



Palaeocurrent and environmental implications from anisotropy of magnetic susceptibility (AMS): a case study from Talchir and Barakar formations, Raniganj Basin, West Bengal, India

Saurodeep Chatterjee¹ · Supriya Mondal¹ · Punyotoya Paul¹ · Pritwish Das¹

Received: 2 August 2017 / Accepted: 29 May 2018 / Published online: 8 June 2018
© Saudi Society for Geosciences 2018

Abstract

Oriented cylindrical cores of rock samples were collected from the Talchir and Barakar formations of the Lower Gondwana Supergroup of the Raniganj Basin exposed in and around Kalyaneshwari and Maithon areas. The cores (2.54 cm diameter and 2.2 cm height) were studied in the low field anisotropy of magnetic susceptibility (AMS) measurement to determine the nature of magnetic fabrics, to correlate it with the sedimentological characteristics and to determine the palaeocurrent patterns. The results derived from the statistical parameters (especially the q -factor), the shapes of the susceptibility ellipsoids and directional data of the AMS indicate that the magnetic fabrics within the studied units are primary (depositional) and are correlatable from the palaeoenvironmental features. The orientation of the maximum (K_1), intermediate (K_2) and minimum (K_3) susceptibility axes is dispersed on the lower hemisphere equal area diagram rather than strong clusters which is not because of secondary (tectonic) influence but due to the moderate to high-energy environment of deposition of the sediments in the studied units. Based on the q -factor (which is 0.581 for Barakar Formation and 0.565 for Talchir Formation which are both < 0.7), it is suggested the AMS indicates that the imbrication of the K_1 axis is the indicator of palaeocurrent. Also, the magnetic foliation (average value = 1.255) exceeds the magnetic lineation (average value = 1.107) and the shape parameter exceeds 0 in most cases pointing towards an oblate fabric. The palaeocurrent in the present study as indicated by the K_1 axis imbrication is very similar in both the units under study and is due SW. However, apart from this precise palaeocurrent direction, there exists a certain degree of randomness of the susceptibility axes which are very clear indication of corresponding depositional environments.

Keywords Anisotropy of magnetic susceptibility · India · Raniganj Basin · Gondwana Supergroup

Introduction

Investigations of palaeocurrent are the ubiquitous requirements for sedimentary basin analysis which are keys towards the understanding of facies, primary sedimentary structural features and provenances (Potter and Pettijohn 1977). The low field anisotropy of magnetic susceptibility (AMS) is increasingly gaining importance in the field of fabric determination of the igneous, metamorphic and sedimentary rocks (Chatterjee et al. 2016, 2017, 2018a, b; Mondal et al. 2017; Nagata, 1961; Ellwood 1980; Knight and Walker, 1988; Ernst

and Baragar 1992; Cañón-Tapia 2000). Ising (1942) and Graham (1954) were the pioneering scientists who proposed the idea of using AMS as a tool to determine the petrofabric and palaeocurrent (Jackson 1991; Schieber and Ellwood 1993; Park et al. 2000; Baas et al. 2007; Parés et al. 2007; Veloso et al. 2007). The fact which is basically the backbone of palaeocurrent determination from the AMS parameters is the tendency of magnetic particles (ferro-, para- or diamagnetic) within the sedimentary rock to align along the geomagnetic field which varies with grain shape and circulation (Tarling and Hrouda 1993; Papanna et al. 2014). Such studies within the sediments are suggested to be a reliable tool to identify the palaeocurrent direction (Bakhtari et al. 1998; Baas et al. 2007).

Earlier, Schieber and Ellwood (1988) provided interesting palaeocurrent results with shales of the Belt Basin and later within Newland Formation, Montana, and explained the advantages of palaeocurrent analysis using AMS data over

✉ Saurodeep Chatterjee
chatterjeesaurodeep@gmail.com

¹ Department of Geological Sciences, Jadavpur University, Kolkata 700032, India

other common techniques. Later Liu et al. (2001) carried out palaeocurrent analysis using AMS data at Yangtze delta, China, in perspective of sedimentary environmental studies. More recently, Papanna et al. (2014) documented the AMS characteristics of Campanian-Maastrichtian sediments of Ariyalur group, Cauvery Basin, Tamil Nadu, to determine palaeocurrents. Das et al. (1999) studied the magneto-petrologic characteristics of the Gondwana Supergroup but the magnetic fabrics are still to be reported. In the present study, the authors made an attempt to summarise the viability of using AMS as a petrofabric indicator in sedimentary rocks and to determine the palaeo-flow patterns of the lower Gondwana rocks from the Raniganj Basin exposed in and around Kalyaneshwari and Maithon areas, West Bengal, India (Fig. 1).

Geological setting

The Gondwana Basin of the Damodar Valley belt lies within the Chhotanagpur Granite Gneissic Complex. Here, the rocks of Raniganj Basin are displaying a concordant relationship with the Gneissic basement (Mazumdar 1988). The Raniganj Basin is elliptical to semi-elliptical shaped, which covers an area of 3000 km² within the Damodar and Ajoy rivers which is bounded within latitude of 23° 03' and 23° 51' N and

longitude 86° 42' E and 87° 28' E (Ghosh 2002). The uniqueness of the Raniganj Basin is that it is one of those successions of peninsular India which preserves both the Lower Gondwana (Permian) and Lower Gondwana (Tertiary) (Ghosh et al. 1996; Ghosh 2002). The generalised succession of the Gondwana rocks of the Raniganj Basin is provided herein in Table 1. As the Gondwana successions are exposed throughout India in several basins, Dutta (2002) classified the Gondwana rocks into four facies: facies A, facies B, facies C and facies D to avoid the different nomenclature of the same lithounits in different basins. Based on this, the Talchir Formation comes under the heading of facies A and the Barakar Formation comes under facies B.

The present study was carried out in the rocks of the Raniganj Basin exposed in and around Maithon and Jitpur areas. The Talchir Formation mainly consist of matrix supported conglomerate (Fig. 2a) with angular faceted and striated clasts restricted to the basal part (Fig. 2b). Besides, it contains tillite, boulder bed, conglomerate, sandstone, shale and varve deposits (Ghosh and Mitra 1975; Dutta 2002). The sandstones of Talchir Formation are characterised by abundant slump structures and hummocky cross-stratification (Fig. 2c). The sandstone beds of Talchir Formation have an attitude of 110°/14°→200° (SWly). The coarse clastic pebble, cobble and granules belonging to the Talchir Formation are immature and arkosic in composition and consists of abundant

Fig. 1 a Locations of all Gondwana basins in India (Bhattacharya et al. 2016) and b generalised geological map of the studied area

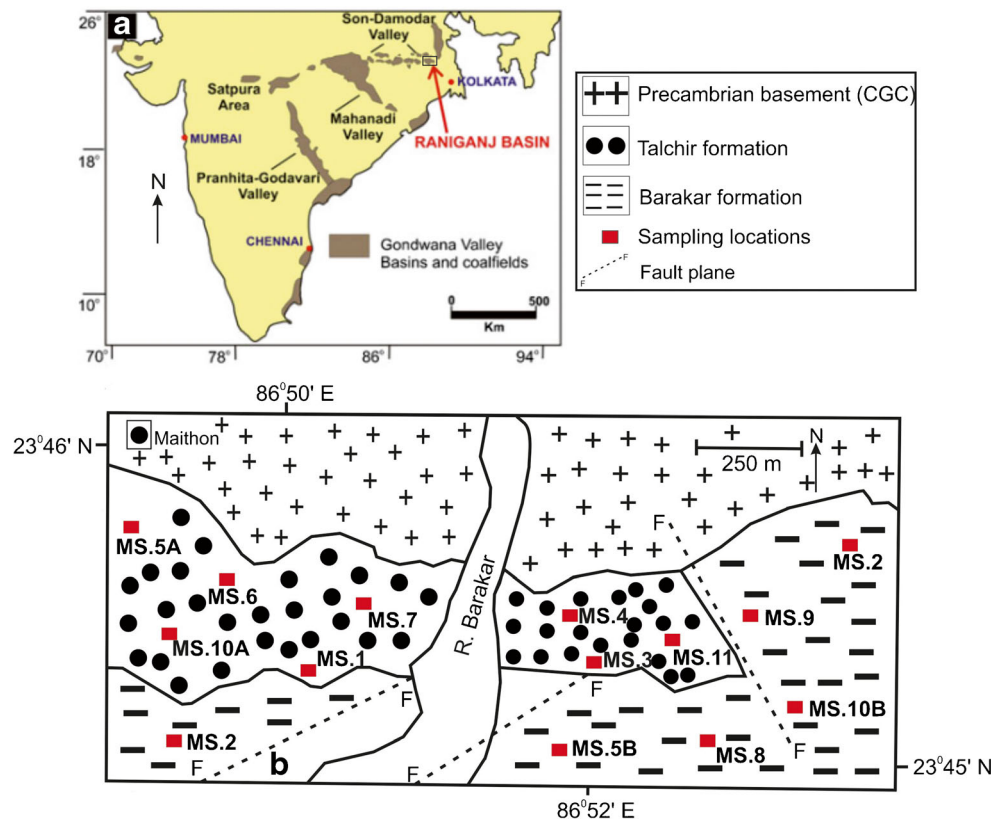


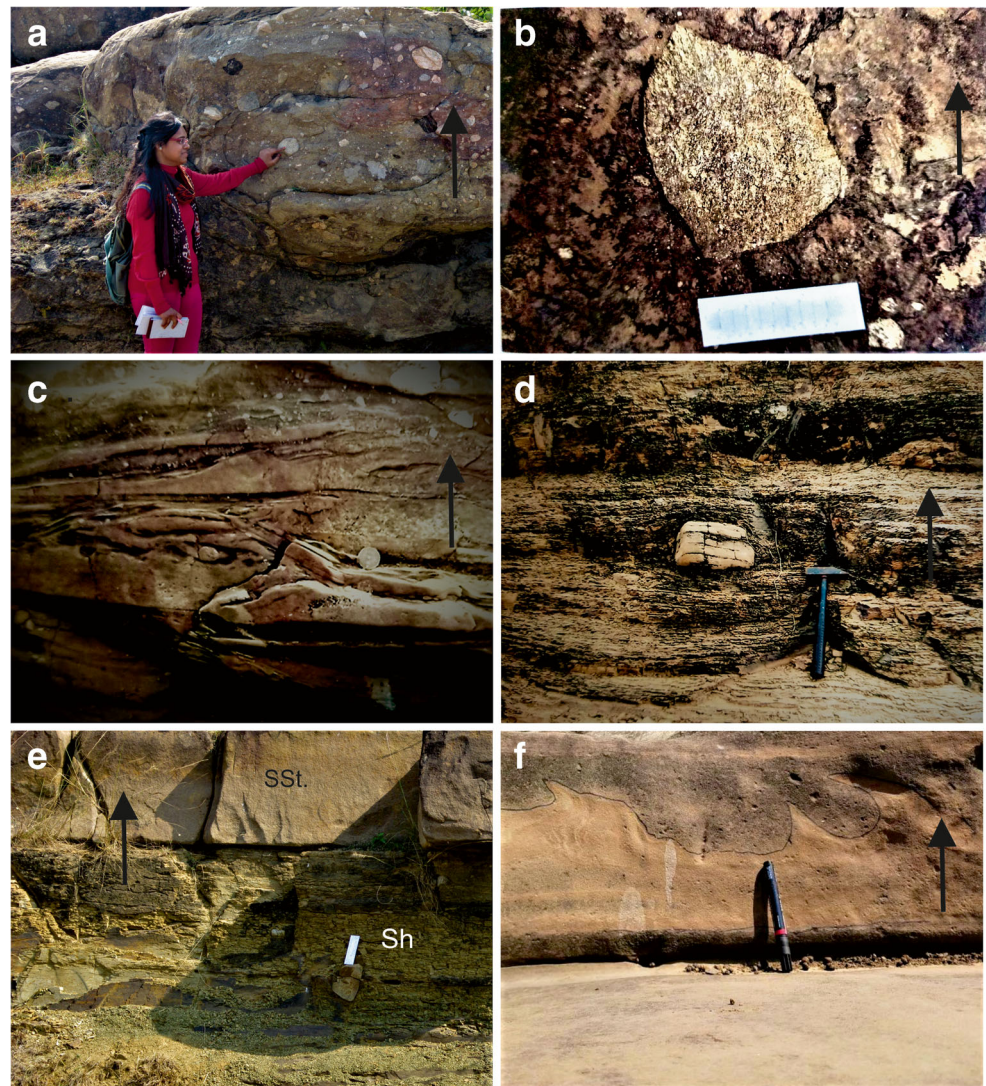
Table 1 Generalised lithostratigraphy of the Gondwana rocks in Raniganj area (Ghosh 2002)

Geological Age	Formation	Maximum thickness (m)		
Tertiary	Bengal basin clay, sand and limestone	300+		
----- <i>Unconformity</i> -----				
Jurassic – Cretaceous	Rajmahal traps/intratrappans	85+		
----- <i>Unconformity</i> -----				
Late	Supra-Panchet	200-300		
Triassic	----- <i>Angular unconformity</i> -----			
Early	Panchet	≈600		
----- <i>Mostly gradational contact, unconformity (local)/overlap at places</i> -----				
Permian	Late	Raniganj	1000	
	Middle	Damuda Group	Iron Stone Shale	900
			Barakar	600
	Early	Talchir	300	
----- <i>Unconformity (erosional)</i> -----				
Precambrian	Metamorphic rocks/granite gneiss, schists with pegmatites and intrusives of metadolerite, dolerite and lamprophyre.			

of feldspars, rock fragments with an assemblage of accessory minerals (Dutta 1997; Suttner and Dutta 1986; Ghosh and Mitra 1975). The source rock for the Talchir Formation is granitic (Dutta 2002). The cold glacial climate during the deposition of the Talchir sediments (as depicted by the presence of drop stones within laminated shales, Fig. 2d) is depicted by the abundance of the unstable detrital minerals within sandstones and shales. The formations exhibit a thickness of 100–200 m, the maximum thickness being observed at the Damodar basin which is about 300 m. The Talchir Formation is underlain by the Precambrian Granite Geissic basement rocks with an unconformable contact. The Barakar Formation basically marks the lowest unit of the Damuda

Group and rests unconformably over the Talchir Formation which has a varying thickness of about 700–1100 m. The contact with the underlying Talchir Formation is sharp (Dutta 2002; Ghosh 2002). The Barakar Formation consists of pebbly sandstone, sandstone, black and grey shales which are sometimes carbonaceous (Dutta 2002). The sandstones and shales are present as alternations (Fig. 2e). The Barakar Formation consists of large-scale flame structures (Fig. 2f). The sandstones have an average attitude of 180°/15°→265° (Wly) or 84° (Ely). The shales have an attitude of 190°/10°→260° (Wly). Compositionally, the sandstones are sub-arkosic which occasionally grades to quartz-arenite. Mineralogically matured sandstones and the abundance of

Fig. 2 **a** Matrix supported conglomerate of the basal Talchir Formation. **b** Bullet-shaped clast (pebble) in matrix supported conglomerate. **c** Hummocky cross-stratification present in the sandstone of Talchir Formation. **d** Drop stone present within greenish shale of Talchir Formation. **e** Sandstone-shale alternations in Barakar Formation. **f** Flame structures present within the alternating sandstone and shale units of Barakar Formation. The arrow in each figure indicates younging direction



clay minerals reveal the change of glacial environment to a temperate humid climate.

Besides, the Raniganj Basin of the Gondwana successions are extremely faulted according to Ghosh (2002); the faults can be classified as boundary fault zone, faults at the basin margins and intra-basinal faults. The southern boundary of the Raniganj Basin is defined by an east-west striking fault zone whose geometric and kinematic signatures imply that the boundary represents extensional tectonics (Gibbs 1984; Ghosh 2002). The unconformable contact existing between the Precambrian basement and sediment cover is affected by some transfer faults (Ghosh 2002; Gibbs 1984). Besides, there are several intra-basinal faults which affect all the six Gondwana formations.

The palaeocurrent pattern as described by Suttner and Dutta (1986) and Dutta (2002) is almost similar and varies from southwards to westwards with the maximum flow towards SW which is analogous in both the Talchir and Barakar formations. Bhattacharya et al. (2004), Bhattacharya

and Bhattacharya (2015) carried out palaeocurrent analysis in the Talchir Formation using a variety of primary structures among which the channel axes and the trough axis yielded exclusive SW palaeocurrents. Other features like ripple crest lines, gutter axes, prod marks, groove marks and bounce marks yielded a dominant NE-SW trend with subordinate NW-SE trends. The present study marks the first attempt to bring out the environmental implications and palaeocurrent patterns in an Indian Gondwana basin from AMS study.

AMS as a petrofabric indicator in sedimentary rocks: a theoretical overview

Primary magnetic fabrics of a rock are those that are developed within the igneous and sedimentary rocks during the time of their formation (Tarling and Hrouda 1993). In case of sedimentary rocks, during the time of their formation, the primary fabrics are developed during the deposition of the

sediments after weathering and erosion (Tarling and Hrouda 1993; Rees 1961; Papanna et al. 2014). With increasing degrees of diagenesis of the sediments, they may gradually lose the primary (depositional) fabric and develop a secondary one. Generally, the geological processes that contribute towards the development of the secondary magnetic fabrics are bioturbation, shallow physical and chemical processes, compaction and most importantly tectonic disturbances (Chatterjee et al. 2018a, b; Tarling and Hrouda 1993; Papanna et al. 2014). The medial spine of the development of the primary magnetic fabric within sedimentary rocks is the gravity dependent settling of the detrital grains. This causes the long and intermediate axes of the grains parallel to the depositional surface or the bedding planes (Papanna et al. 2014; Tarling and Hrouda 1993). This can only lead to the development of a flattened (or oblate) shaped fabric which is confirmed to the bedding plane (Tarling and Hrouda 1993). However, this is the case when there is complete absence of current within the depositional environment because presence of a weak to moderate (< 1 cm/s) current will tend to align the long axis of the grains along the flow direction (Tarling and Hrouda 1993; Piper et al. 1996; Liu et al. 2001; Parés et al. 2007; Papanna et al. 2014). In this case, the long axis of the grains will remain imbricated at angles $< 20^\circ$ so that the bedding confined oblate fabric remains retained (King 1955; Tarling and Hrouda 1993). However, with the increasing current strength (> 1 cm/s) the angle of imbrication is increased and the oblate fabric tilts $5\text{--}20^\circ$ from the boundary plane and in such a situation the prolate grains will remain stable with their long axis perpendicular to the flow direction (Granar 1958; Tarling and Hrouda 1993; Hamilton and Rees 1970). Another factor which can contribute towards the development of primary magnetic fabric in sedimentary rock is the nature of depositional surface: inclined or horizontal. The nature of the depositional surface is negligible in current free environments but important in the moderate and strong current environments (Tarling and Hrouda 1993). Thus, in a nutshell, it can be summarised that the orientation of the maximum and the minimum susceptibility axes are aligned towards the palaeocurrent and the stereographic projection of the same are the palaeocurrent directions (Hrouda 1982; Lowrie and Hirt 1987; Taira 1989; Rochette et al. 1992; Sangode 2001; Rathi et al. 2007; Papanna et al. 2014).

Sampling and measurements

A total 83 Nos. of oriented cores were obtained from the in-situ exposures of Talchir and Barakar formations using portable drill machines in the fields out of a total number of 14 sites from different exposures of the formations. Six sites were selected in the Barakar Formation which yielded a total of 35 cores (6–8 cores per site). Similarly, the rest of 8 sites were in the Talchir Formation with a total of 48 cores (6–7 cores per

site). The cores were drilled out by vertical drilling from top horizontal surfaces of the in situ exposures so that the drilled core is at perfect right angle with the horizontal exposure surface. All the cores were thus collected from the field were cut to prepare standard core samples with 2.2 cm length and 2.54 cm diameter. The selected oriented cores were measured using the Bartington Susceptibility Meter (MS-2) housed in the Geophysics Laboratory, Department of Geological Sciences, Jadavpur University, Kolkata, India. This works synchronously with the AMS-Bar Software which calculates the parameters related to AMS from the raw data measured by the susceptibility meter. The samples were subjected to AMS measurements in 18 different orientations following standardised processed described by Jelínek (1978).

Methodology: routine methods versus AMS

Although studies of palaeocurrent are quite hurdle less in the sandstone and carbonates because of the presence of primary sedimentary structures, routine methods are tedious and time consuming which involve determination of fossil orientation, shape orientation of silt-sized particles, detection of sediment dispersal patterns or measurement of the orientation of the concretions (Schieber and Ellwood 1988). However, these needs to be done manually and thus involves manpower which in turn invites error factors. The shales on the other hand pose difficulties to the sedimentary geologists because these are virgin in terms of flow-indicating primary structures. These are the reasons why the palaeocurrent data from the shales throughout the globe (Potter et al. 1980) are limited.

The instrument used for AMS measurements provided the bulk magnetic susceptibility (K) of the cores which is obtained when the samples are subjected to an induced magnetisation (J) by an applied magnetic field (H) according to the formula $K = J/H$. Apart from the bulk susceptibility, the values of susceptibilities in correspondence with the three principal susceptibility axes are yielded (generally termed as eigenvalues). The average of these three eigenvalues is calculated as the mass susceptibilities (K_m). The magnetic foliation (F) are developed when the shortest (K_3) axis of the platy minerals remain perpendicular to the plane and thus the foliation defined by the plane passing through the maximum (K_1) and intermediate (K_2) axes. The magnetic lineation (L) are defined by the imbrication of the maximum susceptibility axes (K_1) on lower hemisphere equal area diagram, which will depict the orientation of the magnetic lineation. The plane passing through the maximum (K_1) and intermediate (K_2) is termed as magnetic foliation. The shape parameter (T) is the criteria for the ellipsoid shape determination. The direction of these three axes is plotted over the lower hemisphere equal area diagram to determine their patterns. The value of T lies within -1 and $+1$; the shape of the ellipsoid being oblate (disc shaped) when $T >$

0 and prolate (cigar shaped) when $T < 0$. Granar (1958) and Graham (1966) described two parameters q and V ; a combination of the results of the two can provide the nature of fabric: oblate or prolate (Tarling and Hrouda 1993). Although, results based on T value are more reliable. However, the q -factor serves as a very simple tool in determining the nature of magnetic fabric: primary (depositional) or tectonic (Hamilton and Rees 1970; Sinha et al. 2009). The workers suggested that the fabric is depositional when the value of q -factor lies within 0.06 and 0.7 and is tectonic when it is 0.7. The ellipsoid shapes are herein determined by using the P_j versus T plot (Jelinek 1981; Hrouda 1982). AMS analysis proves to be a robust tool in overcoming the hurdles associated with determining palaeocurrent using classical methods because of the following: (a) the directional properties of AMS are independent of the mineralogical concentration. Very small amount of paramagnetic or diamagnetic mineral with very low susceptibility can provide accurate orientations of magnetic fabric elements (Hrouda 1982); (b) AMS is a very sensitive tool and records even a slight change in the orientation of the flow and thus much accurate than field data (Basavaiah et al. 2010); (c) the studied sections (Barakar and Talchir Formations) are enriched in shales (Dutta 2002; Raja Rao 1987) lacking primary structures; and, lastly, (d) as the method involves less tedious tasks, more number of samples can be analysed making the data statistically strong.

The abovementioned parameters used for AMS analysis in the present case are as follows (Nagata 1961; Stacey et al. 1960; Blasley and Buddington 1960; Jelinek 1981; Granar 1958):

$$\text{Mean susceptibility } K_m = (K_1 + K_2 + K_3)/3 \quad (1)$$

$$\text{Foliation } F = K_2/K_3 \quad (2)$$

$$\text{Lineation } L = K_1/K_2 \quad (3)$$

$$\text{Shape factor } T = (2\eta_2 - \eta_1 - \eta_3)/(\eta_1 - \eta_3) \quad (4)$$

$$q\text{-factor } q = (K_1 - K_2)/(0.5(K_1 + K_2) - K_3) \quad (5)$$

Corrected anisotropy degree (P_j) = $\exp\{2[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2]^{1/2}\}$ (Jelinek 1981)

K_1 , maximum; K_2 , intermediate; K_3 , minimum susceptibility

$$\eta_1 = \ln K_1; \eta_2 = \ln K_2; \eta_3 = \ln K_3; \eta_m = (\eta_1 \cdot \eta_2 \cdot \eta_3)^{1/3}$$

Now, for the determination of the palaeocurrent, first, we need to characterise the fabric, i.e. depositional or tectonic from the q -factor value. If, the fabric is found to be primary (q -factor < 0.7), the imbrication of the maximum susceptibility axis (K_1) is as indicator as during flow, the magnetic minerals which impinge the anisotropy gets aligned in the direction of the current, thereby defining an imbrication of K_1 parallel to the palaeocurrent (Tarling and Hrouda, 1993).

Petrography

For petrographic studies, a total of 28 thin sections were prepared, two from each sampling site both from the Talchir and Barakar formations. Of the two sections prepared from the samples, one was parallel to the strike and the other to the dip of the rocks in the corresponding location. The polished thin sections were studied using Leica DM 2700 microscopes at the Image Analyser Laboratory, Department of Geological Sciences, Jadavpur University.

Petrography of the rocks of the Talchir Formation depicts the presence feldspar rich (arkosic) sandstones consisting of quartz with accessory biotite, plagioclase and muscovite as the framework minerals bounded by ferruginous matrix (Fig. 3a). The quartz grains are found to be polycrystalline in nature. The grains are medium to fine grained, moderate to orientation within the framework grains (Fig. 3b). In most cases, the rocks are framework supported with very minor matrix content; however, locally some are matrix supported also. The matrix material is basically the finer variety of the framework components (Fig. 3c).

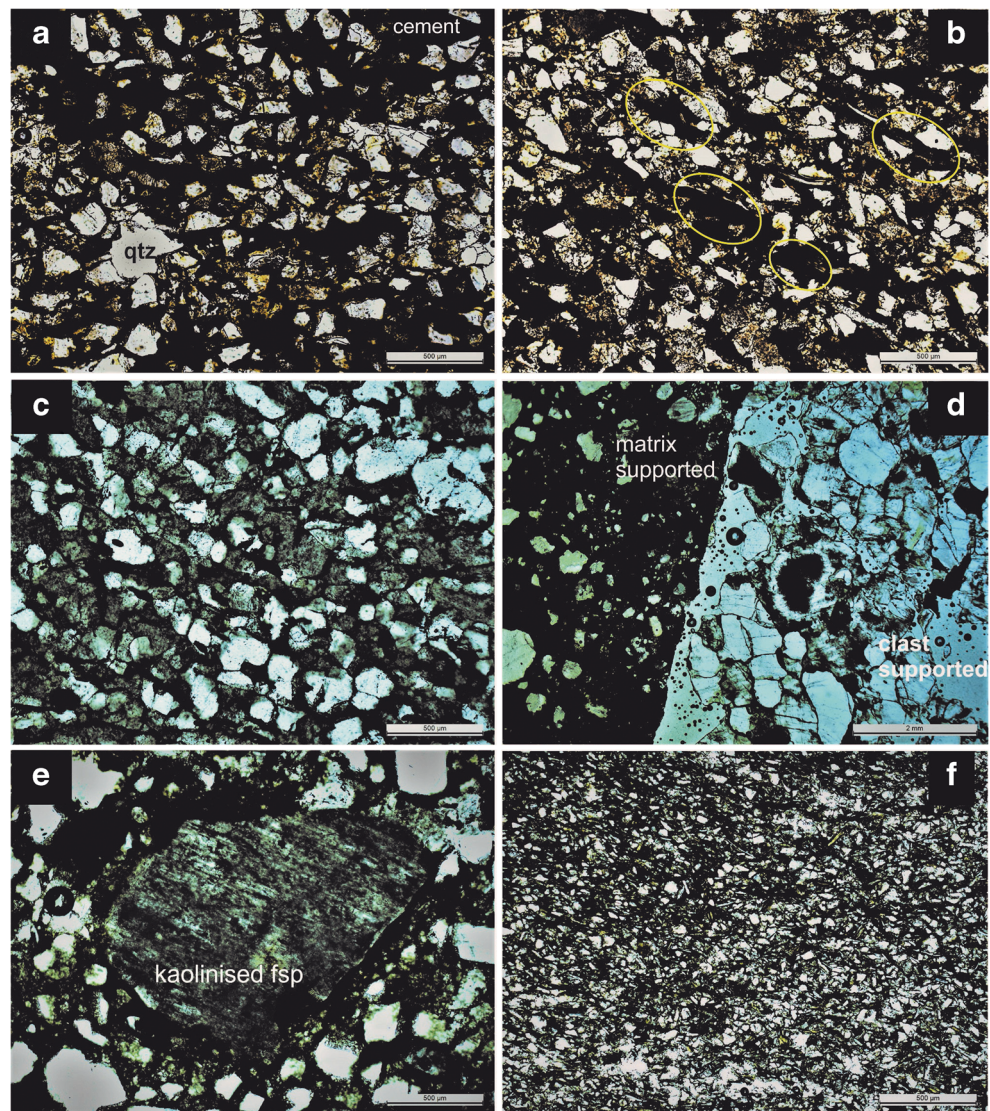
The Barakar rocks consist of quartz, feldspars, biotite and opaque minerals as the terrigenous components (Fig. 3d). The feldspars are ubiquitously kaolinised and possess altered grain boundaries (Fig. 3e). The sorting observed within the grains of Barakar sandstone is poor. The orientation of the biotite grains is relatively random over here. The Barakar sandstones are often associated with thinner units of shales which are abundant in carbon matter (Fig. 3f).

Results

Nature of the AMS parameters

The AMS parameters associated in the present study of the sediments were calculated which are mean magnetic susceptibility (K_m), corrected degree of anisotropy (P_j), magnetic lineation (L), magnetic foliation (F) and the ellipsoid shape factors: T and q -factor (Ellwood and Crick, 1988; Tarling and Hrouda 1993) based on the formulae in Eqs. (1) to (5). The overall mean susceptibilities of the studied area vary within a large range from 2.9×10^{-6} CGS to 51.24×10^{-6} CGS with an average value of 16.538×10^{-6} CGS (Table 2). The low values of the susceptibility for the studied rocks are the replication of the facts that the susceptibilities are the contributions by the paramagnetic minerals (viz. biotite). The maximum, minimum and average values of magnetic lineation are 1.5112, 0.606 and 1.107 respectively. The corrected degree of anisotropy (P_j) varies within 1.023 to 3.304 with an average value of 1.419. The highest value of mean susceptibility (K_m) is observed in Talchir. And the lowest value is observed in Barakar. The K_m versus P_j plots show that the degree of anisotropy

Fig. 3 **a** Sandstones of Talchir Formation cemented by ferruginous cement (PPL, 50×). **b** Imbrication of lath-shaped biotite grains within sandstones of Talchir Formation (PPL, 50×). **c** Matrix dominant sandstones from Talchir Formation. **d** Contact of clast dominated and matrix-dominated rocks observed in Barakar rocks. **e** Kaolinised feldspar encountered in the rocks of Barakar Formation. **f** Overall appearance of the shales of the Barakar Formation



does not bear a positive correlation with the mean susceptibility (Fig. 4) and thus it is well understood that the magnetic fabrics will be controlled by petrofabric orientations and not by bulk susceptibility of the rocks. Hence, the magnetic fabrics, in the present study, will be significant in explaining the palaeocurrent patterns. The values of the degree of anisotropy (P_1) and magnetic lineation (L) show much lesser variation than the mean susceptibility (K_m). The highest value of the corrected degree of anisotropy is observed in Talchir and the lowest value is observed in Barakar. The shape parameter (T) > 0 in most samples however, values < 0 are also not less common. The variation of the AMS parameters in both the studied stratigraphic units is mentioned herein.

In the case of the Barakar Formation, the mean susceptibility (K_m) varies within a range of 2.9×10^{-6} CGS units and 17.73×10^{-6} CGS units. The corrected degree of anisotropy varies from 1.058 to 1.991 with an average value of 1.30. The shape parameter T has an average value of 0.243; however,

some of the values are necessarily < 0 pointing towards a prolate ellipsoid shape (Fig. 5). Besides, the magnetic foliation (F) ranges within 1.033 to 1.684 and the magnetic lineation (L) within 1 and 1.512. The q -factor for the Barakar Formation possesses an average value of 0.581 which is less than 0.7. Only a few samples are having q -factor values > 0.7 . Necessarily, it was found that the same samples which have q -factor values greater than 0.7 have T values < 0 , both pointing towards localised disturbances in the sites and hence these sites were not considered during palaeocurrent determination to obtain more accurate results. However, as the average values of $T > 0$ and q -factor < 0.7 , the studied rock formations are necessarily suitable for palaeocurrent studies.

Now, in the Talchir Formation, the values of mean susceptibility (K_m) varies within a larger range of 3.37×10^{-6} CGS and 51×10^{-6} CGS with an average of 10.813×10^{-6} CGS units. The corrected degree of anisotropy degree varies within a limit of 1.022 and 3.304 with an intermediate value of 1.514.

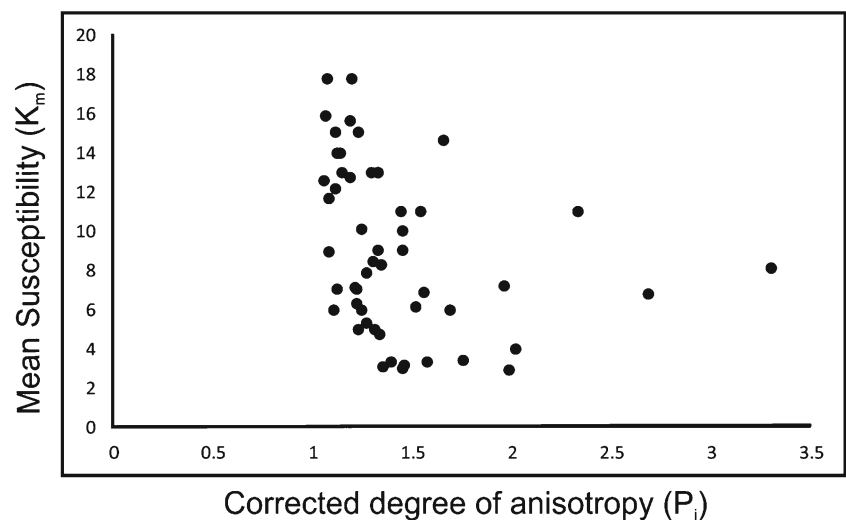
Table 2 Database containing the orientations of principal susceptibility axes and values of AMS parameters from representative cores from each sampling locations

Sample No.	$K_1 (D^0/I^0)$	$K_2 (D^0/I^0)$	$K_3 (D^0/I^0)$	K_m	F	L	P_j	T	q -factor
MS-2(1)	250.9/30.8	17.5/45.1	141.5/29.1	4.366	1.28	1.13	1.4682	0.3351	0.461
MS-2(2)	221.3/16.4	79.5/68.5	315.1/12.6	7.5	1.254	1.0506	1.342	0.6417	0.2222
MS-2(4)	260/22.7	21.9/51.6	156.5/29.1	14.8	1.0493	1.0268	1.0786	0.2899	0.4444
MS-5A(2)	9.2/42.7	216.3/44.5	112.8/14.3	14.9	1.03521	1.07483	1.11511	-0.35176	1.04762
MS-5A(5)	34.4/5.8	305.7/1.2	201.4/85.2	7.9	1.60377	1.16471	1.9215	0.51197	0.35897
MS-5B(1)	159.2/65.5	284.9/14.6	20.1/19	15.8667	1.05229	1.00621	1.06474	0.78334	0.11765
MS-5B(2)	216.5/12.3	308/6.7	66.1/75.9	15	1.03497	1.07432	1.1143	-0.35192	1.04762
MS_5B(6)	228.9/1.5	319.4/13.3	132/76.5	12.7333	1.13913	1.03817	1.19255	0.55334	0.27027
MS-6(3)	265.2/60.1	132.8/21.2	34.6/20	8.23333	1.26087	1.04598	1.34604	0.67515	0.2
MS-6(6)	78.7/7.3	169.3/4.6	291.5/81.3	7.8333	1.08571	1.17105	1.27654	-0.31509	1.04
MS-7(2)	225/20.2	315/0.1	45.3/69.8	6.3	1.17857	1.01515	1.22021	0.8323	0.09524
MS-7(3)	241.8/2.3	62.1/87.6	331.8/0	6	1.05263	1.05	1.10528	0.02501	0.66667
MS-7(6)	191.4/33	293.6/18	47.5/51.2	5.3333	1.12766	1.13208	1.27675	-0.016	0.73684
MS-8(1)	200.1/76.9	358.8/12.2	89.9/4.6	17.7333	1.04878	1.13953	1.11352	0.68026	1.2
MS-8(5)	72/44.9	176.9/15.1	280.7/41.4	12.9667	1.23423	1.0292	1.29858	0.7594	0.14286
MS-10A(3)	258.3/73.9	6.7/5.2	98.1/15.2	6.83333	1.32075	1.17143	1.55645	0.27491	0.52174
MS-10A(4)	279.9/82.6	115.7/7.2	25.4/2	5.96667	1.28889	1.31034	1.69068	-0.0315	0.81818
MS-10B(4)	234.4/53.3	73.4/35.1	336.9/9.2	3.3	1.14286	1.21875	1.3965	-0.19403	0.93333
MS-10B(5)	281.3/30.5	180/18.4	63.4/53.3	2.9	1.68421	1.125	1.9907	0.6314	0.26667
MS-10B(6)	333.5/5.8	70.1/48.4	238.4/41	3.3333	1.26923	1.24242	1.57947	0.04687	0.72727
MS-12B(1)	144.3/70.1	13/13.5	279.5/14.4	9.96667	1.11905	1.28723	1.45357	-0.38364	1.14894
MS-12B(3)	190.5/53.1	317.6/24.4	60.3/25.9	15.6333	1.06944	1.11039	1.17394	0.2269	0.91892
MS-12B(5)	117.1/41.2	19.4/8.7	279.8/47.5	8.4	1.20833	1.06897	1.30424	0.47884	0.3333

The average value of the shape parameter (T) is 0.274. Analogous to the Barakar Formation, a considerable number of samples show T values < 0 , thereby possessing a prolate-shaped ellipsoid (Fig. 5). The magnetic foliation (F) ranges from 1 to 4.56 and the magnetic lineation (L) varies within

1.310 to 1.917 which is considerably larger a range than in the Barakar Formation. Here, the q -factor possesses an average value of 0.565.

The values of the calculated AMS parameters from representative samples are tabulated here in Table 2.

Fig. 4 K_m versus P_j plot for the studied sections

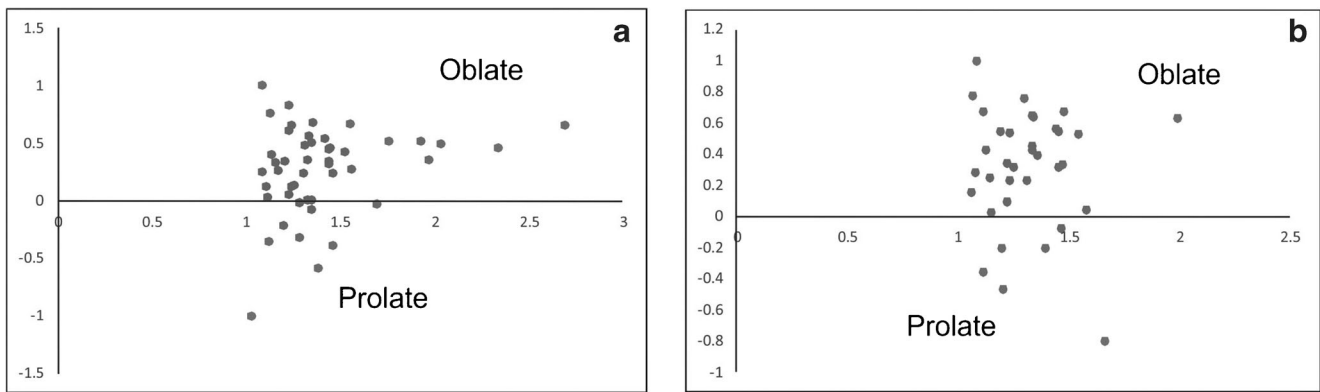


Fig. 5 P_j versus T plots for the rocks of a Talchir Formation and b Barakar Formation

Directional characteristics of susceptibility axes

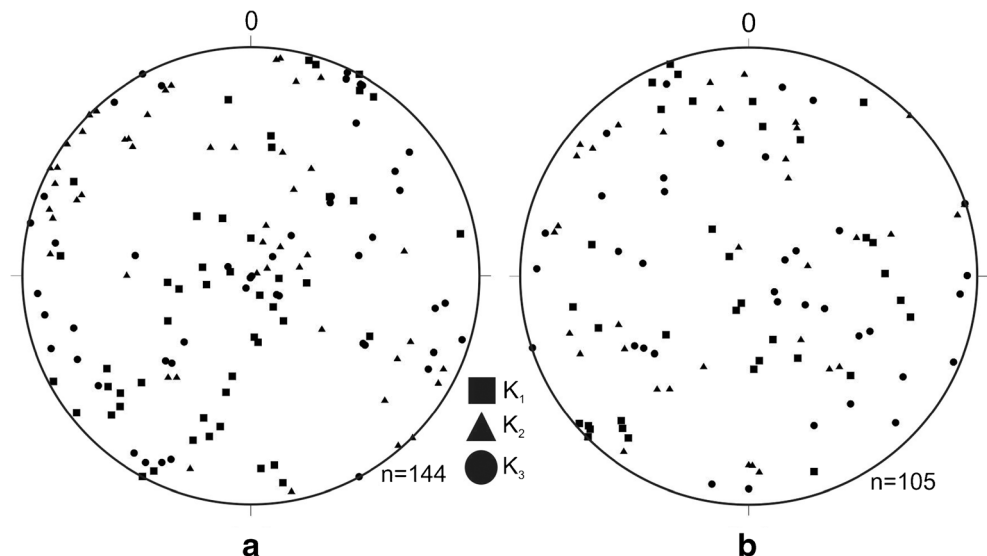
The distribution of the maximum, intermediate and minimum susceptibility axes on the lower hemisphere equal area diagram for the Talchir and Barakar formations are shown in Fig. 6. The stereographic plots of the axes for both the Barakar and Talchir formations are somewhat dispersed rather than clusters. In the Talchir Formations, the maximum (K_1) susceptibility axes are found to display a girdle in the south-western quadrant. The trend of the K_1 axes in the Talchir Formation seems to be dominantly NE-SW from the circular diagram. The intermediate susceptibility axes (K_2) on the other hand tends to girdle with NW-SE trends. However, the plots of the maximum and intermediate susceptibility axes are principally towards the periphery. This basically points towards a near horizontal attitudes of the foliation plane (plane passing through the maximum and intermediate susceptibility axes).

Similar to Talchir Formation, susceptibility axes in the Barakar Formation also exhibits girdle rather than clusters. However, the maximum susceptibility axes (K_1) displays a weak cluster in the south-western quadrant. Otherwise, they are dispersed in all orientations with varying amounts of inclinations. The intermediate axes (K_2) has relatively larger inclinations than those of the Talchir Formation, and still, the magnetic foliation planes in the Barakar Formation is having low dips.

The attitudes (declination and inclination) of the principal susceptibility axes of the representative samples are mentioned in Table 2.

The near horizontal nature of the magnetic fabrics in both the studied rock successions is obvious from the values of T and q -factor which suggested oblate (flattened) magnetic fabric. Thus, the values of AMS parameters and the orientations of the magnetic fabric elements strongly argue towards the nature of magnetic fabric being primary (depositional) and thus can be served as a proxy for determination of the magnetic fabric.

Fig. 6 Plots of the principal susceptibility axes for a Talchir Formation b Barakar Formation



Discussions: environmental implications and palaeocurrent patterns

Environmental implications from magnetic fabrics

The nature of the magnetic fabrics in the studied units of the Lower Gondwana in the Raniganj Basin seems to be primary with some local disturbances. Because of the similarity of the values of AMS parameters in the Talchir and Barakar formations, the general nature of the magnetic fabrics in both the formation are discussed under the same heading.

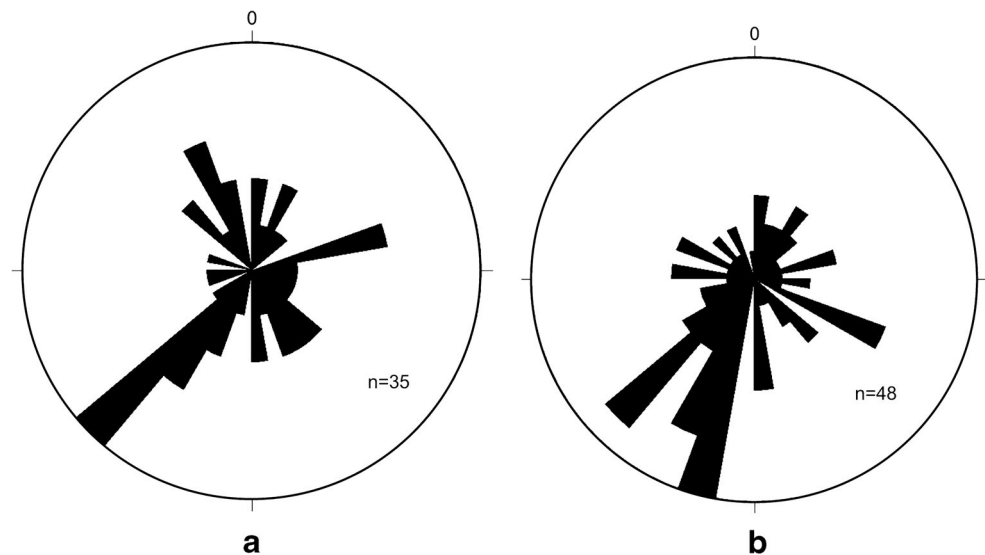
The distribution patterns of the principal susceptibility axes in the equal area diagrams are evidences for the same (Fig. 6). Although it is observed that the principal susceptibility axes are slightly dispersed rather than clusters, the average trend of the magnetic foliation planes can be identified from the lower hemisphere equal area diagrams. The plots of the maximum and intermediate susceptibility axes are found over here to be near the periphery which signifies low dips of the magnetic foliation plane and thus the nature of the magnetic fabric is pointed towards an oblate one in both the units. The plots on P_j versus T diagram are dominantly over the oblate field which corroborates the contention (Fig. 5). However, there are a considerable number of plots in the prolate field too, which of course needs explanation. The ideal condition for the development of an oblate fabric is a calm and quite (still water) sedimentary environment where there is an absence of currents which can disrupt the perfect oblateness of the magnetic fabric (Tarling and Hrouda 1993). However, the sedimentary environments that prevailed during the deposition of these two units were not calm enough to develop a strict oblate fabric. The Talchir Formation was deposited in a glacio-fluvial environment (Dutta 2002; Suttner and Dutta 1986) and, also, with some stormy events and open marine storm surges evident from various primary sedimentary features, especially, sole marks (Bhattacharya et al. 2004; Bhattacharya and Bhattacharya 2015). Thus, the magnetic grains (ferro-, para- or diamagnetic) over here in this unit, which contributes towards the susceptibility and its anisotropy, were not deposited in the basin only due to gravitational settling. There were effects of other sedimentary environmental factors. Consequently, although a predominant oblate fabric prevailed parallel or sub-parallel to the bedding there has developed a superimposing lineation impinging a degree of prolateness in the fabric. Such natures of magnetic fabrics are generally supported by the presence of slump structures (Tarling and Hrouda 1993) which are abundant in the hummocky cross-stratifications of the Talchir Formation. In the case of the Barakar Formation, the explanation of the magnetic fabrics needs some other environmental explanation. The Barakar sediments were deposited in a fluvial environment (braided to meandering) with ample evidences of channel shifting and accretion of point bar (Dutta 2002; Ghosh 2002; Suttner

and Dutta 1986; Casshyap and Tewari 1987; Bhattacharya et al. 2016). The randomness noticed in the orientations of the principal susceptibility axes in the Barakar Formation can thus be attributed towards the presence of a number of channel migrating events. However, similar degrees of prolateness were observed in the fabrics of Barakar Formation similar to Talchir, which has similar explanations too, i.e. the environment of deposition in Barakar Formation was also not a still water one which prevents the development of an ideal oblate fabric and impinges a deviation towards prolate fabric therein.

Palaeocurrent patterns

The first and foremost criterion which is required for palaeocurrent analysis using AMS data is that the rock unit must preserve its original primary (depositional) fabric. The values of q -factor in the studied sections served for the same. The q -factor here assumes an average value of 0.581 in the Talchir Formation and 0.565 in the Barakar Formation. Both these values are less than 0.7 which is the threshold value for the magnetic fabrics being tectonic rather than primary (depositional). Thus, in spite of the dispersion (rather than clusters) depicted by the principal susceptibility axes, their orientations are controlled by primary depositional factors and the imbrication of K_1 (maximum) axes can be treated as the palaeocurrent directions for both Talchir and Barakar formations. The palaeocurrent pattern in the available literature and are quoted herein in the text. Figure 7 shows the rose diagram for the imbrication described by the K_1 axes as an indication of the palaeocurrent direction. From the figures, it is observed that the palaeocurrent patterns both in the Barakar and Talchir formations are due SW dominantly. The figures also very clearly show that the palaeocurrent direction towards SW is stronger in the case of the Talchir Formation which depicts that the imbrication of the K_1 axes is much stronger here than in the Barakar Formation. The higher values of the degrees of anisotropy (P_j) in Talchir supports for the same. Thus, the current strength was more in the Talchir Formation (glacial with marine surges) is more than that in Barakar Formation (braided to meandering channels). The palaeocurrent patterns thus obtained from the AMS data thus bears a strong analogy with those earlier obtained from the same rock units using sedimentological methods (Suttner and Dutta 1986; Dutta 2002; Ghosh 2002; Bhattacharya et al. 2004; Bhattacharya and Bhattacharya 2015). However, apart from the strong south-westerly palaeocurrent directions, there is a very prominent orientation of the K_1 axes all throughout 360° of the diagram, although very few in number. This is basically due to the strongly oblate-shaped grains which remained unaffected by the currents and settled in the sedimentary basin exclusively by gravitational settling. The same inference can be drawn from the orientations of the biotite laths with are

Fig. 7 Rose diagram representing the palaeocurrents (imbrication of K_1 axes) in the **a** Barakar Formation and **b** Talchir Formation



strongly imbricated in the Talchir Formation and are relatively random in the Barakar samples.

Conclusions

Conclusions that can be highlighted from the present study can be classified into two categories: (a) robustness of AMS as a supporting tool in understanding the depositional sedimentary environments and palaeocurrent patterns in basin analysis studies and (b) patterns of palaeocurrent and their correlation with the depositional environment in the Lower Gondwana of the Raniganj Basin.

First, it is well established from the present case study that AMS is a powerful tool in palaeocurrent and sedimentary environment analysis as it has the capability of recording any minimum changes in directional attributes viz. current direction. The nature of variation of the orientations of the principle susceptibility axes also has strong implication towards changes in the depositional environment. However, similar AMS data variations and changes can also be shown by rocks of multiply deformed terrain where the magnetic fabric elements have no primary (depositional and palaeocurrent related) significances (Chatterjee et al. 2018b). Thus, it is strongly recommended to define the genesis of the magnetic fabric (depositional or tectonic) before using them as proxies for sedimentological characteristics by calculating the values of q -factor.

Secondly, the usefulness of AMS study in sedimentary environment and palaeocurrent analysis proved its usefulness in the present study. The magnetic fabrics observed in the Talchir and Barakar formations of the Lower Gondwana succession is primary and are developed during the deposition of the sediments in the concerned environment. Both the nature of the magnetic fabrics within the studied section and the

palaeocurrent patterns have strong accordance with the sedimentary environment discussed in available literature. The results from the various AMS parameters and the distribution of the principal susceptibility axes over the lower hemisphere equal area diagram support for the same. The palaeocurrent directions in both the Talchir and Barakar formations are found to be strongly towards SW. However, the imbrication of K_1 is stronger in the Talchir Formation because of the absence of the braided to meandering channels which are present in the Barakar Formation.

Acknowledgements The authors are grateful to the Department of Geological Sciences, Jadavpur University, Kolkata, for providing the scopes for the present research work. SM thankfully acknowledges the Department of Science and Technology (DST-Purse-II Research Scheme) for providing financial supports during the field work. PD and PP expresses deep gratitude to Kapil Singh and Debesh Gain for the assistance during field works. SC acknowledges Susmita Ganguly and Angikar Roy (Jadavpur University) for helping with the field photographs and Sudeshna Sarkar for moral supports during the tenure of the work. Finally, we acknowledge Dr. Abdullah M. Al-Amri and Dr. Domenico Doronzo for the editorial assistance and the anonymous reviewers for their useful and valuable comments which improved the paper.

References

- Baas JH, Hailwood EA, McCaffrey WD, Kay M, Jones R (2007) Directional petrological characterization of deep-marine sandstones using grain fabric and permeability anisotropy: methodologies, theory application and suggestions for integration. *Earth Sci Rev* 82: 101–142
- Bakhtari HR, Dominique FL, Charles A, Jamshid H (1998) Magnetic fabrics of tertiary sandstones from the Arc of Fars (Eastern Zagros, Iran). *Tectonophys* 284:299–316
- Basavaiah N, Appel E, Lakshmi BV, Deenadayalan K, Satyanarayana KVV, Misra S, Juyal N, Malik MA (2010) Revised magnetostratigraphy and characteristics of the fluviolacustrine

- sedimentation of the Kashmir Basin, India, during Pliocene-Pleistocene. *J Geophys Res* 115:B08105
- Bhattacharya HN, Bhattacharya B (2015) Lithofacies architecture and paleogeography of late Paleozoic glaciomarine Talchir Formation, Raniganj Basin, India. *J Paleogeogr* 4:269–283
- Bhattacharya HN, Bhattacharya B, Chakraborty I, Chakraborty A (2004) Sole marks in storm event beds in the Permian-carboniferous Talchir Formation, Raniganj Basin, India. *Sediment Geol* 166(3–4):209–222
- Bhattacharya B, Bhattacharjee J, Banerjee S, Bandyopadhyay S, Das R (2016) Seismites in Permian Barakar Formation, Raniganj Basin, India: implications on Lower Gondwana basin evolution. *Arab J Geosci* 9:300
- Blasley JR, Buddington AF (1960) Magnetic susceptibility anisotropy and fabric of some Adirondack granites and orthogenesis. *Am J Sci* 258A:6–20
- Cañón-Tapia E (2000) The anisotropy of magnetic susceptibility of lava flows: an experimental approach. *J Volcanol Geotherm Res* 98: 219–233
- Casshyap SM, Tewari RC (1987) Depositional models and tectonic evolution of Gondwana basins. *Palaeobotanist* 36:214–229
- Chatterjee S, Gain D, Mondal S (2016) Magneto mineralogy characterization and analysis of magnetic fabrics of the high-grade rocks from Chilka Lake area, Eastern Ghats Belt, India. *Earth Sci India* 9(1):29–47
- Chatterjee S, Mondal S, Roy B, Gain D (2017) Magnetic fabric as a tool to determine kinematic vorticity number of the high-grade rocks from Chilka Lake area, Eastern Ghats Belts, India. *Int J Recent Sci Res* 8(6):17845–17850
- Chatterjee S, Mondal S, Roy P, Gain D, Bhattacharya A (2018a) Magneto-mineralogical characterization and manifestations magnetic fabrics from the gneissic rocks and associated intrusive bodies in and around Bankura and Purulia districts, West Bengal. *Curr Sci* 114(9):1894–1902
- Chatterjee S, Mondal S, Gain D, Baidya TK, Mazumdar D (2018b) Interpretation of magnetic fabrics in the Dalma volcanic rocks and associated meta-sediments of the Singhbhum Mobile Belt. *J Earth Syst Sci*, forthcoming
- Das AK, Piper JDA, Bandyopadhyay G, Mallick SB, Sherwood GJ, Mondal S (1999) Magnetopetrologic study of sediments of the Gondwana Supergroup, Northeast India. *Mem Geol Soc India* 44: 117–127
- Dutta PK (1987) Upper Kamthi: a riddle in the Gondwana stratigraphy of Peninsular India. In: McKenzie GD (ed) *Geophysical monograph* 41. Amer. Geophys. Union, pp 229–238
- Dutta PK (1997) Interpreting glacial climate from detrital minerals in sediments. In: Martini P (ed) *Late glacial and postglacial environmental changes*. Oxford University Press
- Dutta P (2002) Gondwana lithostratigraphy of Peninsular India. *Gondwana Res (Gondwana Newsletter Section)* 5:540–553
- Ellwood BB (1980) Application of the anisotropy of magnetic susceptibility method as an indicator of bottom water flow direction. *Mar Geol* 34:83–90
- Ellwood BB, Crick RE (1988) Paleomagnetism of Paleozoic asphaltic deposits in southern Oklahoma, USA. *Geophys Res Lett* 15:436–439
- Ernst RE, Baragar WRA (1992) Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. *Nature* 356:511–513
- Ghosh SC (2002) The Raniganj Coal Basin: an example of an Indian Gondwana rift. *Sediment Geol* 147:155–176
- Ghosh PK, Mitra ND (1975) History of Talchir sedimentation in Damodar Valley basins. *Geol Surv India Mem* 105:1–117
- Ghosh SC, Nandi A, Ahmed G, Roy DK (1996) Study of Permian–Triassic boundary in Gondwana sequence of Raniganj Basin. *Proc. IXth International Gondwana Symposium*. Oxford and IBH Pub., New Delhi, pp 195–206
- Gibbs AD (1984) Structural evolution of extensional basin margins. *J Geol Soc Lond* 141:609–620
- Graham JW (1954) Magnetic susceptibility anisotropy, an unexploited petrofabric element. *Geol Soc Am Bull* 65:1257–1258
- Graham JW (1966) Significance of magnetic anisotropy in Appalachian sedimentary rocks. *Am Geophys Union* 10:627–648
- Granar L (1958) Magnetic measurements on Swedish varved sediments. *Ark for Geophys* 3:1–40
- Hamilton N, Rees AI (1970) The use of magnetic fabric in paleocurrent estimation. In: Runcorn SK (ed) *Paleogeophysics*. Academic Press, London, pp 445–464
- Hrouda F (1982) Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophys Surv* 5:37–82
- Ising G (1942) On the magnetic properties of varved clay. *Ark Mat Astron Fys* 29:1–37
- Jackson MJ (1991) Anisotropy of magnetic remanence a brief review of mineralogical sources, physical origins and geological applications and comparison with susceptibility anisotropy. *Pure Appl Geophys* 136:1–28
- Jelínek V (1978) Statistical processing of magnetic susceptibility measured on groups of specimens. *Stud Geophys Geod* 22:50–62
- Jelinek V (1981) Characterization of the magnetic fabric of rocks. *Tectonophysics* 79:T63 T67
- King RF (1955) The remnant magnetization of artificially deposited sediments. *Mon Not R Astron Soc* 7:115–134
- Knight MD, Walker GPL (1988) Magma flow directions in dikes of the Koolau Complex, Oahu, determined from magnetic fabric studies. *J Geophys Res* 93(B5):4301–4319
- Liu B, Saito Y, Yamazaki T, Abdeldayem A, Oda H, Hori K, Zhao Q (2001) Paleocurrent analysis for late Pleistocene–Holocene incised-valley fill of the Yangtze delta, China by using anisotropy of magnetic susceptibility data. *Mar Geol* 176:175–189
- Lowrie W, Hirt AM (1987) Anisotropy of magnetic susceptibility in the Scaglia Rossa pelagic limestone. *Earth Planet Sci Lett* 82:349–356
- Mazumdar SK (1988) Crustal evolution of the Chotanagpur gneissic complex and the mica belt of Bihar. In: Mukhopadhyay D (ed) *Precambrian of the Eastern Indian Shield*. Geol. Soc. India, Mem, vol 8, pp 49–83
- Mondal S, Mazumdar D, Chatterjee S, Gain D, Shil R (2017) Nature of flow patterns of Rajahmundry lava, Gowripatnam area, West Godavari, India: insights from AMS studies. *Curr Sci* 113(9): 1719–1728
- Nagata T (1961) *Rock magnetism*. Maruzen, Tokyo
- Papanna G, Venkateswarlu M, Periasamy V, Nagendra R (2014) Anisotropy of magnetic susceptibility (AMS) studies of Campanian–Maastrichtian sediments of Ariyalur group, Cauvery Basin, Tamil Nadu, India: an appraisal to paleocurrent directions. *J Earth Syst Sci* 123(2):351–364
- Parés JM, Hassold NJC, Rea DK, van der Pluijm BA (2007) Paleocurrent directions from paleomagnetic reorientation of magnetic fabrics in deep-sea sediments at the Antarctic peninsula Pacific margin (ODP Sites 1095, 1101). *Mar Geol* 242:261–269
- Park CK, Doh SJ, Suk DW, Kim KH (2000) Sedimentary fabric on deep-sea sediments from KODOS area in the Eastern Pacific. *Mar Geol* 171:115–126
- Piper JDA, Elliot MT, Kneller BC (1996) Anisotropy of magnetic susceptibility in a Paleozoic flysch basin: the Windermere Supergroup, northern England. *Sediment Geol* 106:235–258
- Potter PE, Pettijohn FJ (1977) *Paleocurrents and basin analysis*. Academic Press, New York
- Potter PE, Maynard JB, Pryoy WA (1980) *Sedimentology of shale*. Springer Verlag, Heidelberg

- Raja Rao CS (ed) (1987) Coalfields of India. Bull. Geol. Surv. India, Ser. A, vol. 45, IV. Part I. Geological Survey of India Publication, Calcutta, pp 1–247
- Rathi G, Sangode SJ, Kumar R, Ghosh SK (2007) Magnetic fabrics under high-energy fluvial regime of the Himalayan Foreland Basin, NW Himalaya. *Curr Sci* 92(7):933–944
- Rees AI (1961) The effect of water current in the magnetic remanence and anisotropy of susceptibility of some sediments. *Geophys J* 5:235–251
- Rochette P, Jackson M, Aubourg C (1992) Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Rev Geophys* 30:209–226
- Sangode SJ (2001) Application of magnetic fabric studies in an ancient fluvial sequence of NW Himalaya. *Curr Sci* 81(1):66–71
- Schieber J, Ellwood BB (1988) The coincidence of macroscopic paleocurrent indicators and magnetic lineation in shales from the Precambrian belt basin. *J Sediment Petrol* 58(5):830–835
- Schieber J, Ellwood BB (1993) Determination of basin wide paleocurrent patterns in a shale succession from anisotropy of magnetic susceptibility (AMS): a case study of the mid-Proterozoic Newland Formation, Montana. *J Sediment Petrol* 63:878–880
- Sinha S, Sen K, Sangode SJ, Kumar R, Ghosh SK (2009) Sedimentology and magnetic fabric studies of Mio-Pliocene fluvial succession in the NW Himalayan foreland basin. *Curr Sci* 96(2):260–267
- Stacey FD, Joplin G, Lindsay J (1960) Magnetic anisotropy and fabric of some foliated rocks from S.E. Australia. *Pure Appl Geophys* 47:30–40
- Suttner LJ, Dutta PK (1986) Alluvial sandstone composition and paleoclimate: I. Framework mineralogy. *J Sediment Petrol* 56(3):329–345
- Taira A (1989) Magnetic fabric and depositional processes in sedimentary facies in the active plate margin, Tokyo. Terra Scientific Publishing
- Tarling DH, Hrouda F (1993) The magnetic anisotropy of rocks. Chapman and Hall, London
- Veloso EE, Anma R, Ota T, Komiya T, Kahashuma S, Yamazaki T (2007) Paleocurrent patterns of the sedimentary sequence of the aita ophiolite constrained by anisotropy of magnetic susceptibility and paleomagnetic analysis. *Sediment Geol* 201:446–460