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# Mineral Magnetic Characterization of the Godavari River and Western Bay of Bengal Sediments: Implications to Source to Sink Relations

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**Abstract:** Godavari Drainage Basin (GDB) represents the largest Peninsular source of sediment flux into the Bay of Bengal. Mineral magnetic measurements are carried out on the GDB sediments along with the surface sediment cores from the adjoining western Bay of Bengal to explore the relationship between the two. The sediments from Godavari river transact shows varied floodplain to bed load composition with the former dominated by unimodal soft ferrimagnetic, Deccan basalt source. Whereas, the bed load show polymodal composition of mixed nature dominated by silici-clastic sediments derived from the Precambrian granites and Proterozoic sequences. The surface sediment cores (~100-300 cm) from the Bengal fan region off the Godavari delta broadly display an increasing trend in ferrimagnetic mineralogy towards top. Based on mineral magnetism the ferri- and para-magnetic susceptibilities are assigned to the basaltic and siliciclastic sources, respectively which also represents the low and high rain fall zones. The increasing upwards trend of the ferrimagnetic minerals in the western Bay of Bengal sediments, therefore, can be related to the predominance of basaltic source over the siliciclastic/cratonic source from the GDB. These controls of magnetic susceptibility in the Bengal fan sediments are assigned to the fluctuation of the two sources as a result of differential weathering in response to monsoonal variability.

**Keywords:** Godavari River, Bengal fan, Mineral magnetism, Deccan basalt, Monsoon, Bay of Bengal.

## INTRODUCTION

The Bay of Bengal represents the largest depo-centre in Asia to receive huge amount of sediment loads from contrasting sources of the Himalaya, the Indo-Myanmar ranges and the peninsular India. The Ganga and Brahmaputra rivers represent the two major distributaries for the Himalayan source in the Bengal fan. Meghna, Irrawadi and Salween rivers bring majority of the sediments from the Indo-Myanmar ranges, whereas, Godavari, Mahanadi and Cauvery rivers are the major peninsular sources in Bengal fan (Fig. 1a). Amongst these, the Godavari river makes the most characteristic source (Sangode et al., 2001; Reddy and Rao, 2001) due to its major (~50%) catchment over the Deccan Volcanic Province (DVP) (Fig. 1b). Further the sediment flux from these sources is greatly influenced by the Indian monsoon (Cullen, 1981; Goodbred, 2003; Chauhan et al., 2006).

The GDB with an area of catchement ~3,13,147 km$^2$ covers about 10% of surface area of peninsular India and the entire basin lies in the latitudinal range of 17°N to 22°N. The large scale weathering and erosion in the Godavari basin is mainly controlled by the SW monsoon (the tectonic factor can be neglected for Late Holocene period) and about 95% of the total annual load in Godavari river is transported during monsoon (Biksham and Subramanian, 1980). The non-basaltic terrain marked by the Precambrian granites and the sedimentary to meta-sedimentary and metamorphic sequences (Fig.1b) also contributes to large part of the catchment in GDB which can be characteristic source of siliciclastics. Considering these two contrasting sources the mineral magnetic studies makes the most suitable approach to discriminate between the ferrimagnetically rich basaltic source and the para- and diamagnetically rich siliciclastic source. The later can largely produce a dilution effect in combination of the former as the magnetic methods are more sensitive to the ferrimagnetic minerals (Tarling and Hrouda, 1993; Dunlop and Özdemir, 2001).

The GDB lies in the Core Monsoonal Zone (CMZ)

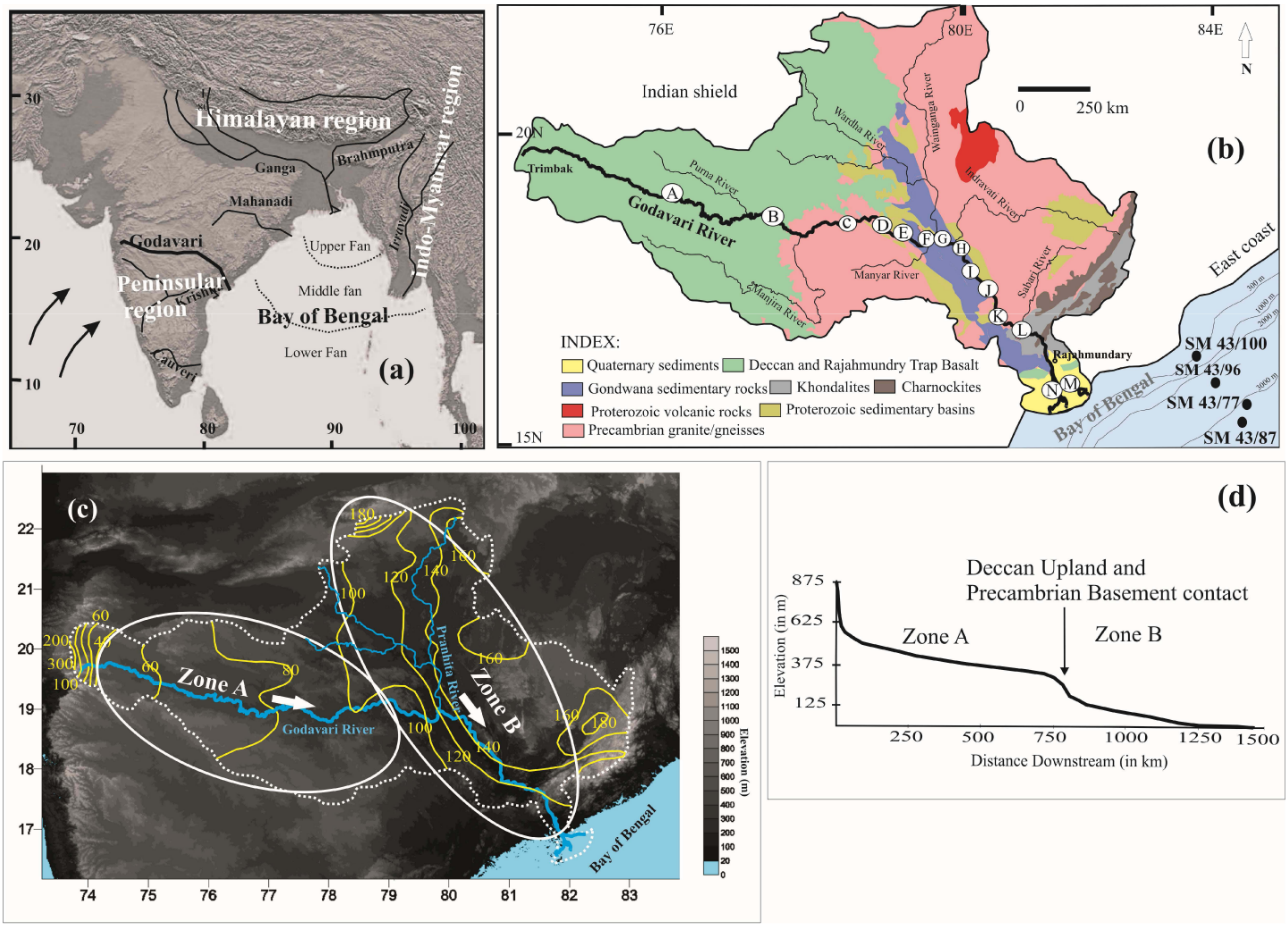

**Fig.1. (a)** Schematic map showing major rivers for Himalayan, Indo-Myanmar and Peninsular sources into the Bay of Bengal sink. Arrows indicate Arabian Sea branch of SW monsoon. **(b)** Generalized Geological and drainage basin map of Godavari, drawn after Geological map of India (scale 1:250000). A to N are sediment sampling locations along Godavari River. SM 43/100 to SM 43/87 are sediment cores from Godavari fan in Bay of Bengal. **(c)** DEM of central India, White dotted line demarcate the Godavari basin boundary, yellow lines are contours of Mean monsoonal rainfall (values in cm) [After Nageshwar rao, 1999] and white circles represents two different zones of sediment sources in Godavari (detail discuss in text). **(d)** Long Profile of Godavari channel (after Sangode et al., 2013).

receiving rainfall dominantly from Indian summer monsoon. Nageshwar Rao (1999) demonstrates a spatial variability of SW monsoon over the central and eastern parts of GDB. The western part of the basin which mainly covers the Deccan basaltic province falls under the rain shadow zone and receives less Mean Monsoonal Rainfall (MMR) compared to the non-basaltic eastern and northeastern part (Fig. 1c). This MMR division can be associated with two different lithologic and mineral magnetic domains *i.e.* ferrimagnetic Deccan basalt in the western part and paramagnetic/antiferromagnetic Precambrian granites and Proterozoic sediments in the eastern part. Further the digital elevation model of GDB shows distinct topographic variation between basaltic terrain and Precambrian granitic and Gondwana terrain that is clearly observed in the long profiles of Godavari river with steeper gradient after its exit from the Deccan plateau (Fig. 1d). The topographic variation thus coincides with the spatial rainfall variation and lithologies like Deccan upland associated with the basaltic lithology and low monsoonal rainfall, whereas, cratonic lowland associated with non-basaltic lithologies and high monsoonal rainfall. Considering these distinct domains of lithology, climate and morphology; the present attempt is to characterize the Godavari source in the context of developing its relationship with the sedimentation in Bengal fan sink using mineral magnetism.

**Mineral magnetism:** Mineral magnetism is a widely used technique to characterize the sediment source and their mixing patterns under variety of depositional environments (Thompson and Olfield, 1986; Yu and Oldfield, 1989, 1993; Walling et al., 1993; Lees, 1994; Walden, et al., 1997;

Caitcheon 1998; Sangode et al. 2007; Horng and Huh, 2011). The mineral magnetic parameters are also commonly used as a proxy for paleoenvironmental and plaeoclimate reconstructions (e.g. Alekseeva et al., 2007; Geiss et al., 2008). Recently Balsam et al. (2011) reviewed worldwide magnetic susceptibility data and suggested its better relationship with rainfall for tropical and temperate region. With a set of remnant magnetic hysteresis parameters, mineral magnetism provides a robust technique of rapid and accurate qualitative and quantitative estimates on various aspects of sedimentation (Thompson and Oldfield, 1986; Evans and Heller, 1994; Dekkars, 1997). Mineral magnetic studies were previously exercised in Bengal fan sediments (Sagar and Hall, 1990; Sangode et al., 2001; Haiyan et al., 2006) although there are very few attempts on Godavari river sediments. Sangode et al. (2007) previously carried out mineral magnetic studies on some tributaries and mainstreams in GDB, whereas, Kulkarni et al. (2014) carried out preliminary rock magnetic studies in Godavari river to understand the weathering of DVP. The present study also discuss some of the basic data of Kulkarni et al. (2014) to establish a relationship between the Godavari source and the Bengal fan sink.

## SAMPLING AND LABORATORY ANALYSIS

### Sampling

Total 113 samples were collected from 14 representative sites (marked in Fig. 1b) representing the mid-channel/point bars and connected floodplains of the Godavari river. Out of these, two sites are from the Deccan province (A, B in Fig 1b), three from Precambrian granites (C, D, E), six from the Gondwana (F, G, H, I, J, K), one from charnokitic belt (L) and two from the distributaries of Godavari i.e. Gautami-Godavari (M) and Vashisti-Godavari (N) in the delta plain region.

Geological Survey of India Research Vessel (*Samudra Manthan* Cruise: 43) provided four deep-sea sediment cores (100 to 300 cm length) to Wadia Institute of Himalayan Geology, Dehradun, from the western Bay of Bengal off Godavari submarine fan area (Table 1). The cores were sampled at 5cm interval and subjected to detailed mineral magnetic studies.

### Laboratory Analysis of Magnetic Measurements

Each sample from GDB was further reduced to about 50gm by coning and quartering in the laboratory and tightly filled into 10cc polystyrene bottles for magnetic measurements. The low field magnetic susceptibility ($\chi_{lf}$) was measured using Bartington's MS2B sensor which operates at frequencies of 0.465 and 4.65 KHz. The frequency dependent susceptibility ($\chi_{fd}$) was determined by measuring the samples in both the frequencies (0.465 and 4.65 KHz). The ASC impulse magnetizer and Minispin fluxgate spinner magnetometer (both from Molspin, UK) were used to generate the IRM spectra for forward fields up to 1000 mT and the back fields of -5, -10, -20, -30, -50, -75, -100 and -300 mT. All the samples were saturated well below the fields of 1000 mT and hence the parameter Saturation Isothermal Remanant Magnetization (SIRM) was calculated using mass normalized IRM at 1000mT. Further the hard and soft contributions to SIRM are represented by the parameters HIRM {= (SIRM+ (-300mt))/2} and $\text{Soft}_{IRM}$ {= (SIRM-(-20mt))/2}, respectively. An Anhysteretic Remnant Magnetization (ARM) was grown with an alternating decaying field of 100 mT superimposed over 0.1 mT DC field using Molspin Alternating field demagnetizer. The susceptibility of ARM ($=\chi_{ARM}$) was calculated by normalizing the mass specific ARM with the Bias field. The sediment core samples were further analyzed under VSM (Vibrating Sample Magnetometer) for hysteresis loop analysis and $\chi_{ferri}$ and $\chi_{para}$ percentage was calculated. The basic statistical analysis and some standard bivariate plots are used to standardize data presented in the results.

## RESULTS

### Mineral Magnetic Characteristics of GDB Sediments

The mean $\chi_{lf}$ for the floodplain sediments is more than twice to that of bed load sediments (Table 1). The parameters indicating variability of data (standard deviation, kurtosis and skewness) are larger for the bed load sediments than that for the floodplains. This suggests the higher ferrimagnetic concentration of uniform source for the floodplains compared to the channel sediments. The frequency dependency of susceptibility ($\chi_{fd}$%) is moderately higher for the floodplains due to higher content of the finer ferrimagnetic fraction compared to channel sand. The higher $\chi_{ARM}$ with low variability for the floodplains further supports the above inferences depicting predominance of the SD ferrimagnets. The S-Ratio for the floodplains varies between -0.5 to -0.9 compared to that of -0.38 to -1 for the channel

**Table 1.** Geographic locations of studied Western Bengal fan sediment cores

| Name | Geographic Position | Water Depth (m) |
|---|---|---|
| SM 43/100 | 16°59.046' N, 83°08.902' E | 448 |
| SM/43/96 | 16°37.327' N, 83°26.263' E | 2769 |
| SM/43/77 | 15°44.525' N, 84°44.525' E | 3000 |
| SM/43/87 | 15°22.260' N, 84°30.405' E | 3041 |

sand. This suggests relatively higher heterogeneity within the ferrimagnetic grains for the channel sand. The higher HIRM/Soft$_{IRM}$ ratios for the channel sand further indicate input of 'hard fraction' such as hematite and goethite probably derived from the Gondwana sedimentary terrains. Rest of the parameters (SIRM/$\chi_{lf}$ and $B_{(0)CR}$) too supports the above inference. Thus the bulk rock magnetic data decipher relatively uniform (/unimodal) ferrimagnetic mineralogy for the floodplain sediments in contrast to the polymodal nature of mineralogy for the bed load.

In order to further characterize the mineral magnetic scatter domains we used bivariate plots as described below.

*$\chi_{lf}$ vs. SIRM:* This bi-plot (see Fig. 2A) after Thompson and Oldfield (1986) depicts the grain size and concentration distribution within the ferrimagnetic grains. The SIRM vs. $\chi_{lf}$ variation in floodplain sediments shows a better linear trend ($R^2$= 0.82) compared to the channel sands which shows clustering. After correlation with the data based standard plot of Bradshaw and Thompson (1985), this bi-plot suggests a ferrimagnetic (/magnetite) grain size range from 1 to 2 micron for the floodplain sediments in contrast to large variability in channel sand.

*SIRM/$\chi_{lf}$ vs. $B_{(0)CR}$:* This is another bi-plot after Thompson and Oldfield (1986) used to discriminate the mineralogical and grain size contrasts. The plot for floodplain sediments (Fig. 2B) typically shows clustering at the boundary of Single Domain (SD) and Multi Domain (MD) magnetites suggesting the unimodal mineralogy, whereas, the channel sediments disperse over a range from SDM to MDM and SPM indicating variable (polymodal) nature within the given magnetic mineralogy.

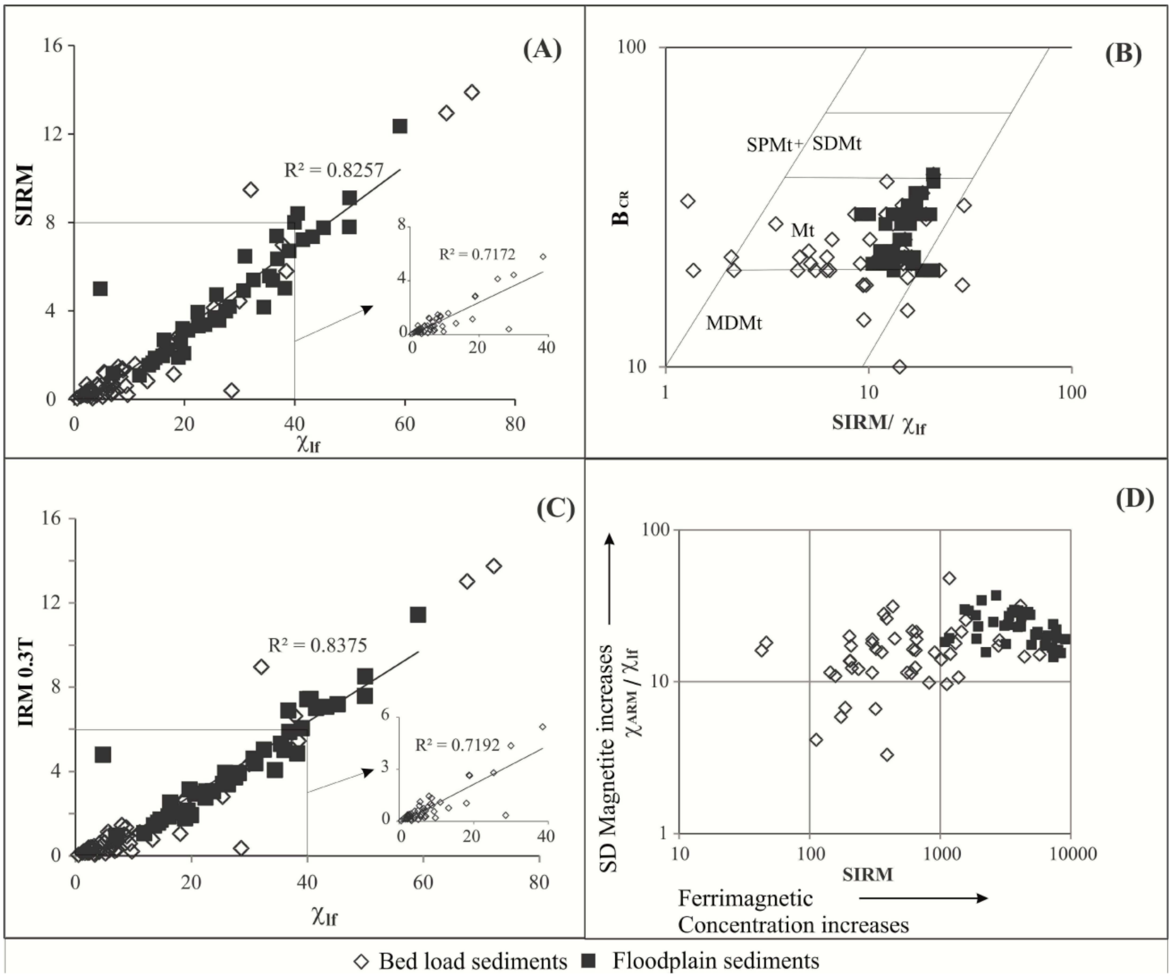

**Fig.2.** Standard bi- plots for Godavari River sediments (detail discussed in text). The regression line and $R^2$ values in main plots are for floodplain sediments. Inset plots are for bed loads excluding the sediments from Deccan basalt. (Units for magnetic parameters: $\chi_{lf} = 10^{-8}$ m$^3$/kg, SIRM = $10^{-2}$ Am$^2$/kg, SIRM/$\chi_{lf} = 10^4$ kA/m, Klf and ARM = Dimensionless).

**Table 2**. Descriptive statistics of some major mineral magnetic parameters (Units for magnetic parameters: $\chi_{lf} = 10^{-8}$ m$^3$/kg, SIRM = $10^{-5}$ Am$^2$/kg, $\chi_{ARM} = 10^{-5}$ m$^3$/kg, $B_{(0)CR}$ = mT, $Soft_{IRM}$ and HIRM = $10^{-2}$ A/m$^2$, SIRM/$\chi_{lf} = 10^3$ kA/m)

| Floodplains | $\chi_{lf}$ | $\chi_{fd\%}$ | $\chi_{ARM}$ | SIRM | S-Ratio | $B_{(0)CR}$ | $Soft_{IRM}$ | HIRM | HIRM/ $Soft_{IRM}$ | SIRM/$\chi_{lf}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Mean* | 28.42 | 1.60 | 0.64 | 4703.08 | -0.73 | 27.23 | 1784.96 | 142.96 | 83.10 | 176.60 |
| *Median* | 26.91 | 1.59 | 0.66 | 4173.55 | -0.72 | 28.00 | 1684.80 | 47.26 | 42.04 | 156.51 |
| *Standard Deviation* | 12.58 | 0.89 | 0.22 | 2559.86 | 0.07 | 5.36 | 855.49 | 278.49 | 186.31 | 144.95 |
| *Kurtosis* | -0.41 | 1.56 | -0.43 | 0.43 | 2.53 | -0.60 | -0.18 | 15.52 | 27.31 | 36.44 |
| *Skewness* | 0.29 | 0.78 | -0.26 | 0.75 | 0.77 | 0.35 | 0.51 | 3.73 | 4.97 | 5.91 |
| *Minimum* | 4.75 | -0.57 | 0.14 | 1089.77 | -0.89 | 20.00 | 423.84 | 0.85 | 0.49 | 91.82 |
| *Maximum* | 59.11 | 3.82 | 1.04 | 12343.87 | -0.50 | 40.00 | 3846.46 | 1503.73 | 1134.20 | 1051.33 |
| Bed load | $\chi_{lf}$ | $\chi_{fd\%}$ | $\chi_{ARM}$ | SIRM | S-Ratio | $B_{(0)CR}$ | SoftIRM | HIRM | HIRM/ SoftIRM | SIRM/$\chi_{lf}$ |
| *Mean* | 11.53 | 0.92 | 0.20 | 1684.11 | -0.81 | 24.19 | 672.98 | 32.97 | 59.49 | 121.47 |
| *Median* | 6.28 | 0.94 | 0.09 | 609.26 | -0.83 | 22.00 | 291.37 | 6.45 | 26.08 | 129.94 |
| *Standard Deviation* | 15.12 | 2.71 | 0.28 | 2997.30 | 0.12 | 6.12 | 1101.66 | 103.72 | 99.25 | 63.34 |
| *Kurtosis* | 7.36 | 3.60 | 4.45 | 8.58 | 3.20 | 0.04 | 8.62 | 38.71 | 7.57 | 0.50 |
| *Skewness* | 2.62 | -0.74 | 2.30 | 2.94 | 1.37 | 0.43 | 2.87 | 5.97 | 2.85 | 0.43 |
| *Minimum* | 0.54 | -8.11 | 0.01 | 43.02 | -1.00 | 10.00 | 7.45 | 0.04 | 0.44 | 12.88 |
| *Maximum* | 72.18 | 7.63 | 1.11 | 13871.33 | -0.38 | 40.00 | 5222.71 | 716.74 | 444.64 | 295.33 |

$\chi_{lf}$ *vs.* $IRM_{0.3T}$: This plot (Fig. 2C) is used to discriminate the softer ferrimagnetic concentration in both floodplains and bed load. The better linear regression ($R^2$= 0.83) for floodplains is observed than bed load confirming the uniform concentration of soft ferrimagnetic mineralogy in floodplains.

$\chi_{lf}$*/M vs. SIRM/*$\chi_{lf}$: The $\chi_{lf}$ /M vs. SIRM/$\chi_{lf}$ plot (Fig. 2D) where M=IRM0.3T/IRM1T is devised here to broadly depict the grain size variation within the magnetite (*s.s.* titanomagnetites) grains. Since most of the magnetite grains are saturated well within an IRM forward field of 300mT, the M=1 can be related to unimodal magnetite dominant mineralogy. While M<1 indicates a mixed mineralogy mainly due to the harder fraction of anti-ferromagnetic origin. The ratio $\chi_{lf}$/M would, therefore, be affected by the mixed (polymodal) to unimodal variability of magnetite. The well-defined parameter of SIRM/$\chi_{lf}$ is further used to depict the relative variation in grain size (Evans and Heller, 2003). The biplot of $\chi_{lf}$/M vs. SIRM/$\chi_{lf}$ therefore, demonstrates the variability of magnetites (/titanomagnetites) for the floodplains with better cluster and the channel sand with higher scattering.

Overall the commonly used ratios and bi-plots confirm a unimodal ferrimagnetic nature with high concentration for the floodplain sediments. The polymodal nature with relatively low ferrimagnetic concentration of variable domain size is demonstrated for the bed load sediments. These two contrasts in the magnetic mineralogy can, therefore, be used further to elaborate the characteristics of the GDB sedimentation and sediment transport.

### Mineral Magnetic Characteristics of Bengal Fan Sediments

The sediment cores collected from the continental slope to deeper fan region of western Bay of Bengal are also analyzed for the routine mineral magnetic parameters. These sediments are further analyzed on VSM to calculate the $\chi_{ferri\%}$ and $\chi_{para\%}$ from hysteresis loop analysis. Locally weighted least squares (LOWESS)- smoother lines (0.5 degree of smoothing per 2 steps) are derived using the MINITAB statistical software further to depict the broad trend for variation in the rock magnetic parameters as a function of depth. In the absence of any chronologic control and considering the age-depth model of cores located in the vicinity of Godavari submarine fan (e.g. for turbidity free core KL 31/1 of Chauhan and Vogelsang, 2006), at 300 cm depth the $^{14}$C age asigned is ~11 ka BP. This help us to describe a broad trend upwards from Holocene to Recent.

The vertical distribution of concentration dependent parameters ($\chi_{lf}$, $\chi_{ARM}$ and SIRM) in all the cores notably shows an increasing upward trend (Fig. 3). These parameters indicate increasing ferrimagnetic content towards the Recent sedimentation. The core SM 43/100 located near the upper continental shelf region shows increasing trend in $\chi_{lf}$, $\chi_{ARM}$, SIRM and $Soft_{IRM}$ from 120 cm towards top. The dashed lines in figure 3 depicting the correlation for this increasing trend agrees well with rest of the distal cores further satisfying with the low rate of sedimentation towards the deeper part. Such an increasing trend towards top is also well marked in the detail susceptibility analysis of the Bengal fan cores from the middle fan region off the Godavari delta (Sangode et al., 2001). If we correlate the sensitivity of ferrimagnetic concentration of finer (~SD) fraction to the

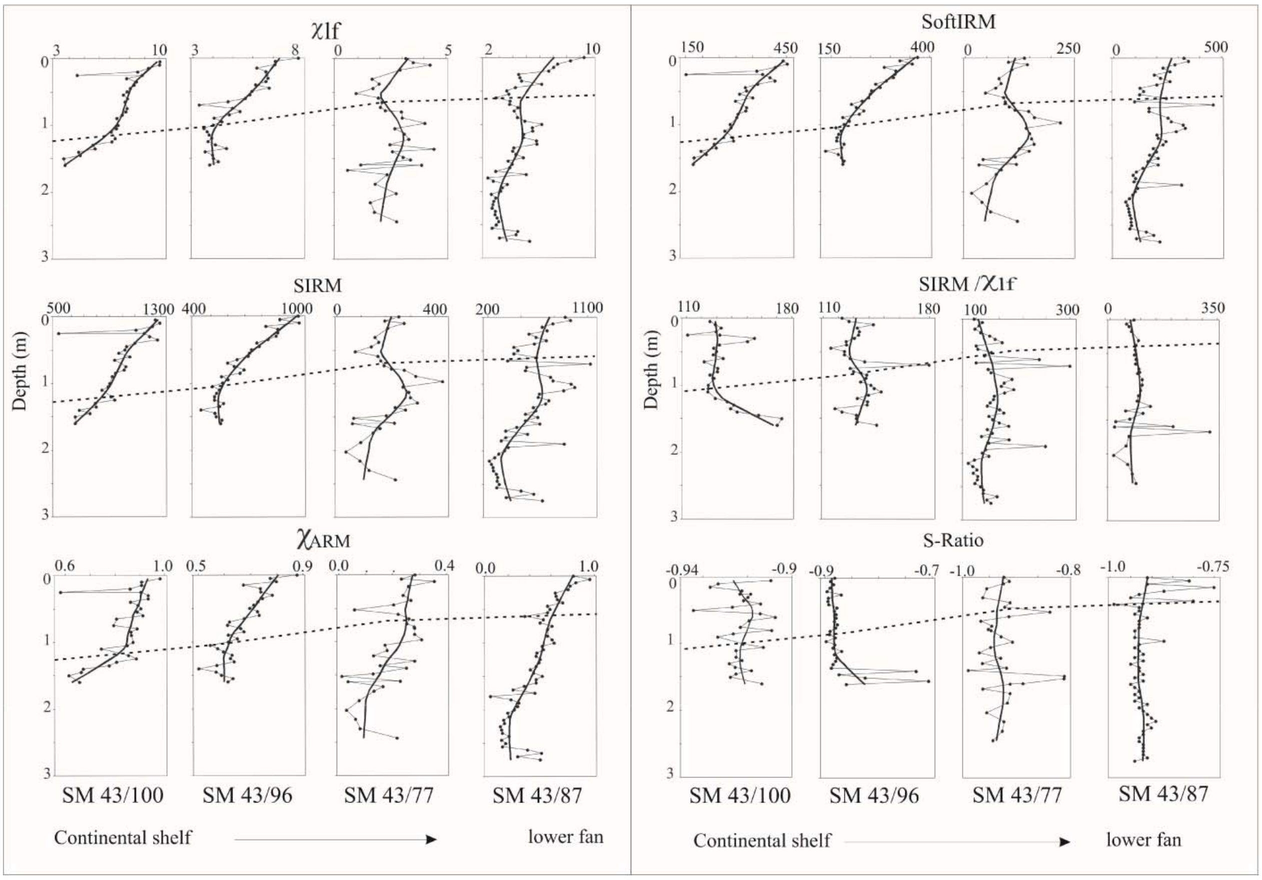

**Fig.3.** Down core variation in major mineral magnetic parameters for four Bengal fan sediment cores (detail discussed in text). (Units for magnetic parameters: $\chi_{lf} = 10^{-8}$ m$^3$/kg, SIRM = $10^{-5}$ Am$^2$/kg, $\chi_{ARM} = 10^{-5}$ m$^3$/kg, Soft$_{IRM}$: $10^{-2}$ A/m$^2$)

Deccan source marked by the floodplain sedimentation, as inferred above, then the increasing trend in the sediment cores can be asigned to relatively higher influx of the Deccan source. Almost similar trend can be observed between SIRM and Soft$_{IRM}$ suggesting the significant contribution of softer ferrimagnetic mineralogy for this interval. The ratio SIRM/$\chi_{lf}$ does not show any significant trend from 120 cm above in all the cores indicating that the mineralogy do not vary significantly with increasing susceptibility. The $\chi_{lf}$/M ratio for Bengal fan core shows increasing trend similar to susceptibility trend, indicating magnetite (titano-magnetite) as major mineral responsible for overall increase in susceptibility. The hysteresis loop analysis of two cores SM 43/100 and SM 43/87 from continental shelf towards deeper fan region respectively, shows increasing trend of $\chi_{ferri\%}$ (Fig. 4) confirming above results. Further the decreasing upward trend in $\chi_{para\%}$ can be attributed to the depleting influx of para/diamagnetic source.

## DISCUSSION

The long term variation (100 to 1000 year scale) of sediment flux into the Bengal fan and the weathering patterns in the GDB is greatly controlled by the distribution and intensity of the monsoon. Large part of the Deccan volcanic province falls in the rain shadow zone experiencing low MMR while the eastern part of GDB, mainly constituting the non-basaltic and silisiclastic terrain falls under high MMR (Nageshwar Rao, 2001). These two provinces with their monsoonal influence therefore can be marked by two distinct zones as shown in Fig.1c. Field observations in Zone B shows extensive channel aggradation and thick sedimentation resulting from physical weathering of sedimentary, granitic and metamorphic terrains with relatively poor ferrimagnetic concentration. Zone A on the other hand shows the degraded and incised channel morphology in Deccan basalt with relatively low physical but higher chemical weathering. This demonstrates the differential monsoonal sensitivity of the sediment source with chemical and physical weathering characteristics for zone A and B respectively. The basalt is relatively more susceptible to chemical weathering due to the presence of the mafic minerals (Goldich, 1938) than other rocks (like granites and quartzo-felspathic sedimentary rocks) present

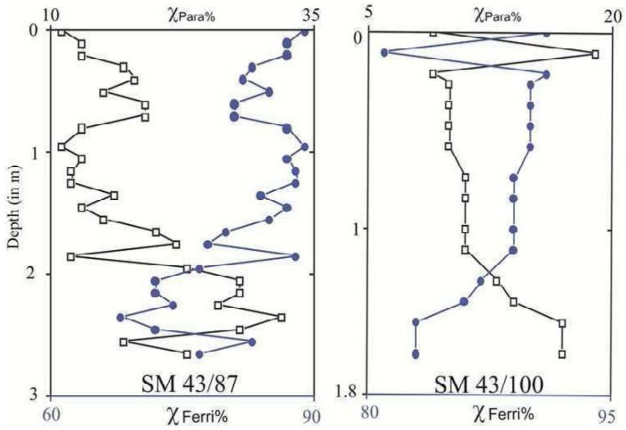

**Fig.4.** $\chi_{ferri\%}$ (line with empty squares) and $\chi_{para\%}$ (lines with filled circles) derived for two distant sediment cores from Bay of Bengal.

in the cratonic region. Hence during weaker monsoon the contribution of suspended and dissolved sediments may dominate from the basaltic province of zone A and this finer sediment load can be transferred to longer distance up to the sink even during low discharge and minimum energy conditions. The unimodal ferrimagnetic nature of the floodplain sediments closely agrees with Deccan basalt source, while its distal extent is further confirmed by the high smectite clay sourced from Deccan basalt weathering previously reported in suspended sediments of Godavari river (Subramanian, 1987). It is postulated that the low MMR in zone A covering DVP can substantially provide the basaltic soil to river and further into the Bay of Bengal during weaker monsoon. Whereas, during stronger monsoon it is anticipated to cause intense physical weathering from zone B producing majority of the quartzo-felspathic material with low ferrimagnetic nature expressed in Bengal fan cores by low magnetic susceptibility.

The rising trend of the ferrimagnetic flux into the western Bay of Bengal marked by the rock magnetic parameters in the sediment cores, therefore, can be related to the weakening of the non-basaltic source and relative increase in the basaltic source. The lower ferrimagnetic concentration in the sediments below ~60 cm for the distal cores like SM 43/87 can also be attributed to the relative predominance of Himalayan sources in agreement with the previous inferences (e.g. Sangode et al., 2001, Reddy and Rao, 2001). With the limitation on age and variable rate of sedimentation, the present work cannot be used for paleomonsoon variability. However the age-depth model of cores located in the middle Bay of Bengal and in the vicinity of Godavari submarine fan can be used for age determination. For middle Bengal fan cores, the Last Glacial Maxima (LGM) was reported at depths of ~60 to 100 cm (Cullen, 1981; Duplessey, 1982). Chauhan and Vogelsang (2006) reported 11 ka BP $^{14}$C age at 300 cm depth in turbidity free core which lies south of Godavari-Krishna rivers on western Bay of Bengal. Nageswara Rao et al. (2012) suggests increasing rate of sedimentation and seaward progradation of Godavari delta during past 6 ka perhaps due to the deforestation and soil erosion in Godavari catchment. Recently Ponton et al. (2012) carried out carbon and oxygen isotope studies on a $^{14}$C AMS dated core off the Godavari delta where hemi-pelagic sediments show accumulation rates higher than 30 cm/ka throughout the Holocene. Based on these age-depth models we can assume that the Deccan basaltic source in the studied cores dominated during late Holocene up to Recent.

## CONCLUSION

The distinct sediment transfer mechanism from Godavari basin to the Bay of Bengal is observed from mineral magnetic studies of the river sediments and sediment cores. This study reveals that the floodplains in Godavari are characterized by ferrimagnetic source from the Deccan basalt weathering that is expressed in the sediment cores from western Bengal fan region. The increasing upwards trend in ferrimagnetic mineralogy from approximately late Holocene in the Bengal fan cores suggests the relative predominance of basaltic source over the siliciclastic cratonic source as an interplay of weathering and monsoonal intensity. More such studies with better chronologic controls on the Bengal fan sediments, Godavari delta and the Godavari drainage basin are warranted to test the hypothesis for reconstruction of paleomonsoon variability using sediment flux and sediment source mixing models based on mineral magnetism.

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## References

Alekseeva, T., Alekseev, A., Maher, B.A. and Demkin, V. (2007) Late Holocene climate reconstructions for the Russian steppe, based on mineralogical and magnetic properties of buried palaeosols. Palaeogeogr. Palaeoclimatol. Palaeoecol., v. 249(1), pp. 103-127.

Balsam, W. L., Ellwood, B. B., Ji, J., Williams, E. R., Long, X. and El Hassani, A. (2011) Magnetic susceptibility as a proxy for rainfall: Worldwide data from tropical and temperate climate. Quat. Sci. Rev., v.30(19), pp.2732-2744.

Caitcheon, G.G. (1998) The application of environmental magnetism to sediment source tracing: A new approach; CSIRO Land and Water technical report, 21/98.

Chauhan, O.S. and Vogelsang, E. (2006) Climate induced changes in the circulation and dispersal patterns of the fluvial sources during late Quaternary in the middle Bengal Fan. Jour. Earth Sys. Sci., v.115/3, pp.379-386.

Cullen, J.L. (1981) Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20,000 years. Palaeogeogr. Palaeoclimatol. Palaeoecol., v.35, pp.315-356.

Dunlop, D.J. and Özdemir, Ö. (2001) Rock magnetism: fundamentals and frontiers (Vol. 3). Cambridge Univ. Press.

Duplessy, J.C. (1982) Glacial to interglacial contrasts in the northern Indian Ocean. Nature, v. 295, pp. 494-398.

Evans, M.E. and Heller, F. (1994) Magnetic enhancement and paleoclimate: study of a loess/paleosol couplet across the Loess Plateau of China. Geophys. Jour. Internat., v.117, pp.257-264.

Evans, M.E. and Heller, F. (2003) Environmental Magnetism: Principles and Applications of Enviromagnetics. Inter. Geophysics Series, v.86, pp.21-22.

Geiss, C.E., Egli, R. and Zanner, C. W. (2008) Direct estimates of pedogenic magnetite as a tool to reconstruct past climates from buried soils. Jour. Geophys. Res, v.113, B11102.

Goldich, S.S. (1938) A study in rock-weathering. Jour. Geol., pp.17-58.

Goodbred, S.L., Kuehl, S.A., Steckler, M.S. and Sarker, M.H. (2003) Controls on facies distribution and stratigraphic preservation in the Ganges–Brahmaputra delta sequence. Sediment. Geol., v.155(3), pp.301-316.

Horng, C.S. and Huh, C.A. (2011) Magnetic properties as tracers for source-to-sink dispersal of sediments: A case study in the Taiwan Strait. Earth Planet. Sci. Lett., v.309(1), pp.141-152.

Kulkarni, Y.R., Sangode, S.J., Meshram, D.C., Patil, S.K. and Dutt, Yatindra (2014) Mineral magnetic characterization of the Godavari River sediments, Jour. Geol. Soc. India, v.83, pp.376-384.

Lees, J. A. (1994) Modelling the magnetic properties of natural and environmental materials. Unpublished Ph.D. Thesis, University of Coventry, UK.

Li, H., Zhang, S., Fang, N. and Wang, H. (2006) Magnetic records of Core MD77-181 in the Bay of Bengal and their paleoenvironmental implications. Chinese Sci. Bull., v. 51(15), pp.1884-1893.

Ponton, C., Giosan, L., Eglinton, T.I., Fuller, D.Q., Johnson, J.E., Kumar, P. and Collett, T.S. (2012) Holocene aridification of India. Geophys. Res. Lett., v.39(3), L03704.

Rao, K.N., Saito, Y., Nagakumar, K.C.V., Demudu, G., Basavaiah, N., Rajawat, A.S., Tokanai, F., Kato, K. and Nakashima, R. (2012) Holocene environmental changes of the Godavari Delta, east coast of India, inferred from sediment core analyses and AMS $^{14}$C dating. Geomorphology, v.175–176, pp. 63–175.

Rao, G.N. (1999) Monsoon rainfall and its variability in Godavari river basin. Jour. Earth Sys. Sci., v.108(4), pp.327-332.

Rao, G.N. (2001) Occurrence of heavy rainfall around the confluence line in monsoon disturbances and its importance in causing floods. Jour. Earth Sys. Sci., v. 110(1), pp. 87-94.

Reddy, N.P.C. and Mohana Rao, K. (2001) Heavy sediments influx during early Holocene: Inference from clay mineral studies in a core from the Western Bay of Bengal. Curr. Sci., v. 81/10, pp. 1361-1364.

Sagar, W.W. and Hall, S.A. (1990) Magnetic properties of black mud turbidites form ODP leg 116, distal Bengal fan, Indian Ocean. *In:* J.R. Cochran and D.A.V.O. Stow, D et al. (Eds.), Proc. Ocean Drilling Program. Scientific Results, v.116, pp.317-336.

Sangode, S.J., Suresh, N. and Bagati, T.N. (2001) Godavari source in the Bengal fan sediments: results from magnetic susceptibility dispersal pattern. Curr. Sci., v.85(5), pp.660-664.

Sangode, S.J., Sinha, R., Phartiyal, B., Chauhan, O. S., Mazari, R.K., Bagati, T.N., Suresh, N., Mishra, S., Kumar, R. and Bhattacharjee, P. (2007) Environmental magnetic studies on some Quaternary sediments of varied depositional settings in the Indian sub-continent. Quat. Int., v.159, pp.102-118.

Sangode, S.J., Meshram, D.C., Kulkarni, Y.R., Gudadhe, S.S., Malpe, D.B. and Herlekar, M.A. (2013) Neotectonic Response of the Godavari and Kaddam Rivers in Andhra Pradesh, India: Implications to Quaternary Reactivation of old fracture system. Jour. Geol. Soc. India, v.81, pp.459-471.

Subramanian, V. (1987) Environmental geochemistry of Indian rivers. Jour. Geol. Soc. India, v. 29, pp. 205-220.

Tarling, D. and Hrouda, F. (Eds.) (1993) Magnetic anisotropy of rocks. Springer.

Thompson, R. and Oldfield, F. (1986) Environmental Magnetism. Allen & Unwin, London, pp.20-22.

Walden, J., Slattery, M.C. and Burt, T.P. (1997) Use of mineral magnetic measurements to fingerprint suspended sediment sources: approaches and techniques for data analysis. Jour. Hydro., v. 202(1-4), pp. 353-372.

Walling, D.E., Woodward, C. and Nicholas, A.P. (1993) A multi-parameter approach to fingerprinting suspended sediment sources. Tracers in Hydrology. Proceedings of the Yokohama Symposium, v.215, pp.329-338.

Yu, L. and Oldfield, F. (1989) A multivariate mixing model for identifying sediment source from magnetic measurements. Quat. Res., v.32, pp.168-181.

Yu, L. and Oldfield, F. (1993) Quantitative sediment source ascription using magnetic measurements in a reservoir-catchment system near Nijar, SE Spain. Ear. Surf. Proc. Land., v.18, pp.441-454.

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