mahanadi (SSK-35/GC-04) rivers. Please note that K1-K4, G1-G11, and M1-M4 represent the sediment intervals showing high magnetic susceptibility peaks in Krishna, Godavari and Mahanadi cores. These peaks are highlighted by horizontal gray colour shading. Two distinct sediment intervals showing low S-ratio in Godavari core are highlighted in light green colour.

Fig. 4: Susceptibility-thermomagnetic heating curves for selected samples from sediment cores from the shelf (a) off Krishna, (b) off Godavari, and (c) off Mahanadi rivers. (d) hysteresis parameters displayed in a Day plot (Day et al., 1977).

Fig. 5: (a-p) Scanning electron microscopy (SEM) of magnetic extracts from different depth intervals of sediment core from the shelf off Krishna River (SSK-35/GC-18). Energy dispersive X-ray spectroscopy (EDS) spectra are presented next to the respective images. Iron (Fe), titanium (Ti), oxygen (O), calcium (Ca), silicon (Si), carbon(C), aluminium (Al), and magnesium (Mg) peaks are indicated.

Fig. 6: (a-m) Scanning electron microscopy (SEM) of magnetic extracts from different depth intervals of sediment core from the shelf off Godavari River (SSK-50/GC-10). Energy dispersive X-ray spectroscopy (EDS) spectra are presented next to the respective images. Iron (Fe), titanium (Ti), oxygen (O), calcium (Ca), silicon (Si), carbon(C), aluminium (Al), and magnesium (Mg), and Vanadium (V) peaks are indicated.

Fig. 7: (a-n) Scanning electron microscopy (SEM) of magnetic extracts from different depth intervals of sediment core from the shelf off Mahanadi river (SSK-35/GC-04). Energy dispersive X-ray spectroscopy (EDS) spectra are presented next to the respective images. Iron (Fe), titanium (Ti), oxygen (O), calcium (Ca), silicon (Si), carbon(C), aluminium (Al), and magnesium (Mg) peaks are indicated.

Fig. 8: X-ray diffractograms (XRD) of minerals extracted from different sediment depth intervals of sediment core from the shelf off Krishna (a-d), Godavari (e-h), and Mahanadi (i-l) Rivers. TM = titanomagnetite and Q = quartz.

Fig. 9: (a-i) Scatter plots of magnetic (magnetic susceptibility (χ_{lf}), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), ARM/SIRM), S-ratio and sedimentological (sand and clay %) parameters for sediment cores from the shelf off Krishna (SSK-35/GC-18), off Godavari (SSK-50/GC-10), and off Mahanadi (SSK-35/GC-04) Rivers.

Fig. 10: Bar plot showing average magnetite concentration for five particle size (clay, fine silt, medium silt, coarse silt, sand) fractions separated from the bulk samples of sediment cores from the shelf off Krishna, Godavari, and Mahanadi rivers respectively. Higher magnetic susceptibility (χ_{lf}) values correspond to higher magnetite concentrations in each of the sieved fractions.

Fig. 11: Plot showing the variation in magnetic mineral concentration (χ_{lf}) and magnetic grain size (ARM/SIRM) within the different particle size fractions representing the sediment core samples from the shelf (a-b) off Krishna, (c-d) off Godavari, and (e-f) off Mahanadi rivers. Vertical light green color band is used to demarcate the boundary limit ($\sim 40 \mu\text{m}$ and $\sim 63 \mu\text{m}$), above which the relationship between magnetic and clastic grain size reverses.

Fig. 12: Optical microscopic images of the representative (>63 μm) fraction from the shelf sediment cores (a-c) off Krishna, (d-f) off Godavari, and (g-i) off Mahanadi rivers. Magnetic inclusion within host quartz (>63 μm) fractions are marked (see arrowed grains).

Fig. S1: (a-n): X-ray diffractograms (XRD) of minerals extracted from different sediment depth intervals of sediment core from the shelf off Krishna River. TM = titanomagnetite and Q = quartz.

Fig. S2: (a-j): X-ray diffractograms (XRD) of minerals extracted from different sediment depth intervals of sediment core from the shelf off Godavari River. TM = titanomagnetite and Q = quartz.

Fig. S3: (a-f): X-ray diffractograms (XRD) of minerals extracted from different sediment depth intervals of sediment core from the shelf off Mahanadi River. TM = titanomagnetite and Q = quartz.

Table. 01: Details of the core location and magnetite content in shelf sediments off Krishna, Godavari, and Mahanadi rivers.

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Figure 1

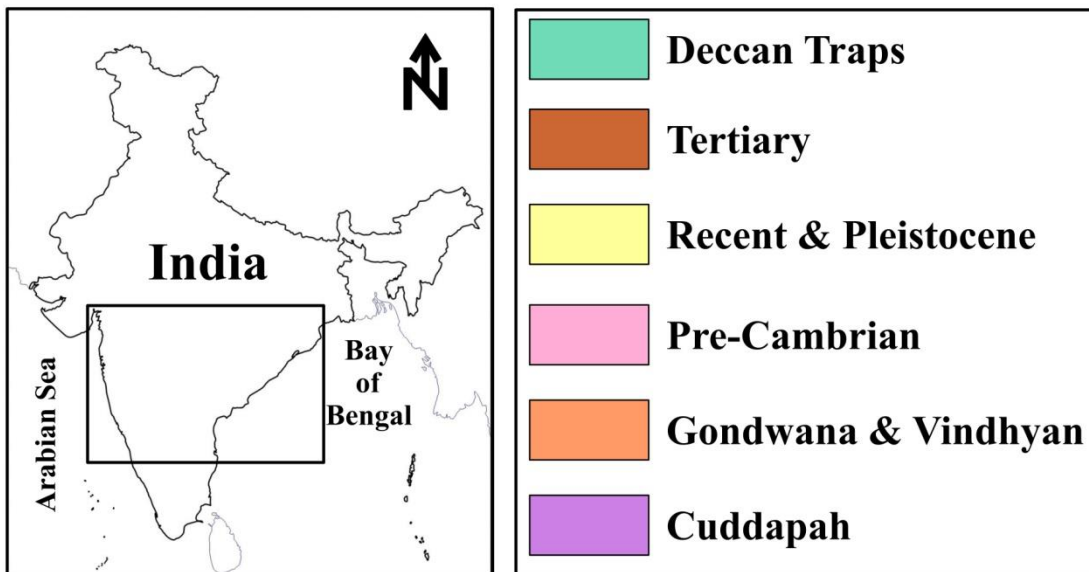
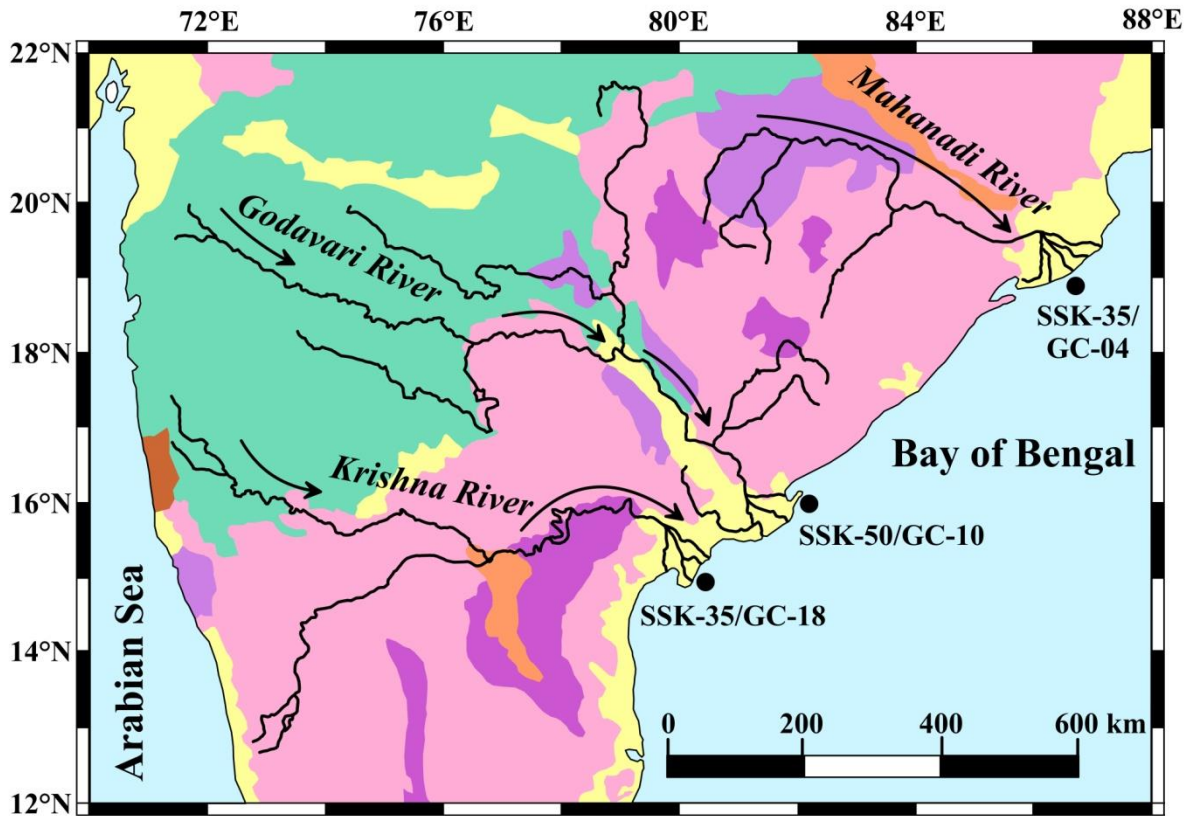


Figure 2

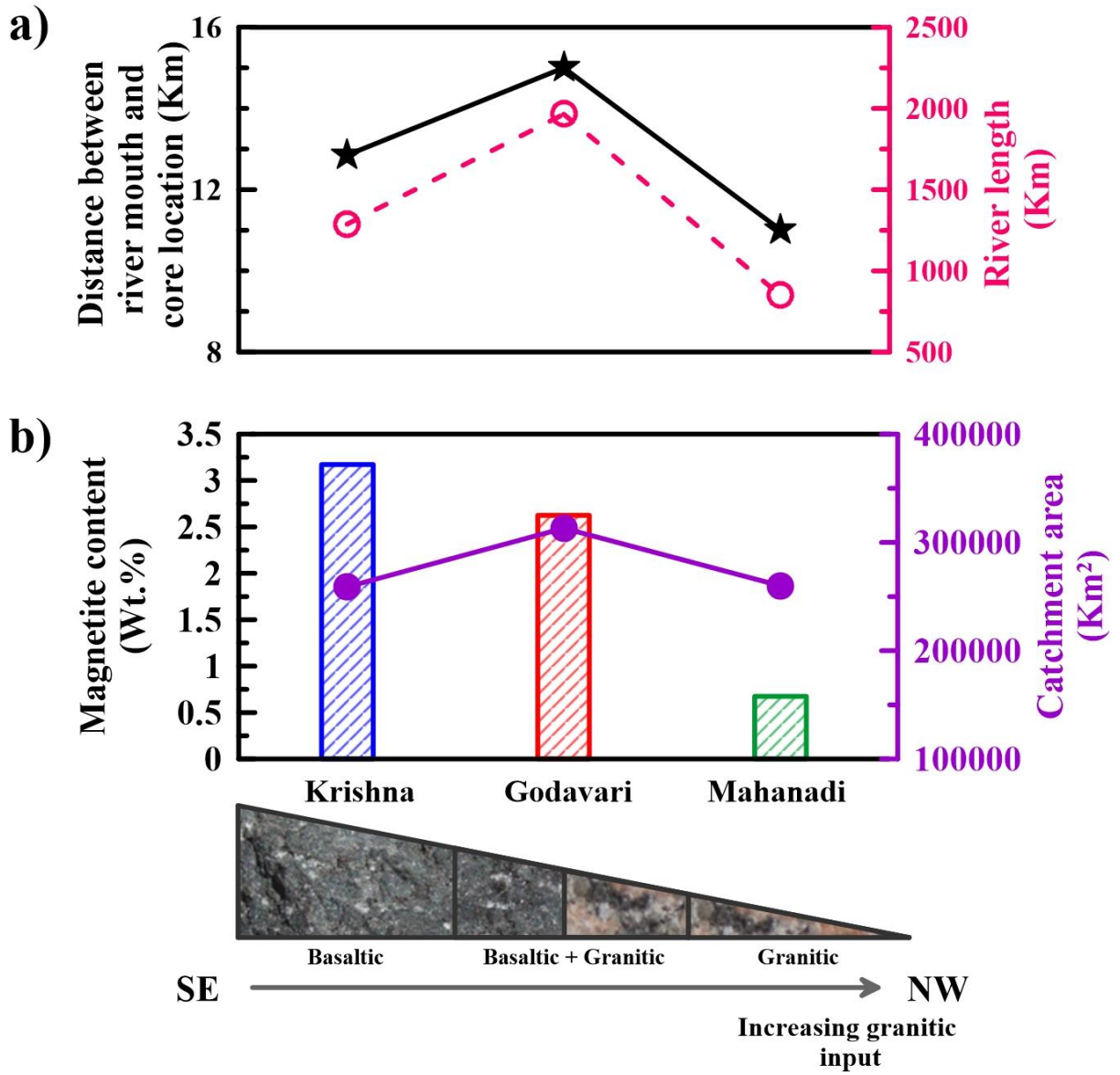


Figure 3

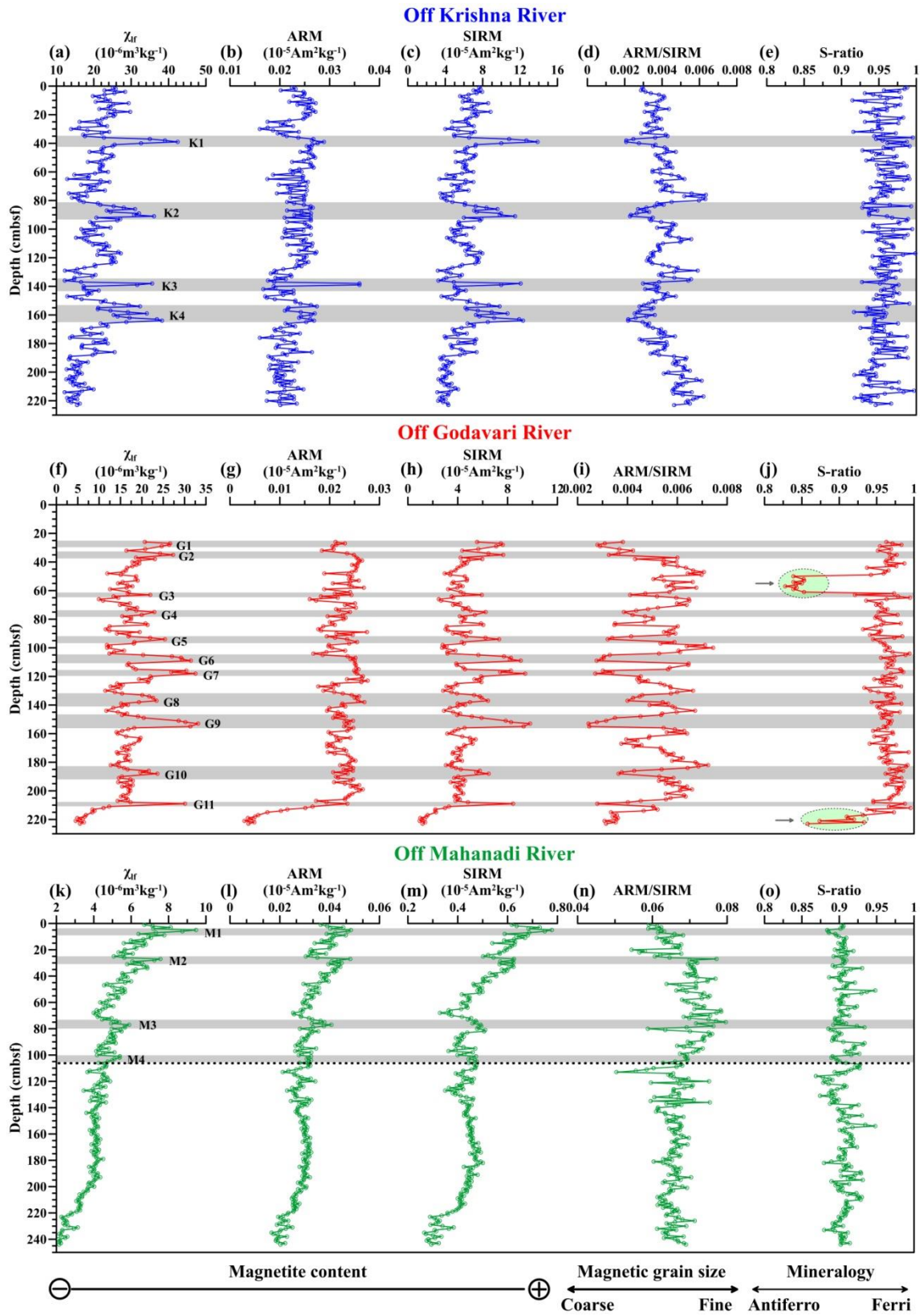


Figure 4

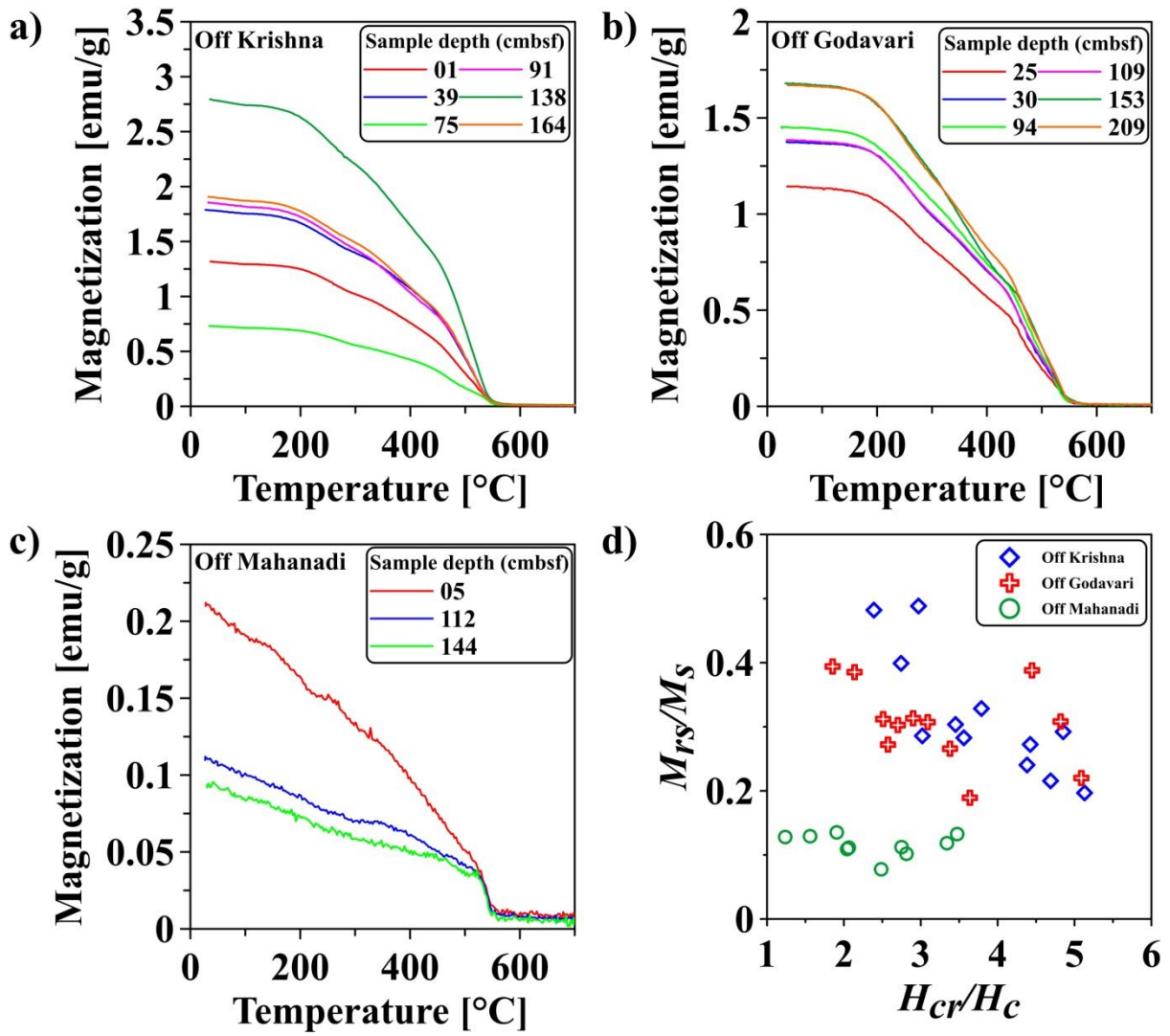


Figure 5

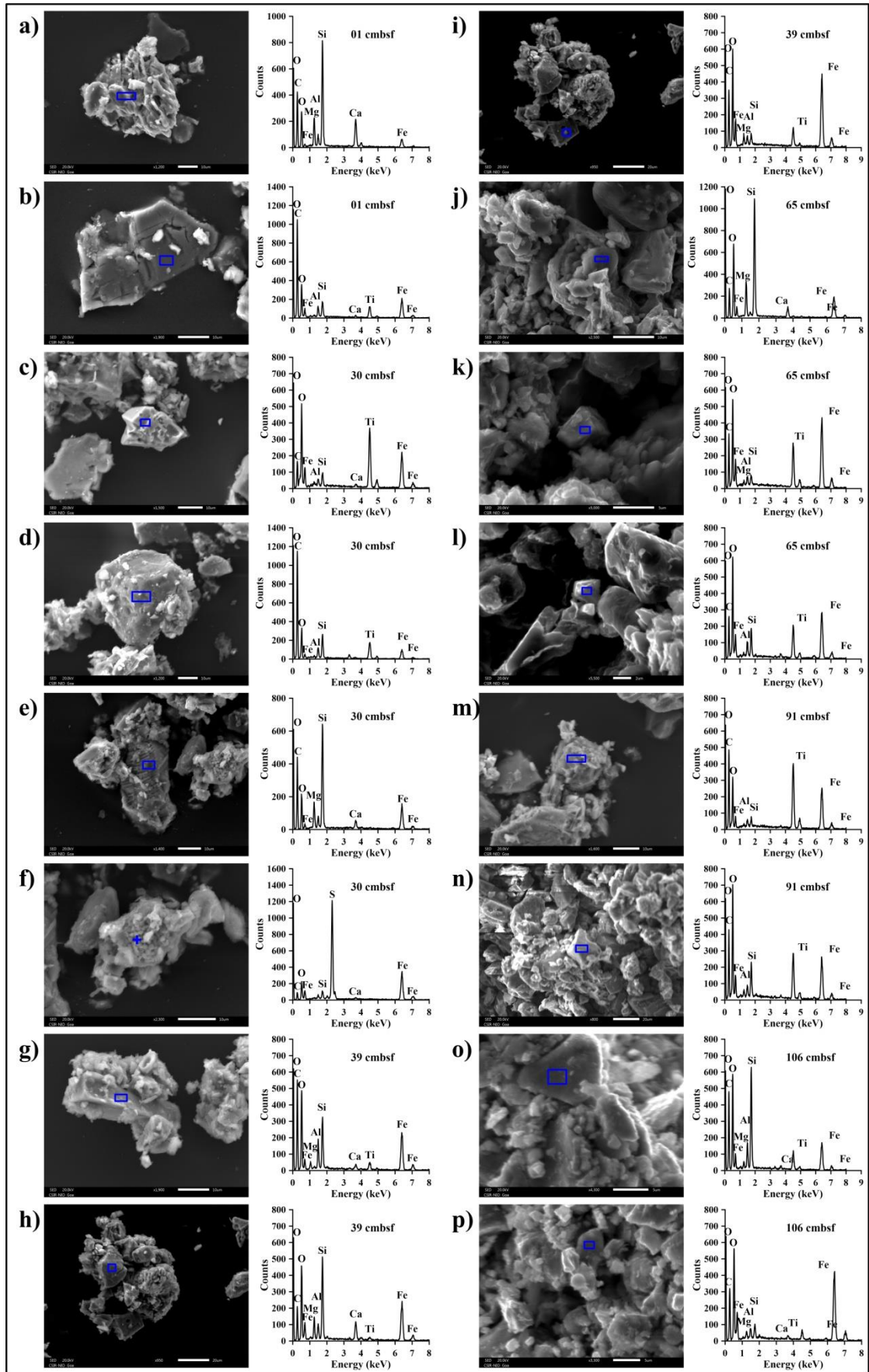


Figure 6

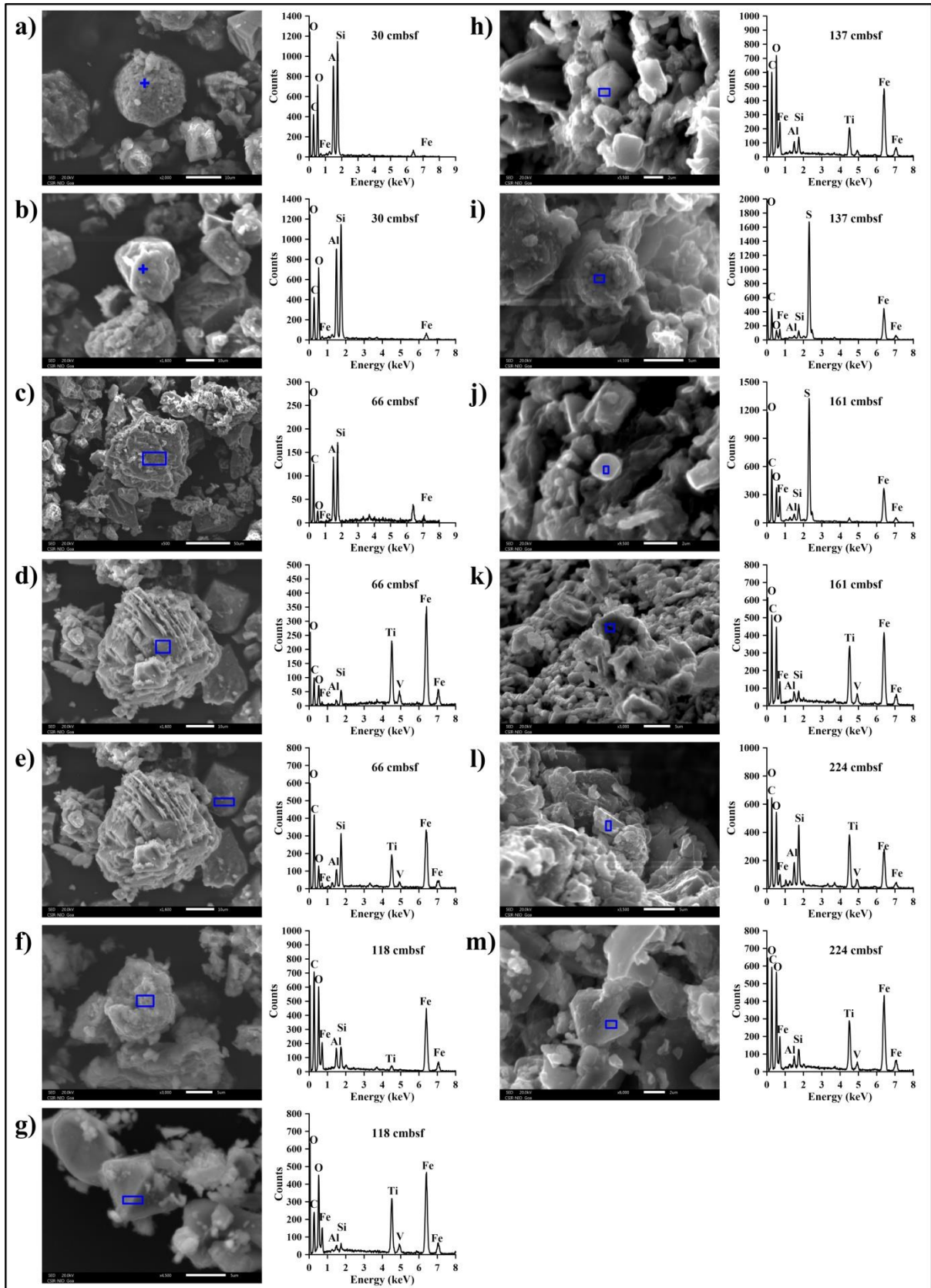


Figure 7

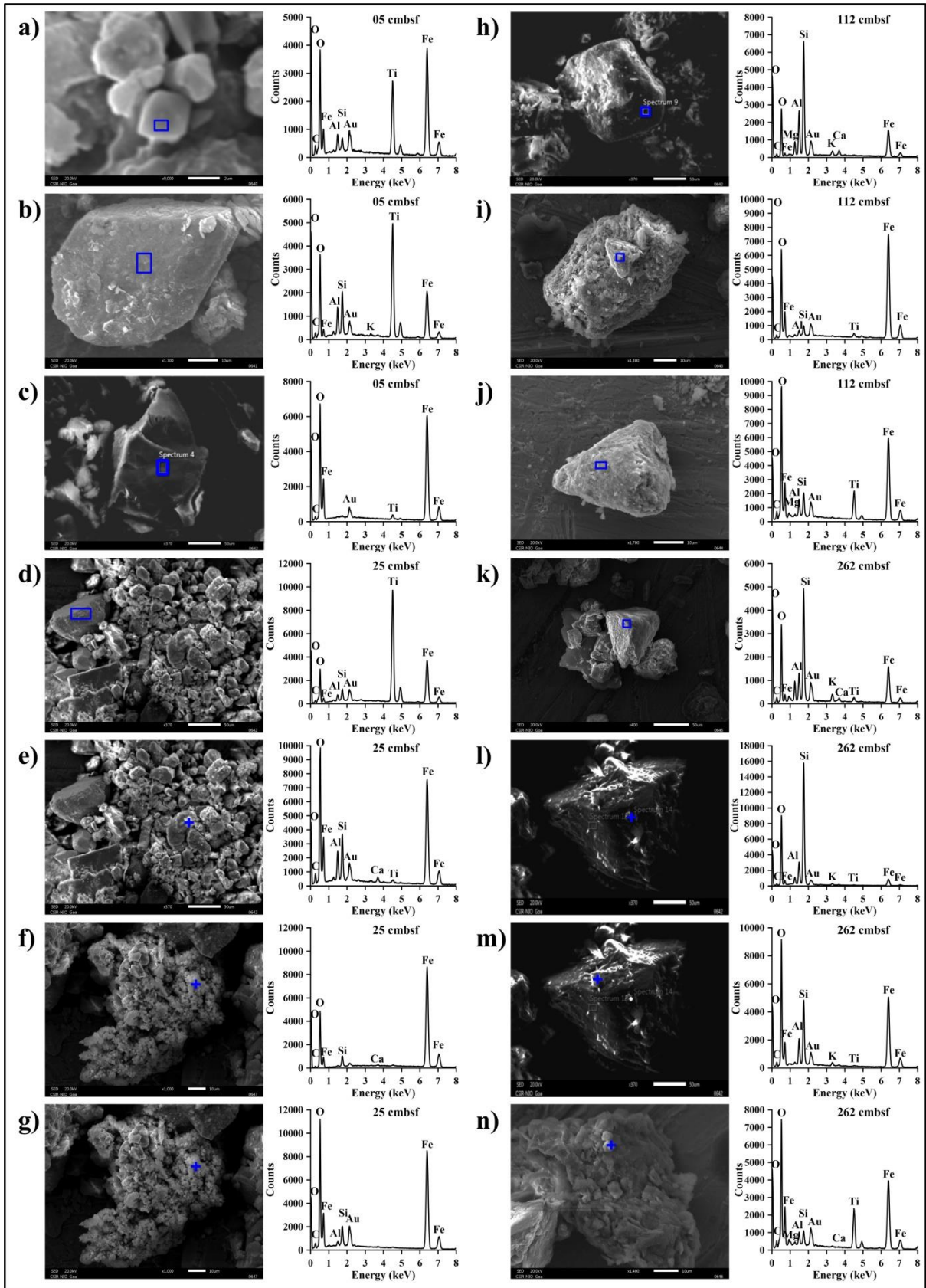


Figure 8

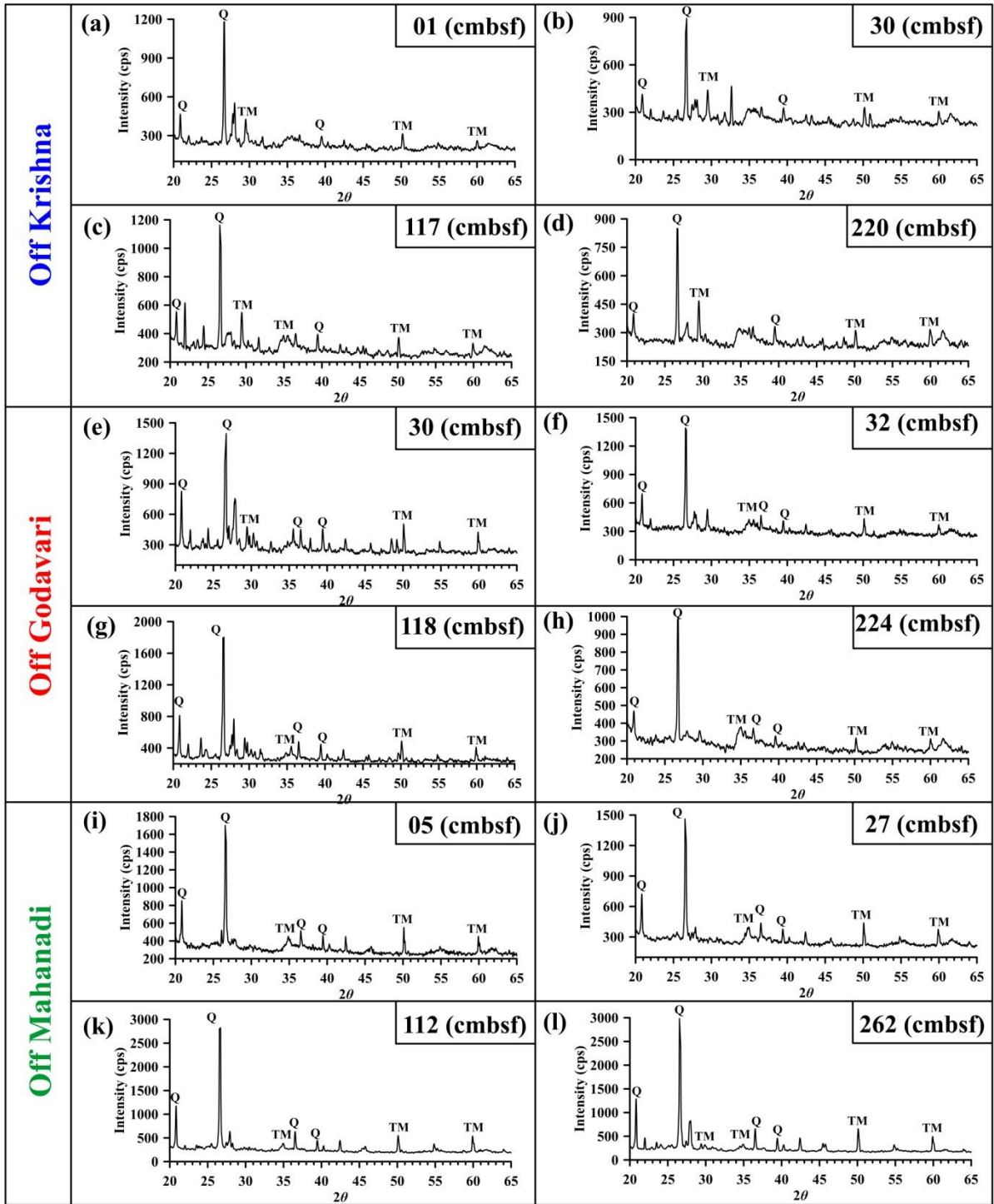


Figure 9

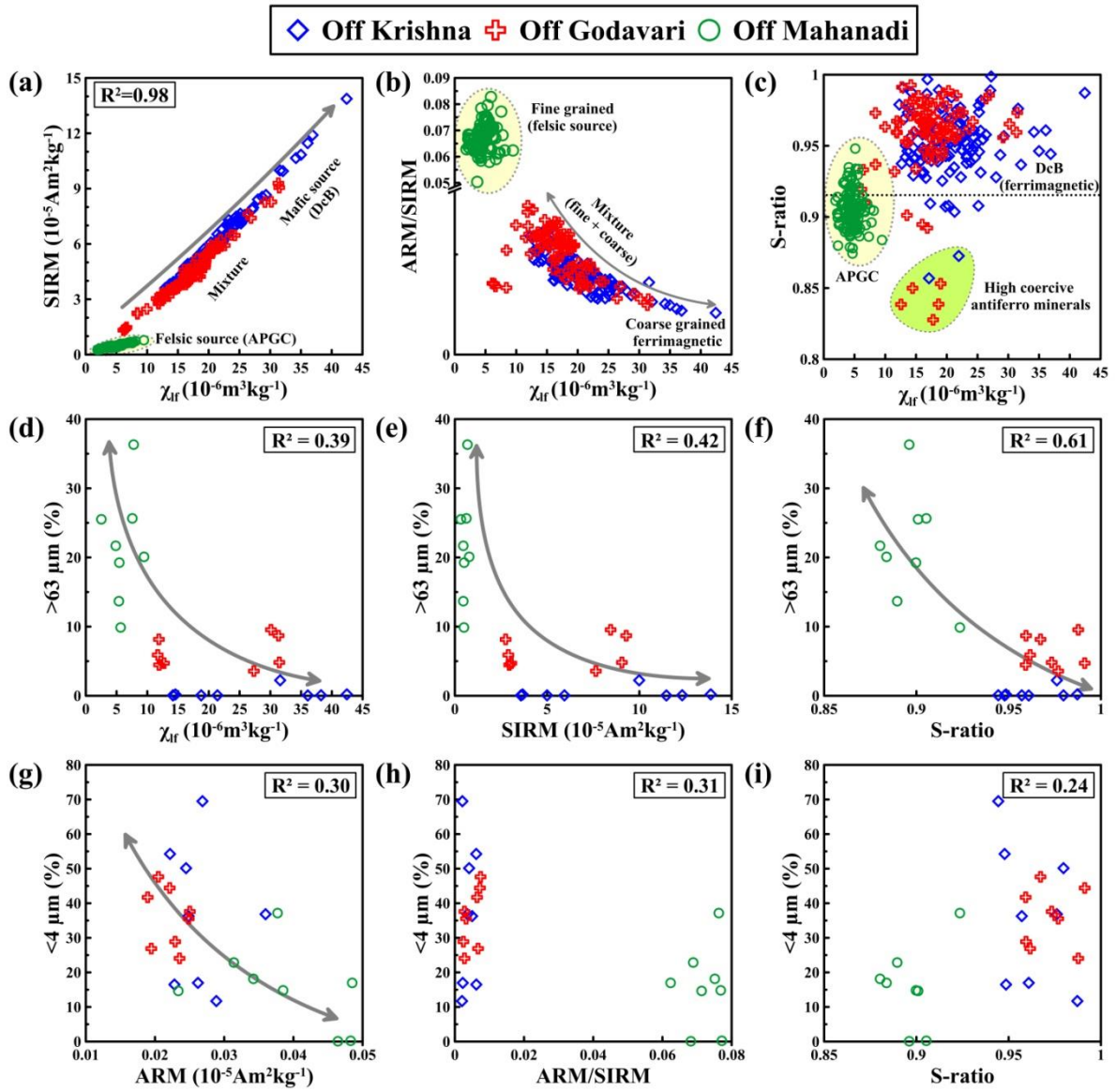


Figure 10

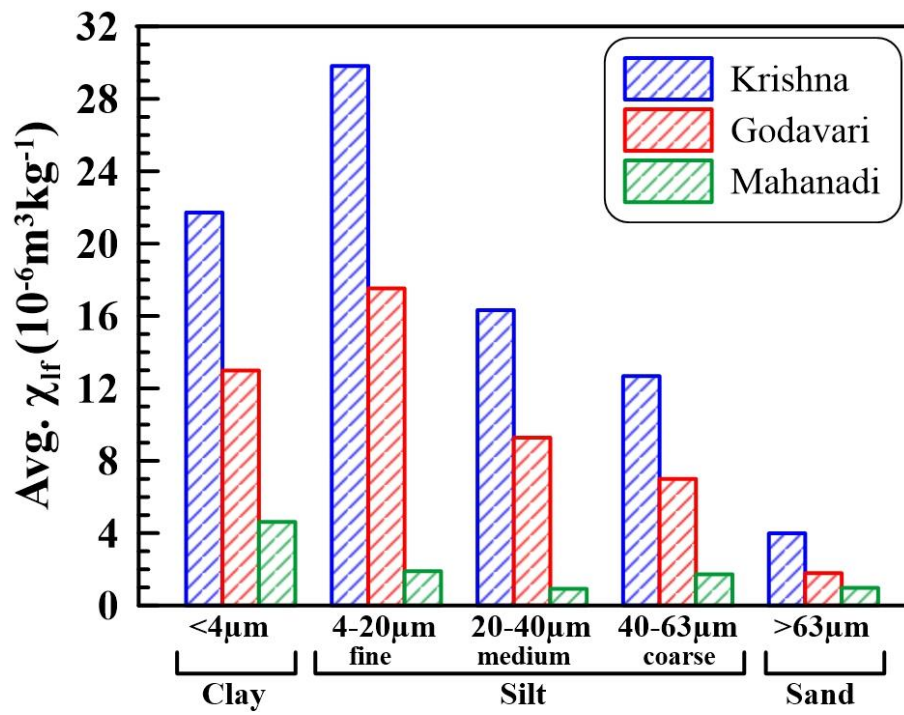


Figure 11

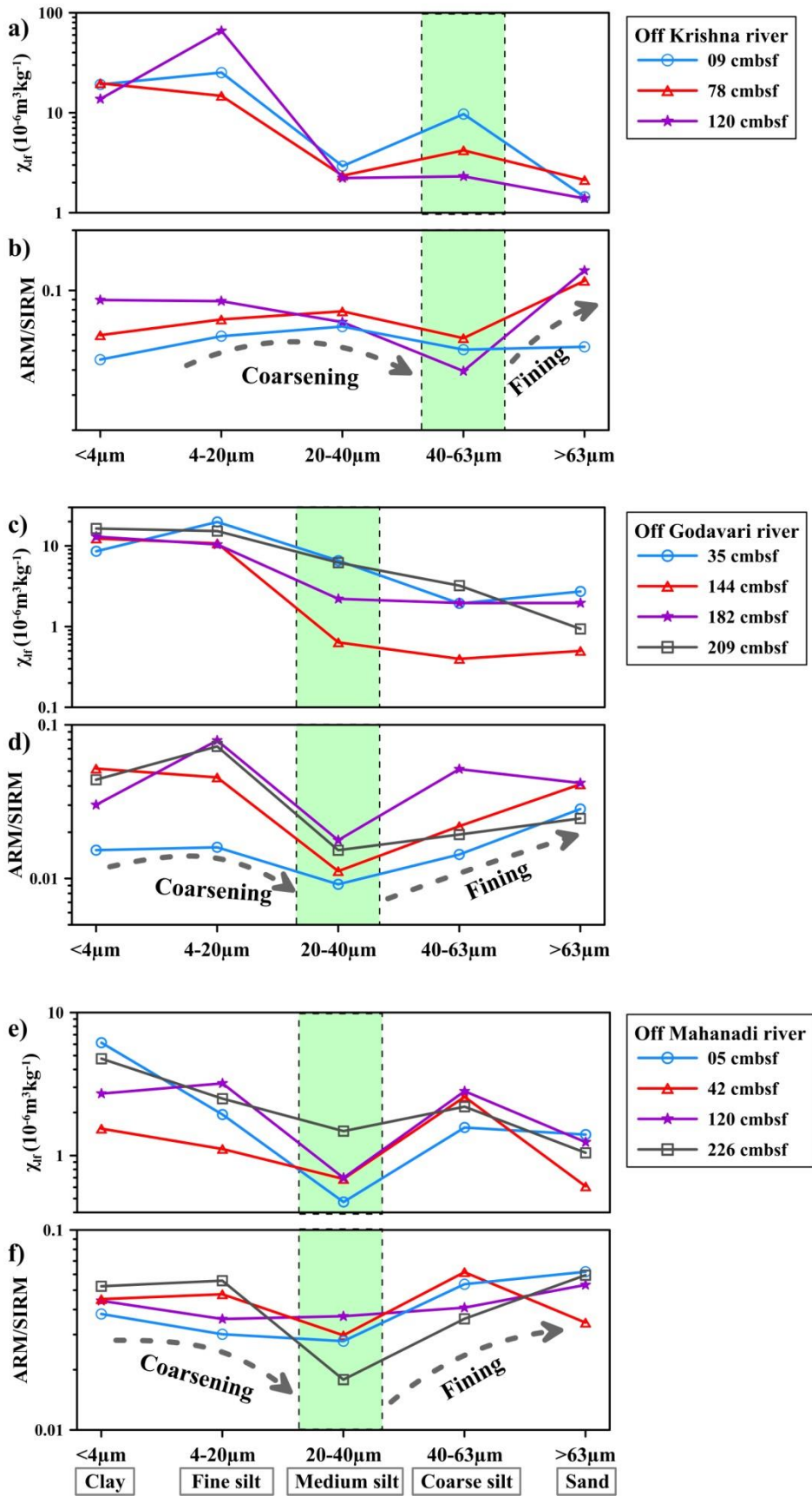


Figure 12

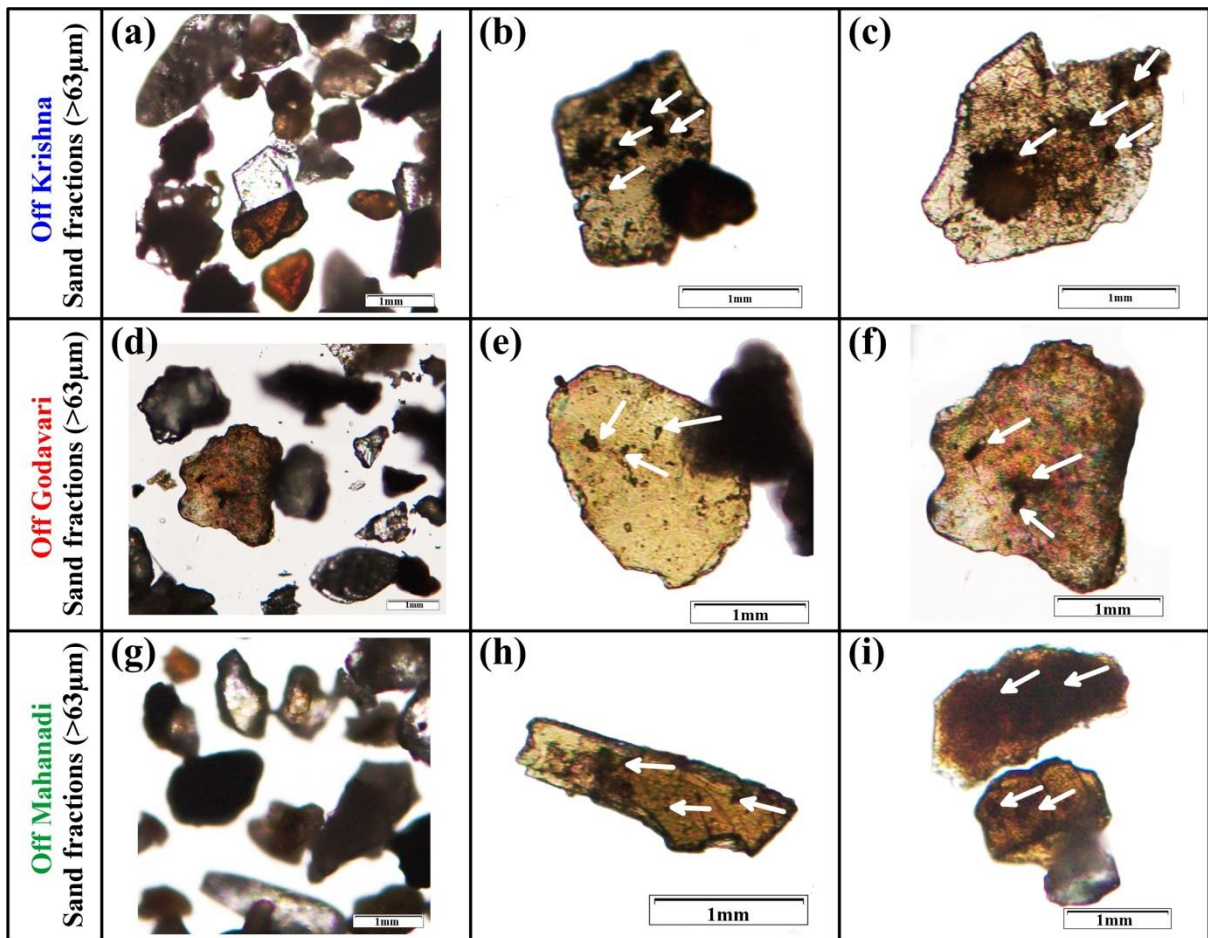


Figure S1

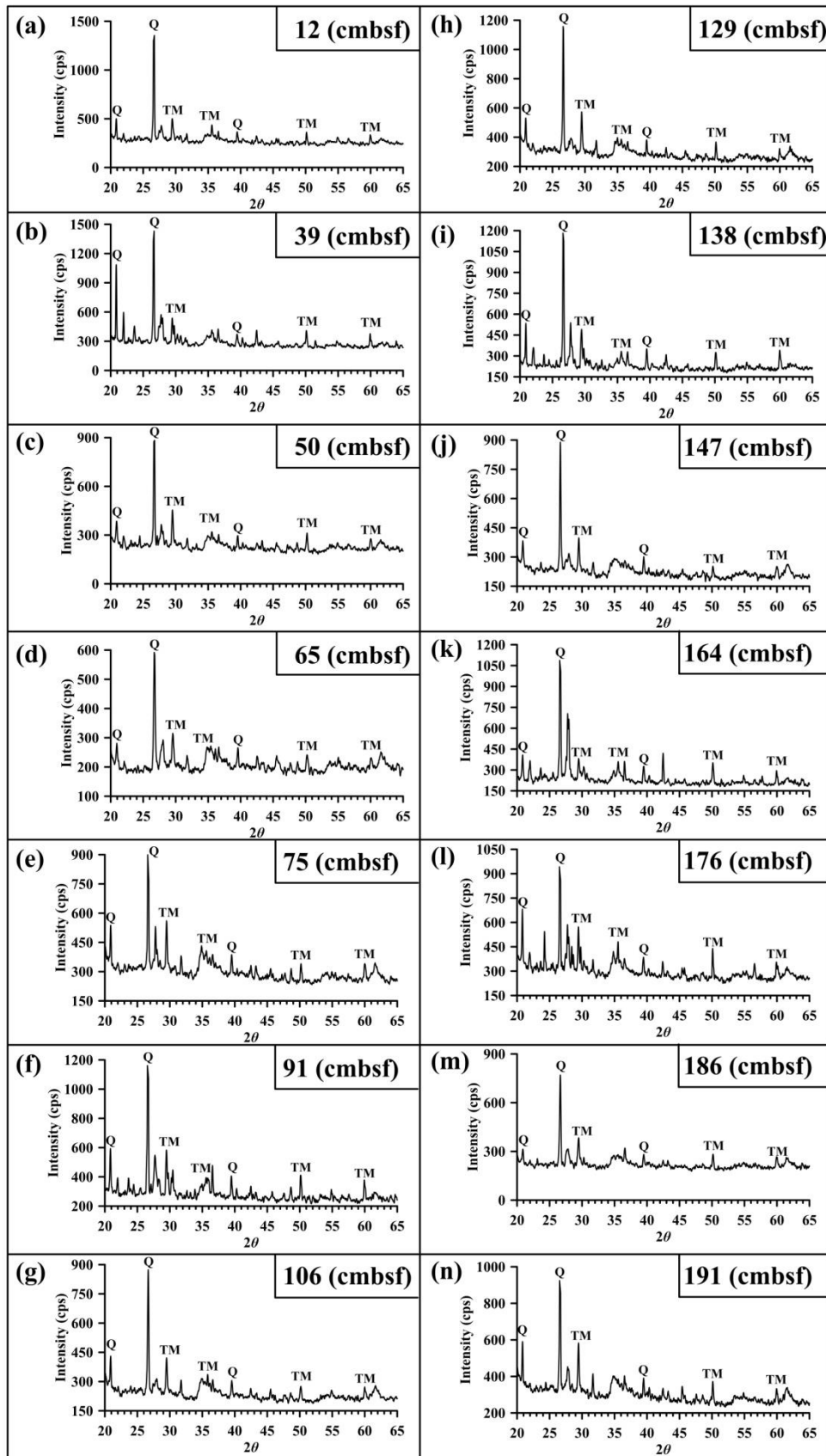


Figure S2

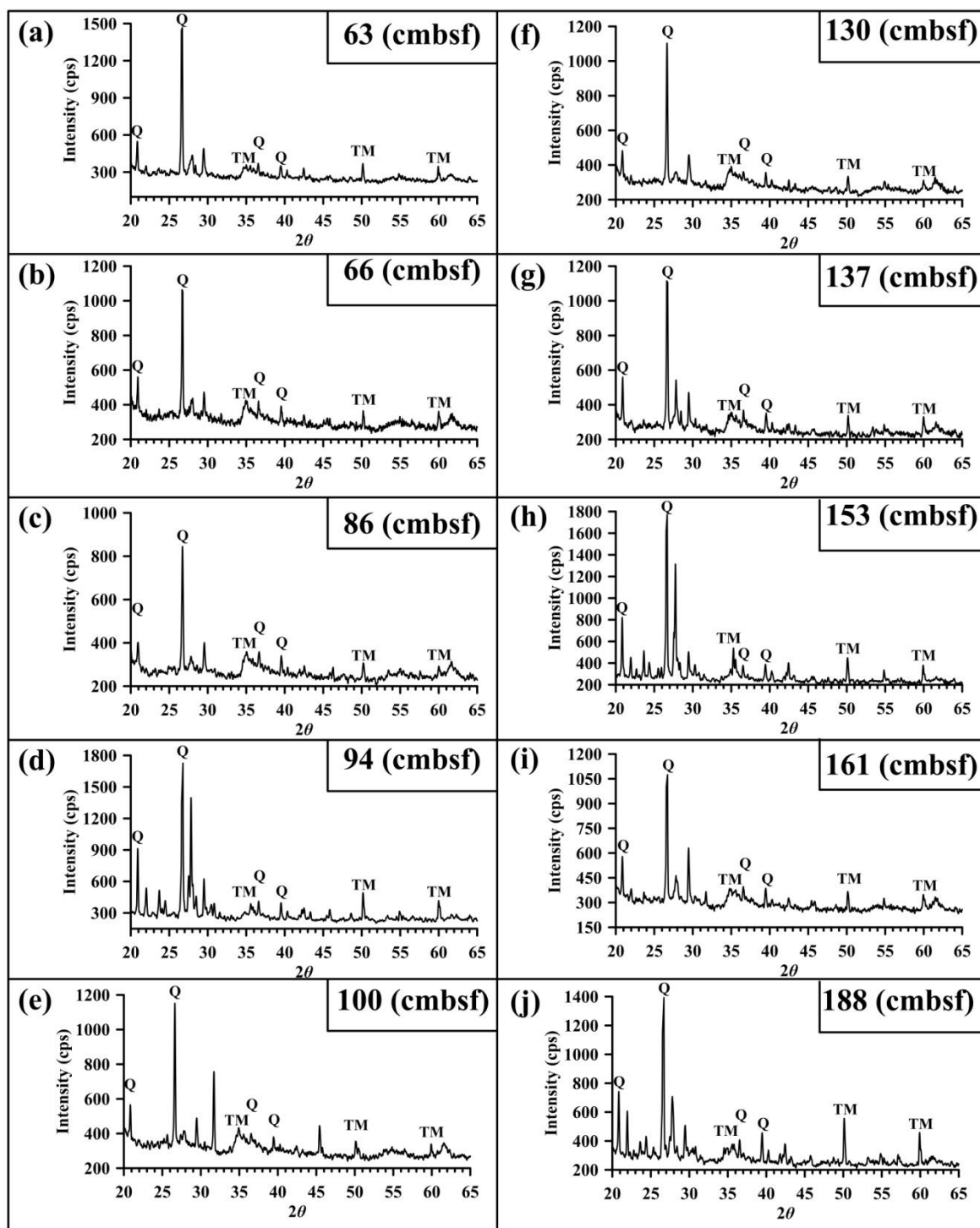


Figure S3

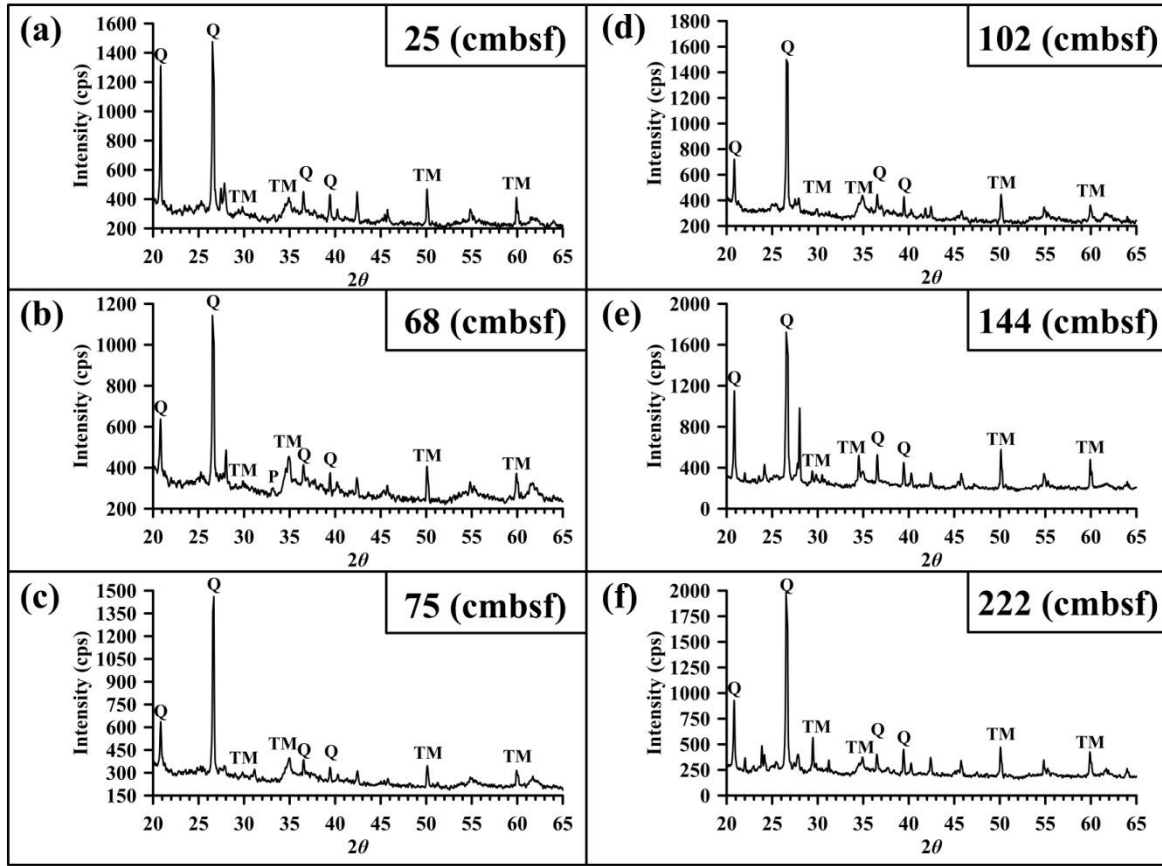


Table 1

Sr. No.	Core Location	Core ID	Position		Water depth (m)	Total core length (cm)	Magnetite Content (Wt. %)			
			Latitude (°N)	Longitude (°E)			Min.	Max.	Avg.	Std. Dev.
1	Off Krishna river	SSK-35 GC-18	15.60	80.87	53	223	1.84	6.43	3.18	0.83
2	Off Godavari river	SSK-50 GC-10	16.20	81.93	106	223	0.68	5.02	2.63	0.81
3	Off Mahanadi river	SSK-35 GC-04	19.94	86.49	30	244	0.29	1.43	0.68	0.19