JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.83, April 2014, pp.376-384

Mineral Magnetic Characterization of the Godavari River Sediments: Implications to Deccan Basalt Weathering

Y. R . Kulkarni[1], S. J. Sangode[1], D. C. Meshram[1], S. K. Patil[2] and Yatindra Dutt[1]
[1]Department of geology, University of Pune, Pune - 411 007
[2]Dr. K.S. Krishnan Geomagnetic Research Laboratory (IIG), Allahabad - 221 505
Email: sangode@unipune.ac.in

Abstract: Mineral magnetic analysis including thermo-magnetic studies and clay mineralogy on bed load and floodplain sediments from the Godavari river indicate distinct mineral assemblages. The floodplain sediments up to the delta region are characterised by unimodal ferrimagnetic mineralogy marked by the presence of maghemite and single domain magnetites derived from Deccan basalts. On the other hand the bed loads show varied magnetic mineral assemblages depicting greater local mixing from the non-basaltic bedrock province. The temperature dependent magnetic susceptibility and clay mineralogy of the floodplain samples show titanomagnetites (Fe_3O_4-Fe_2TiO_4), maghemite (χ_{LF}-Fe_2O_3) and smectite that are characteristic of the Deccan Volcanic Province (DVP). Presence of this ferrimagnetically dominant unimodal assemblage up to the delta region and probably into the Bay of Bengal off the Godavari river is attributed to extensive chemical weathering of the basalt. The quantitative approach of mineral magnetism, therefore, can be used to study the paleomonsoon variability and its relation to Deccan basalt weathering from the Godavari- Bengal fan system.

Keywords: Godavari river, Mineral magnetism, Deccan basalt weathering.

INTRODUCTION

Sediment supplies from continental sources to adjoining seas are greatly influenced by climatic and tectonic variables at various spatio-temporal scales (Milliman and Meade, 1983; Vaithyanathan, et al. 1988; Wasson, 2003, Chakrapani, 2005). Relating the sediment characteristics to their provenance/sources is, therefore, essential to understand the mechanism of transport and sediment flux. Mineral magnetism is a routinely used approach for such studies to characterize the sediment source, sediment dispersal and sediment mixing patterns amongst 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). With a set of remanent magnetic hysteresis parameters, mineral magnetism provides a robust technique of rapid and accurate qualitative and quantitative estimates on various aspects of sedimentation (outlined in Thompson and Oldfield, 1986; Evans and Heller, 1994, 2003; Dekkers, 1997). However a detailed knowledge on the controls of the magnetic mineral assemblages under given sedimentary environments is a prerequisite to correctly infer the mineral magnetic signatures. Mineral magnetic studies were previously carried out in the western Bengal fan sediments suggesting their major source is Deccan volcanic province by pathways of Godavari and Krishna rivers (Sagar and Hall, 1990; Sangode et al., 2001; Sangode et al., 2007). However a proper linkage with the recent sediments from the Godavari drainage basin which carries the Deccan source is yet to be established. We, therefore, attempt to characterize the floodplain and bed load from the Godavari river using mineral magnetism and clay mineral studies.

THE GODAVARI DRAINAGE BASIN

The Godavari drainage basin represents the largest catchment area (3,13,147 km^2) in the Peninsular India covering a variety of rock units with contrasting magnetic mineralogy and their concentrations ideally suited for the mineral magnetic approach. The primary/initial catchment of the Godavari drainage basin is largely represented by the titanomagnetite rich DVP (~50% of the total basin area, see Fig. 1a). This is followed by the moderately ferrimagnetic but abundant para- and dia- magnetic Precambrian granites and gneisses of the eastern Dharwar craton, mixed antiferromagnetic to ferrimagnetic sandstones, shales and limestones of Gondwana Supergroup, various sedimentary units of Cuddapah and Vindhyan basins, charnockites and

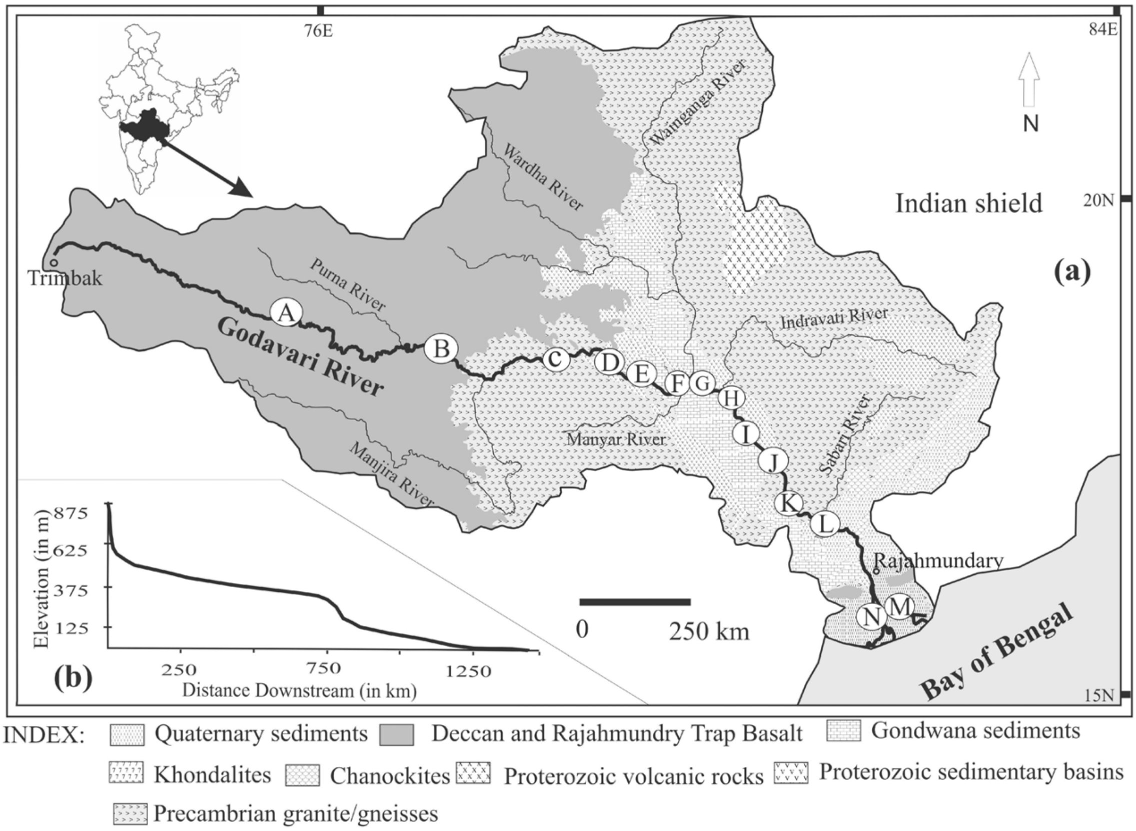

Fig.1. **(a)** Generalized geological map of the Godavari basin prepared from GSI map (scale 1: 2,50,000) showing sampling locations A to N. **(b)** Longitudinal profile of the Godavari River (After Sangode et al., 2013).

khondalites of the Proterozoic EGMB (Eastern Ghat Mobile Belt) and the sandstones of Rajahmundry formation. The Godavari river also carries the largest sediment load ($170x10^6$tonnes/year) amongst the peninsular rivers (Subramanian, 1987) and average sediment load in monsoonal season (for year 2001) is ~9,25,703 tonnes/day (Central Water Commission, 2006). Majority of the mass transfer in Godavari occur during monsoon (Bikshamaiah and Subramanian, 1980) and it is observed that the basin is being eroded at higher rates than the global average (Bikshamaiah and Subramanian 1980, Dessert et al 2001).

The longitudinal profile for Godavari (see Fig. 1b) shows distinct topographic/geomorphic domains marked by the Deccan upland, the Precambrian granitic- fractured lowland and the linear crustal structures of the Pranhita-Godavari rift valley basin. Therefore, we followed the fieldwork and sampling approach based on these unique characteristics of the Godavari river basin.

FIELDWORK, SAMPLING AND LABORATORY ANALYSIS

The floodplains and bed load samples (total 113) were collected from 14 sites along the Godavari river considering different litho-units (see Fig 1a). Out of 14 sites, two sites (A, B) are from Deccan Basalt, three sites (C, D, E) from Precambrian granites, six sites (F, G, H, I, J, K) from the Pranhita-Godavari basin, one site (L) from charnockitic belt and two sites (M, N) from the distributaries of Godavari (*i.e.* Gautami-Godavari and Vashisti-Godavari) within the delta plain. The samples were subjected to coning and quartering in laboratory for the mineral magnetic and clay mineral studies. For X- ray Diffraction study, 3 representative floodplain samples were taken from Site B, I, and M to cover entire stretch of Godavari river.

Three sub-samples (specimens) of 10 gm each were tightly packed into non-magnetic (polystyrene) pots following the standard procedures for mineral magnetism (given in Walden et al., 1999). The low field magnetic susceptibility (χ_{lf}) was measured using Bartington's MS2B sensor which operates at a frequency of 0.465 and 4.65 KHz and at an alternating field intensity of 80 A/m (= 0.1 mT) with measuring range of 1 x 10^{-5} to 9999 x 10^{-5} (SI unit volume specific). The frequency dependent susceptibility (χ_{fd}) was determined by measuring the samples in both the frequencies (0.465 and 4.65 KHz). Isothermal Remanent

Magnetization (IRM) was used to generate the remanent hysteresis spectra for each sample. The Molspin pulse magnetizer and Minispin fluxgate spinner magnetometer (both from Molspin, UK) were used to generate the IRM spectra for forward fields of 300, 500 and 1000 mT and back fields of -5, -10, -20, -30, -50, -75, -100 and -300 mT.

We discovered that all the samples saturate well below the fields of 1000 mT and, hence, the parameter Saturation Isothermal Remanant Magnetization (SIRM) was calculated at this field by mass normalization. Further the hard and soft contributions to SIRM are represented by the parameters HIRM {=((SIRM+(-300mt))/2/mass} and SoftIRM {=((SIRM-(-20mt))/2/mass}, respectively. An Anhysteretic Remanent Magnetization (ARM) was grown with an alternating decaying field of 100 mT peak superimposed over 0.1 mT DC field using Molspin Alternating field demagnetizer. The susceptibility of ARM (=χ_{ARM}) was calculated by normalizing the mass specific ARM with the Bias field. Further the mineral magnetic studies facilitate standard plots for characterization based on bulk natural samples, magnetic separates and various mixtures (e.g., Oldfield and Clark, 1990; Walden et al., 1992; Lees, 1994; Walden and Smith, 1995; Thompson and Oldfield, 1986; Peters and Dekkers, 2003). For the present study we used four most common standard plots i.e. χ_{lf} vs SIRM, χ_{lf} vs HCR, Klf vs ARM and χ_{lf} vs. χ_{ARM}.

Thermo-magnetic (temperature dependent magnetic susceptibility variation) analysis was conducted using Bartington's (UK) MS2WFP unit with high temperature ranges from 30° to 700°C and low temperature ranges from -196°C under liquid nitrogen up to room temperatures. Both high and low temperature susceptibility study was carried out for the floodplain sediments. The high temperature magnetic susceptibility curves for bed load are noisy because of the lower susceptibility for majority of litho units in the province except for Deccan traps. Therefore, we separated and analysed heavy minerals from 63 to 250 µm fraction for the bed load for further low temperature susceptibility analysis.

For X-Ray Diffraction study the samples were treated with acetic acid and hydrogen peroxide for removal of calcium carbonate and organic matters respectively. A dispersal agent (sodium hexa-metaphosphate) was added for effective dispersal. Ultrasonic bath run was given and the samples were allowed to settle for 2 hours to remove any silt fraction if present. Oriented glycolated clay slides were prepared for 3 representative samples and scanned to 2-theta range from 2° to 65° in Bruker's AXS Diffractometer based on Cu-K alpha radiation. The pre-treatment procedure and identification of clay minerals are based on USGS manual for X-ray diffraction (Poppe et al., 2001).

RESULTS AND DISCUSSION

The basic statistical parameters (Table 1) show significantly higher mean values for the concentration dependent parameters χ_{lf}, χ_{ARM} and SIRM for the floodplain sediments depicting high ferrimagnetic concentration compared to the bed load. At the individual sites the bed load show high values only for the samples falling within Deccan trap region. However the floodplain sediments maintain consistent high values for χ_{lf}, χ_{ARM} and SIRM up to the distant sites in the delta region (M & N in Fig. 1) indicating overall predominance of the ferrimagnetic mineralogy for the entire stretch of the Godavari river. The

Table 1. Descriptive Statistics for Mineral magnetic parameters of bed load and floodplain sediments

	χ_{LF}	$\chi_{FD\%}$	χ_{ARM}	SIRM	S-Ratio	SoftIRM	HIRM	SIRM/χ_{lf}	$B_{0(CR)}$
Floodplains									
Mean	28.42	1.60	0.64	4703	-0.73	1784	142.96	176.60	27.23
Median	26.91	1.59	0.66	4173	-0.72	1684	47.26	156.51	28.00
Standard Deviation	12.58	0.89	0.22	2559	0.07	855	278.49	144.95	5.36
Kurtosis	-0.41	1.56	-0.43	0.43	2.53	-0.18	15.52	36.44	-0.60
Skewness	0.29	0.78	-0.26	0.75	0.77	0.51	3.73	5.91	0.35
Minimum	4.75	-0.57	0.14	1089	-0.89	423	0.85	92	20.00
Maximum	59.11	3.82	1.04	12343	-0.50	3846	1503	1051	40.00
Bed loads									
Mean	11.53	0.92	0.20	1684	-0.81	672.98	32.97	121.47	24.19
Median	6.28	0.94	0.09	609	-0.83	291.37	6.45	129.94	22.00
Standard Deviation	15.12	2.71	0.28	2997	0.12	1101	103.72	63.34	6.12
Kurtosis	7.36	3.60	4.45	8.58	3.20	8.62	38.71	0.50	0.04
Skewness	2.62	-0.74	2.30	2.94	1.37	2.87	5.97	0.43	0.43
Minimum	0.54	-8.11	0.01	43.02	-1.00	7.45	0.04	12.88	10.00
Maximum	72.18	7.63	1.11	13871	-0.38	5222	716.74	295.33	40.00

Table 2. Correlation matrix (along with P values) for Mineral magnetic parameters of bed load and floodplain sediments

	χ_{LF}	$\chi_{FD\%}$	χ_{ARM}	SIRM	S-Ratio	SoftIRM	HIRM	SIRM/χ_{lf}
Floodplains								
$\chi_{FD\%}$	-0.215							
χ_{ARM}	0.717	0.05						
SIRM	0.911	-0.342	0.717					
S-Ratio	0.293	-0.07	0.231	0.418				
SoftIRM	0.84	-0.3	0.68	0.946	0.498			
HIRM	0.008	0.091	0.015	0.067	0.468	0.161		
SIRM/χ_{lf}	-0.175	-0.244	0.248	0.179	0.146	0.19	0.032	
B0(CR)	0.657	-0.251	0.478	0.657	0.287	0.435	-0.039	0.089
Bed loads								
$\chi_{FD\%}$	0.04							
χ_{ARM}	0.911	0.084						
SIRM	0.943	0.042	0.962					
S-Ratio	-0.095	-0.157	0.049	0.013				
SoftIRM	0.951	0.053	0.957	0.993	-0.003			
HIRM	0.289	0.182	0.454	0.292	0.382	0.328		
SIRM/χ_{lf}	0.3	0.103	0.504	0.501	0.147	0.493	0.211	
B0(CR)	0.183	-0.001	0.268	0.271	0.349	0.204	0.033	0.245

correlation matrix in Table 2 depicts negative correlation of the grain size dependent parameters ($\chi_{fd\%}$, χ_{ARM} and $B_{0(CR)}$) with the concentration dependent parameters (SIRM and χ_{lf}) for the floodplain sediments. This indicates that as the concentration increases the grain size enhances from Super Paramagnetic (SP) towards the boundary of Single Domain (SD) to Multi Domain (MD) grains. In contrast, the concentration of ferrimagnetic minerals is dependent on grain size in the bed load samples. This suggests that the greater influx of the ferrimagnetic source (likely Deccan basalts) over the flood plains is marked by the increase in grain size from SD to MD indicating overall detrital nature of the flood plain sediments. The mean S-ratios are higher for the bed loads compared to the floodplains suggesting the predominance of MD/larger grain size for bed load compared to floodplains. The parameters $Soft_{IRM}$ and HIRM are indicative of softer (e.g. magnetite) and harder (e.g. hematite, goethite) dominant mineralogy in the sample. The $Soft_{IRM}$ shows positive correlation with χ_{lf} and SIRM in both floodplains and bed load. Thus the routine statistical parameters although indicate ferrimagnetically dominant mineralogy for floodplain and bedload samples, their concentration and grain size behaviour are distinct.

MINERAL MAGNETIC BI-PLOTS

The bivariate (scatter) relation of the rock magnetic parameters (shown in Fig. 2) enables identification of trends and distinct domains of the sample mineral magnetic properties. The plot of χ_{lf} *vs.* SIRM (adopted from Thompson and Oldfield, 1986) is used here to infer the grain size and concentration relations within the ferrimagnetic concentration. The floodplains show a linear trend depicting the unimodal nature of the sampling domain. On the other hand the bed load shows clustering with at least three modes. The two sites at the right hand corner of the bed load plot are from the Deccan province. After comparison with the standard bivariate plot produced by Bradshow and Thompson (1985) it can be inferred that the floodplain sediments are well distributed in linear fashion with ferrimagnetic minerals in the restricted grain size.

The bi-plot χ_{lf} *vs.* $B_{0(CR)}$ after Thompson and Oldfield (1986) is used to discriminate the mineralogical and grain size domains using the coercivity parameter. For floodplain sediments it shows good clustering in the region of SD magnetite attesting the unimodal mineralogy, whereas, the bed load are dispersed over boundaries of SD to MD magnetites and SP ferrimagnets indicating polymodal nature.

The bi-plot χ_{ARM} *vs.* χ_{lf} shows a linear trend for the floodplain sediments. The χ_{ARM} is sensitive to concentration of SD grains and suggests that the concentration of ferrimagnetic grains is largely controlled by the stable variety of ferrimagnetic particles. The K_{lf} vs. ARM plot (after King et al. 1982) characterizes the grain size trends. The linear trend for the floodplain samples depicts the grain size range from 1 to 0.5 micron after comparison with the standard plot of King et al. (1982). Whereas, the bed load show polymodal composition with variable magnetic grain size.

In summary, all the bi-plots show unimodal mineralogy for the floodplains dominated by SD ferrimagnetic mineralogy of Deccan basalt affinity. Whereas the bed load comprises mixture of ferrimagnetic, paramagnetic and

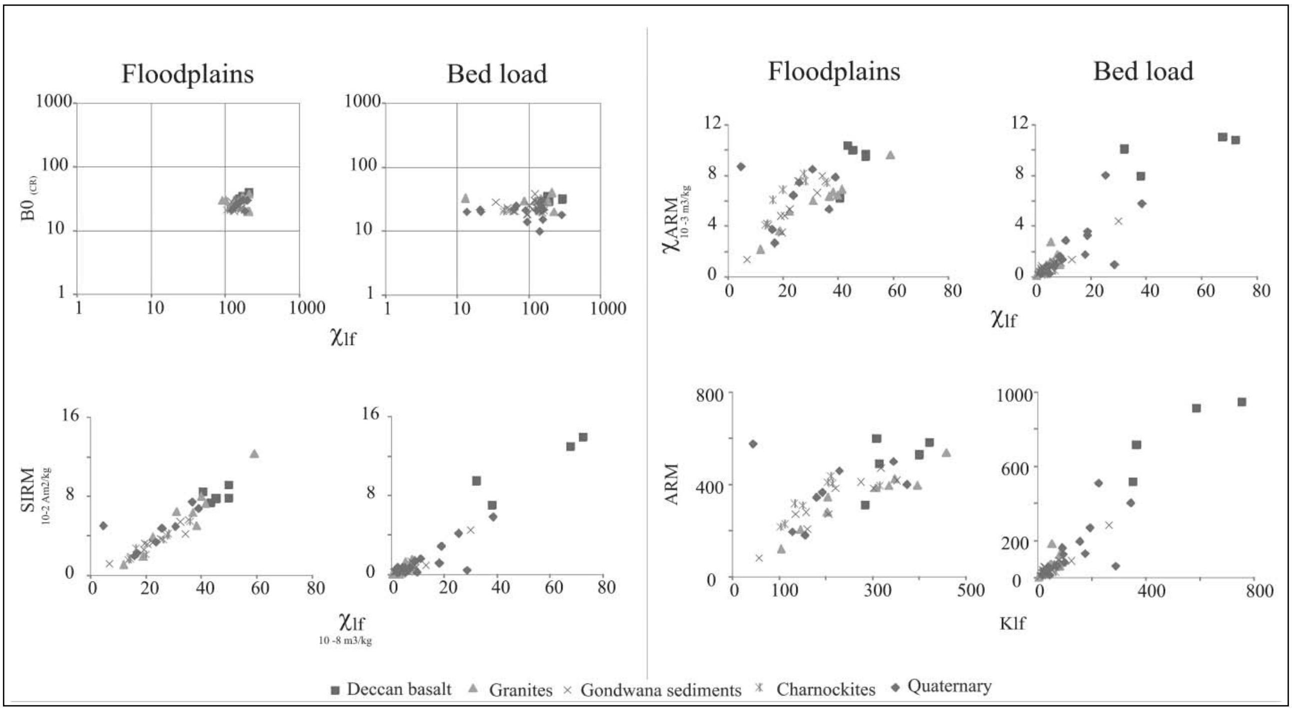

Fig.2. Standard Bi-Plots for the studied mineral magnetic parameters. Details discussed in text.

antiferromagnetic mineralogy derived from a variety of rock types including Precambrian granites, Gondwana sediments and Quaternary deposits.

LONG PROFILE VARIATION IN MINERAL MAGNETIC PARAMETERS OF FLOODPLAINS

The χ_{lf}, χ_{ARM}, SIRM, S-Ratio and SIRM/χ_{lf} values for the floodplain sites are plotted against the downstream distance in long profile (Fig 3). The concentration dependent parameters like χ_{lf}, χ_{ARM} and SIRM show the downward trend due to decrease in concentration of the ferrimagnetic minerals with distance from the Deccan source. The qualitative parameters indicative of mineralogy and domain size maintain a plateau like regression line which justifies the unimodal nature of mineralogy supporting the Deccan source. The qualitative parameters SIRM/χ_{lf} and S-Ratio that are sensitive to mineralogy and domain size do not show any significant slope thus depicting the uniform nature of mineralogy and domain size maintained throughout the Godavari transect.

THERMO-MAGNETIC ANALYSIS

Figure 4 shows the high temperature reversible thermo-magnetic susceptibility variation (from room temperature to 700^{0}C and back to room temperature) for the flood plain samples. All the floodplain samples show irreversible curve with the cooling curve of lower intensity than the heating curve. The sites A and B which fall within the Deccan catchment show high irreversibility with a hump like peak at around 350°C for the heating curve that can either be due to Ti-poor magnetite or the commonly occurring inversion of the meta-stable maghemite (γ-Fe_2O_3) to hematite (α-Fe_2O_3) (as widely discussed in Dunlop and Ozdemir, 1997; Sun et al., 1995; Oches and Banerjee, 1996; Zhu et al., 1999, 2003; Deng et al., 2004). However the drop in susceptibilities above 640°C indicates the later phenomena suggesting significant presence of maghemite and its inversion to hematite (op. cit). The irreversible and lower susceptibilities for cooling curves compared to heating curves further support the production of hematite due to heating in laboratory resulting in the overall lower antiferromagnetic susceptibilities. Another hump like peak at ~550°C in the heating curve for all the samples further marks the presence of Ti-poor magnetite of the titanomagnetite series (Vlag et al., 2000). In general the thermo-magnetic analysis characterizes: a) peak around ~350°C, b) drop after 640°C and c) high irreversibility for all the floodplain samples from sites ‘A’ to the most distal site ‘N’. This depicts the unimodal source for all the floodplain sediments characterising the assemblage of titanomagnetite and maghemite from the DVP catchment till the delta region. The IRM and ARM results in the

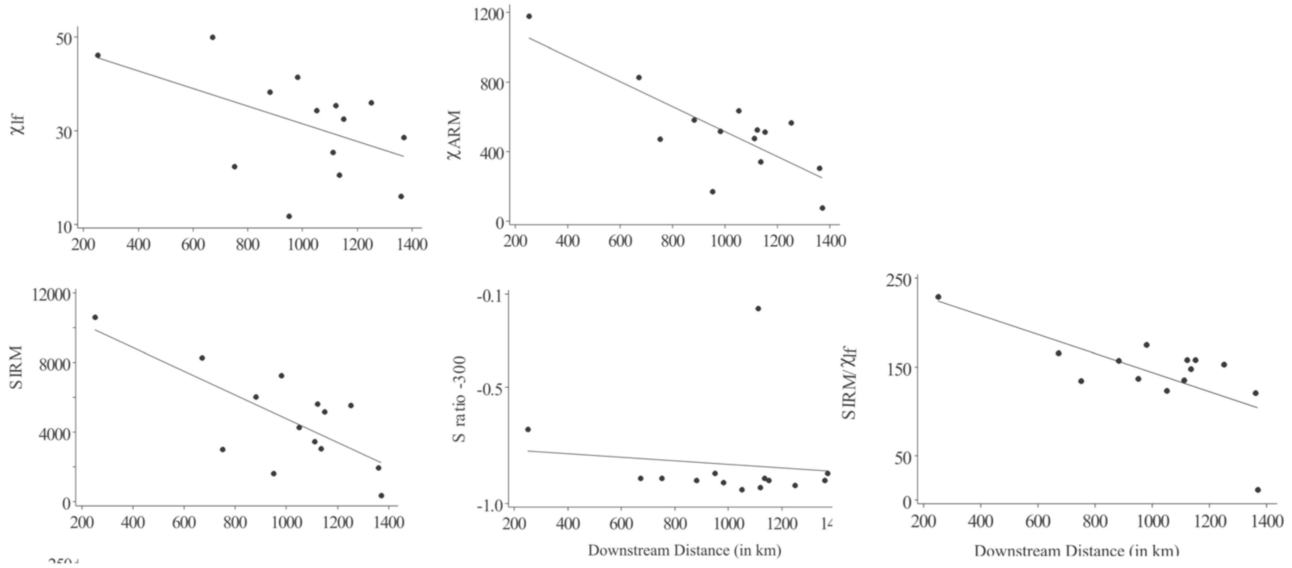

Fig.3. Long profile changes in mineral magnetic parameters for floodplain sediments.

previous sections have shown a range of domain size within SD-MD ferrimagnets whereas thermo-magnetic studies indicate presence of magnetite and maghemite in the entire stretch of floodplains derived from Deccan catchment soils. This overall distribution, therefore, suggests a uniform mineralogy of the finer grain size for the titanomagnetite and maghemites over the flood plains.

As stated earlier, the high temperature thermomagnetic curves show noise in the bed load samples due to weaker ferrimagnetic concentration. Therefore, we used heavy mineral concentration for the bed load samples. These bed load sample concentrates show parabolic nature of the curve for A (Fig. 5a) with high χ_{lf} indicating the presence of Ti-rich magnetites (Moskowitz et al., 1998) characteristic of

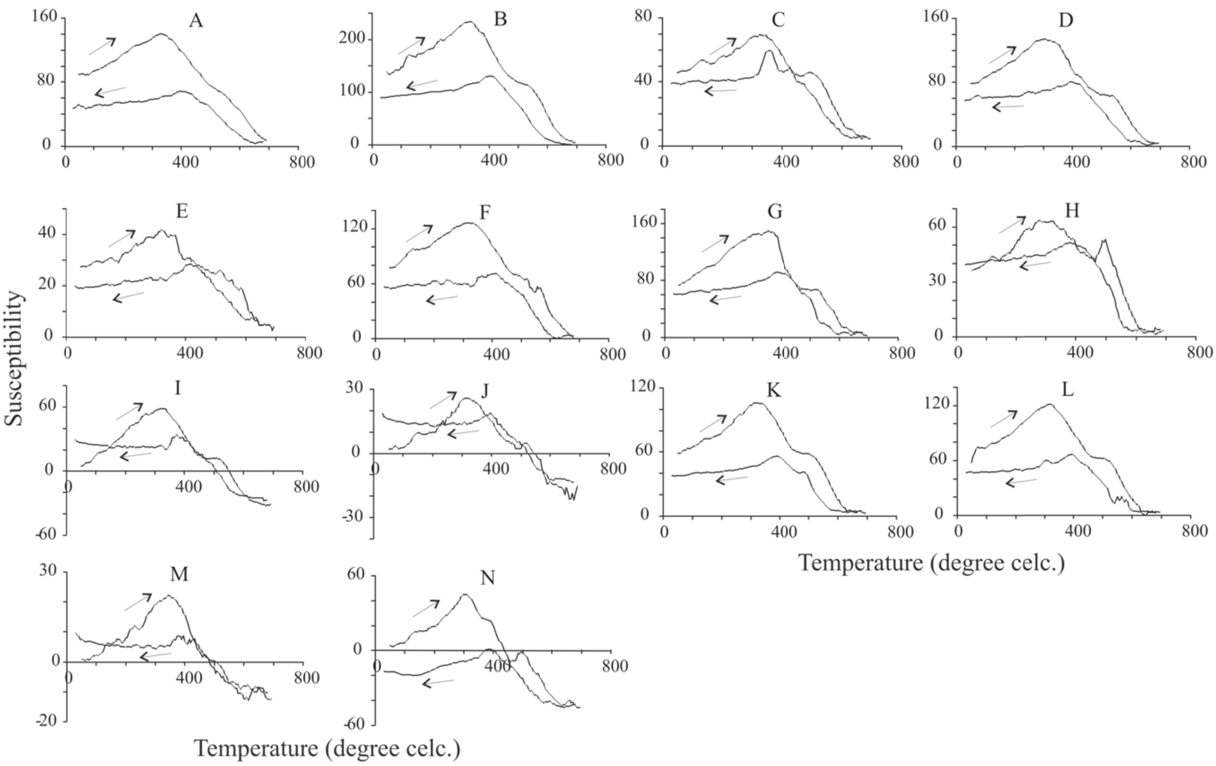

Fig.4. Temperature dependent variation of magnetic susceptibility (K/T) for the floodplain samples.

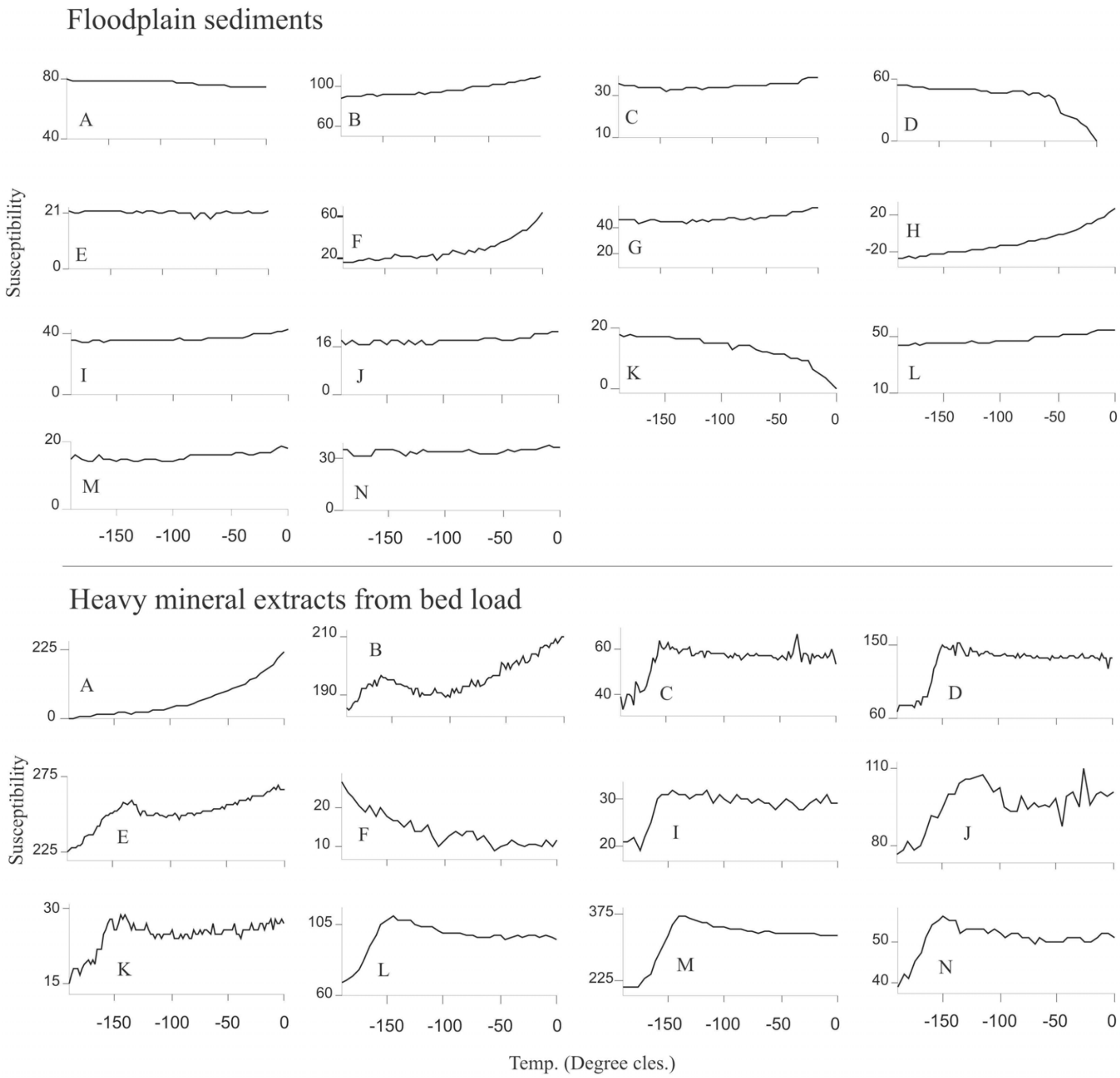

Fig.5. Low temperature (-196^{0}C to Room Temperature) magnetic susceptibility variation for (**a**) heavy mineral extract for the bed load samples and (**b**) the bulk floodplain samples.

DVP. Further a peak at -150°C for the site B along with the parabolic increase in susceptibility during warming to room temperature suggests the presence of MD magnetite along with titanomagnetites. Flat curves with weak Tv (Vervew transition) for the site C suggests the presence of MD magnetites (Ozdemir et al., 1993). Similar trends with Tv are also seen for the sites D and E suggesting the DVP source. The site F shows an entirely different trend marked by the paramagnetic susceptibility suggesting dilution in DVP source and as the site of significant mixing from paramagnetic litho-units. The sites I to N further shows similar trends marked by weak and spread-out Tv. In floodplain sediments (Fig. 5b) majority of the curves have shown flat plateau like nature depicting the predominance of SD ferrimagnets (Thompson and Oldfield, 1986) attesting the results from IRM and ARM.

XRD ANALYSIS

The XRD spectra of glycolated slides for three representative samples show prominent peak at 17.5 Å indicating the presence of smectite (001) clay (Brown and Brindley, 1980; Moore and Reynolds, 1997). This is followed by the peaks for kaolinite (001, 7.18 Å) and illite (003, 3.35 Å). Smectite is the characteristic erosive product of basalt and its presence even in the distal sites of Godavari river, therefore, suggest the DVP source. Previously, the presence of smectite in the middle and western Bengal fan region has been inferred as a result of weathering of the Deccan traps (Kolla and Rao, 1991; Reddy and Rao 2001).

The mineral magnetic results supported by clay mineralogy have shown the unimodal nature of mineralogy for floodplain samples sourced from the DVP. The bed load on the other hand have shown polymodal nature suggesting various detrital modes influenced by the local litho-types and the tributaries joining the Godavari. This indicates the sensitivity of weathering in DVP catchment and its input to suspended sediment load to Godavari during the summer monsoon precipitation. Sangode et al. (2001) previously assigned the Deccan source to high susceptibility peaks for sediments after Last Glacial Maxima (LGM) and in the Bengal fan cores. Further Chauhan and Vogelsang (2006) attributes the Deccan basalt source for the increasing smectite content in the sediment cores from middle Bengal fan region. They suggest that the finer sediments debouching into the Bengal fan off the Godavari coast are likely to be transported farther in the Middle fan region beyond the delta and pro-delta limits attesting a regional control of the DVP source to Bay of Bengal sink.

CONCLUSION

The mineral magnetic, thermo-magnetic and clay mineral studies of Godavari river sediments suggest that the floodplains in the entire stretch of the river are characterized by Deccan basalt source. The bed loads on the other hand are of variable mineralogy and grain size indicating polymodal assemblage due to the local bedrock derived sediment mixing. Influx of Deccan source in the Godavari River up to the delta regions and possibly in the Bay of Bengal off the Godavari, therefore, can be related to the intensive chemical weathering in the DVP. The quantitative approach of mineral magnetism is, therefore, useful to study the weathering of Deccan basalt in the context of monsoonal variability from sediment cores in the western Bay of Bengal off the Godavari delta.

Acknowledgements: The research work was funded by the Department of Science and Technology, New Delhi (grant SR/S4/ES-409/2009). Head, Department of Geology (University of Pune) is acknowledged for providing necessary facilities. We are thankful to Mr. Swapnil Gudadhe for his assistance in fieldwork and Dr S. W. Gosawi of Department of Physics is acknowledged for extending the facility for XRD analysis. An anonymous referee is acknowledged for critical comments and improving the manuscript.

References

Bikshamaiah, G. and Subramanian, V. (1980) Chemical and sediment mass transfer in the Godavari River basin in India. Jour. Hydrol., v.46, pp.331-342.

Bradshaw, R. and Thompson, R. (1985) The use of magnetic measurements to investigate the mineralogy of Icelandic lake sediments and to study catchment processes. Boreas, v.14, pp.203-215.

Brown, G. and Brindley, G.W. (1980) X-ray diffraction procedures for clay mineral identification. *In:* G.W. Brindley and G. Brown (Eds.), Crystal structures of clay minerals and their X-ray identification. Mineralogical Soc. London, pp.305–360.

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

Central Water Commission (2006) Integrated hydrological data book (non-classified river basins). Hydrological Data Directorate, Information Systems Organization Water Planning and Projects Wing, Central Water Commission, New Delhi, India, 383p.

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 System Sci., v.115/3, pp.379–386.

Chakrapani, G.J. (2005) Factors controlling variations in river sediment loads. Curr. Sci., v.88/4, pp.569-575.

Dekkers, M.J. (1997) Environmental magnetism: an introduction. Geologie en Mijnbouw, v.76/1 pp. 163-182.

Deng, C.L., Zhu, R.X., Verosub, K.L., Singer, M.J. and Vidic, N.J. (2004) Mineral magnetic properties of loess/paleosol couplets of the central loess plateau of China over the last 1.2 Myr. Jour. Geophys. Res., 109:B01103. doi:10.1029/2003JB002532.

Dessert, C., Dupre, B., Francois, L. M., Schott, J., Gaillardet, J., Chakrapani, G. and Bajpai, S. (2000) Erosion of Deccan Traps determined by river geochemistry: impact on the global climate and the $^{87}Sr/^{86}Sr$ ratio of seawater. Earth Planet. Sci. Lett., v.188, pp.459-474.

Dunlop, D.J. and Ozdemir, O. (1997) Rock magnetism: fundamentals and frontiers. Cambridge University Press, Cambridge, v.573, pp.266–268.

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

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

King, J., Bannerjee, S.K., Marvin, J. and Ozdemir, O. (1982) A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: some results from lake sediments. Earth Planet. Sci. Lett., v.59, pp.404-419.

Kolla, V. and Rao, N.M. (1991) Sedimentary sources in the surface and near surface sediments of the Bay of Bengal. GeoMarine Lett., v.10, pp.125–136.

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

Milliman, J.D. and Meade, R.H. (1983) World-wide delivery of river sediment to the oceans. Jour. Geol., v.91, pp.1-21.

Moore, D.M. and Reynolds, R.C. (1997) X-ray diffraction and identification and analysis of clay minerals. *2nd edition,* New York: Oxford University Press.

Moskowitz, B.M., Jackson, M. and Kissel, C. (1998) Low-temperature magnetic behavior of titanomagnetites. Earth Planet. Sci. Lett., v.157, pp.141–149.

Oches, E. A. and Banerjee, S.K. (1996) Rock-magnetic proxies of climate change from loess-paleosol sediments of the Czech Republic. Stud. Geophys. Geod., v.40, pp.287–300.

Oldfield, F. and Clark, R.L. (1990) Lake sediment-based studies of soil erosion. *In:* J. Boardman, I.D.L. Foster & J.A. Dearing (Eds.), Soil erosion on agricultural land, pp.201-228.

Ozdermir, O., Dunlop D.J. and Moskowitz, B.M. (1993) The effect of oxidation on the Verwey transition in magnetite. Geophys. Res. Lett., v.20/16, pp.1671-1674.

Peters, C. and Dekkers, M.J. (2003) Selected room temperature magnetic parameters as a function of mineralogy, concentration and grain size. Physics and Chemistry of Earth, v.28, pp.659–667.

Poppe, L.J., Paskevich, V.F., Hathaway, J.C. and Blackwood, D.S. (2001) A laboratory manual for X-Ray powder diffraction. USGS Open-File Report 01-041

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, et al. (Eds.), Proc. ODP–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. Quaternary Internat., 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 river basins - a review. Jour. Geol. Soc. India, v.29, pp.205-220.

Sun, W.W., Banerjee, S.K. and Hunt, C.P. (1995) The role of maghemite in the enhancement of magnetic signal in the Chinese loess-paleosol sequence: An extensive rock magnetic study combined with citrate-bicarbonatedithionite treatment. Earth Planet. Sci. Lett., v.133, pp.493–505.

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

Vlag, P., Alva-Valdivia, L., De Boer, C. B., Gonzalez, S. and Urrutia-Fucugauchi, J. (2000) A rock- and paleomagnetic study of a Holocene lava flow in central Mexico. Physics of Earth Planet. Inter., v.118 (3-4), pp.259-272.

Walden, J. and Smith, J.P. (1995) Factor analysis: a practical application. *In:* D. Maddy and J.S. Brew (Eds.), Statistical modelling of Quaternary Science Data, Technical Guide 5, Quaternary Research Association, Cambridge, pp.39–63.

Walden, J., Smith, J.P. and Dackombe, R.V. (1992) Mineral magnetic analysis as a means of lithostratigraphic correlation and provenance indication of glacial diamicts: Intra- and inter-unit variation. Jour. Quaternary Sci., v.7, pp.257-270.

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. Hydrol., v.202(1-4), pp.353-372.

Walden, J., Oldfield, F. and Smith, J. (Eds) (1999) Environmental magnetism: a practical guide. Technical guide, Issue 6, Quaternary Research Association, London.

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

Wasson, R.J. (2003) A sediment budget for the Ganga–Brahmaputra catchment. Curr. Sci., v.84(8), pp.1041-1047.

Yu, L. and Oldfield, F. (1989) A multivariate mixing model for identifying sediment source from magnetic measurements. Quaternary 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. Earth Surfaces Processes and Landforms, v.18, pp.441–454.

Zhu, R.X., Lin, M. and Pan, Y. X. (1999) History of the temperature dependence of susceptibility and its implications: preliminary results along an E–W transect of the Chinese Loess Plateau. Chinese Science Bulletine, v.44(1), pp.81–86.

Zhu, R.X., Matasova, G., Kazansky, A., Zykina, V. and Sun, J.M. (2003) Rock magnetic record of the last glacial-interglacial cycle from the Kurtak loess section, southern Siberia. Geophys. Jour. Internat., v.152, pp.335–343.

(Received: 14 November 2012; Revised form accepted: 23 March 2013)