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SCARP SANDSTONE: AN EXAMPLE OF ESTUARINE SEDIMENTATION WITHIN THE MESOPROTEROZOIC KAIMUR GROUP OF THE VINDHYAN BASIN, (MIRZAPUR, U.P.), INDIA

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ABSTRACT

Famous for its controversial origin, the Precambrian Scarp Sandstone Member in the studied hillock sections is 20-25 m thick. The rock successions are made up of 3-6 m thick channelized, vertically stacked and laterally shifting sand bodies. Based on primary sedimentary structures such as small to large scale trough- and- herringbone cross - beddings, wave, current and interference ripples, tidal bundles with mud drapes, four major lithofacies and at least two of them, divisible into subfacies are identified and ascribed to above the wave base shallow marine origin. However, channelized nature of the sand bodies and their hundreds of meter wide lateral extent made up of shoaling cycles, and north-west directed polymodal palaeocurrent pattern, imply deposition in sub-tidal to inter-tidal domains of estuarine setting. Nevertheless, the overall coarsening upward trend in the grain-size in the measured sections indicates tendency of deposition in a transgressive system. Sandstones show both textural and mineralogical maturity. Fine to medium-grained quartz arenites having sub-populations of both mono and polycrystalline quartz and heavy minerals such as hypersthene, olivine and zircon demand sediment supply from a provenance comprising rocks of metamorphic, sedimentary and igneous origin.

Keywords: Vindhyan Basin, Kaimur Group, Scarp Sandstone, Lithofacies, Shoaling cycles, Shallow marine

INTRODUCTION

The Vindhyan Basin is an intracratonic Proterozoic basin which forms about 6000 m thick sedimentary prism that covers a long period of 1600 – 500 Ma during Meso-Neo Proterozoic eras (Soni *et al*., 1987) (Fig. 1). The rocks of the Vindhyan Supergroup are mainly divided into two groups, the Lower Vindhyans and the Upper Vindhyans. The Lower Vindhyans are referred to as the Semri Group of rocks which are overlain by the Upper Vindhyans consisting of the Kaimur, Rewa and Bhander Groups (Table 1). Chakrabarty *et al*. (2007) support that sedimentation in the Vindhyan Basin was not continuous and it lasted over ~1 Ga. Also the Nd isotopic studies of the Vindhyan sediments reveal that the sediments for the Kaimur and Bhander Groups have been derived from more juvenile sediments compared to the Semri and Rewa Groups (Chakrabarty *et al*., 2007). The Kaimur Group has been intruded by the Majhgawan Kimberlite at just one location at the Chitrakoot sector at the Northern fringes of the basin. The validity of this limit throughout the strike length of this Group is therefore not firmly established (Mitra, 1996; Ray, 2006). The ages of the Lakheri and Bhander limestones in the western and eastern sectors, respectively validate the traditional view of the Kaimur Group as a marker horizon not younger than 1070 Ma (Gopalan *et al*., 2013). Present study focuses on the Scarp Sandstone Member of the Kaimur Group (Table 1).

Table 1. Stratigraphic succession of the Vindhyan Supergroup (Prakash and Dalela, 1982).

		(Present classification)			(Auden, 1933)		
		Group	Formation	Member/Beds	Sub-Stage	Stage	Series
V							
		Bhander		Sandstones, shales and limestones			
I							
		Rewa		Shales and sandstones			
N							
			Mangesar Formation	Dhandraul Quartzite	Dhandraul Quartzite	Upper	
D					Scarp Sandstone	Kaimur	
				Black Shales			
H	UPPER VINDHYANS	Kaimur	Bijaigarh Shale	Sandy Shales and dark sandy shales	Bijaigarh Shale		Kaimur
Y							
				Upper Quartzites	Upper Quartzite		
			Gurma	Susnai Breccia		Lower	
			Formation	Silicified Shale	Silicified Shale	Kaimur	
A				Lower Quartzite	Lower Quartzite		
------------------				**unconformity**	------------------		
N							
	LOWER VINDHYANS	Semri		Limestones and sandstones			
S							

Rocks of the Vindhyan Supergroup have been extensively studied for various aspects relating to stratigraphy, physical sedimentary structures (Misra *et al*., 1972; Sarkar, 1981), micro-and mega fossils (Kumar and Srivastava, 1992, 1995; Anbarasu, 2001; Kumar, 1999, 2001, 2009; Kumar and Pandey, 2008, etc.), stromatolites (Kumar, 1976; 1980; Valdiya, 1989; Raha and Shastry, 1982), isotopic studies (Kumar *et al*., 2002; 2005; Chakrabarty *et al*., 2007; Gopalan *et al*., 2013) but the sedimentological investigations are still uncommon. Awasthi (1961, 1964), Mathur and Srivastava (1962) and Misra and Awasthi (1962) have studied the Vindhyans of Son Valley from sedimentological point of view, and suggested a shallow water environment for their deposition. Later workers (Banerjee, 1964, 1974; Singh, 1973, 1976) have interpreted depositional environments as varying from beach to barrier bar or shoal through tidal flat (sub-, inter-, and supra-tidal) and lagoon. The Kaimur Group in Rajasthan, India has been reported as a prograding storm and tide dominated (Bose *et al*., 1988 and Chakraborty and Bose, 1990). Despite such important studies, the Scarp Sandstone Formation of the Kaimur Group remained the focus of discussion for its depositional environment mainly because of its sandy character, lacking fine-grained muddy facies and any diagnostic fossil or trace fossils present in them. The purpose of the present study is to highlight the lithofacies character and to characterize the petrographic attributes and palaeocurrent trends in the Scarp Sandstone Formation to re-evaluate its depositional environments. Comment on the sequence stratigraphic context of these rocks is also attempted.

METHODOLOGY

The Scarp Sandstone has been studied in three far spaced hillock sections so as to have a regional perspective. The studied outcrop A and B are located near Rajeev Gandhi Campus at Barkachha located in Mirzapur district, along the National High way 7 leading to Drummondganj (Fig. 1) and located at the co-ordinates of E 82°30' 30" and N 25° 05' 00" at 95 m elevation. The outcrop C is located at Lakhaniadari, on Garai river geographically located at the co-ordinates of N 24° 57' 0.61" and E 83° 00' 0.67" at 283 m elevation. In the studied hillocks, the Scarp Sandstone is characterized by the multistoreyed sandstone bodies with the meager representation of fine-grained silt-mudstones.

The located sections were measured using tape and brunton technique and detailed lithologs were prepared for systematic lithofacies analysis. Geometry of lithounits, sedimentary structures and palaeocurrent azimuths from large-scale cross-beds were recorded in the field using brunton compass. Statistical analysis of palaeocurrent data was carried out up to the modal level and also plotted on rose diagrams to characterize the dominating current modes for sediment dispersal and

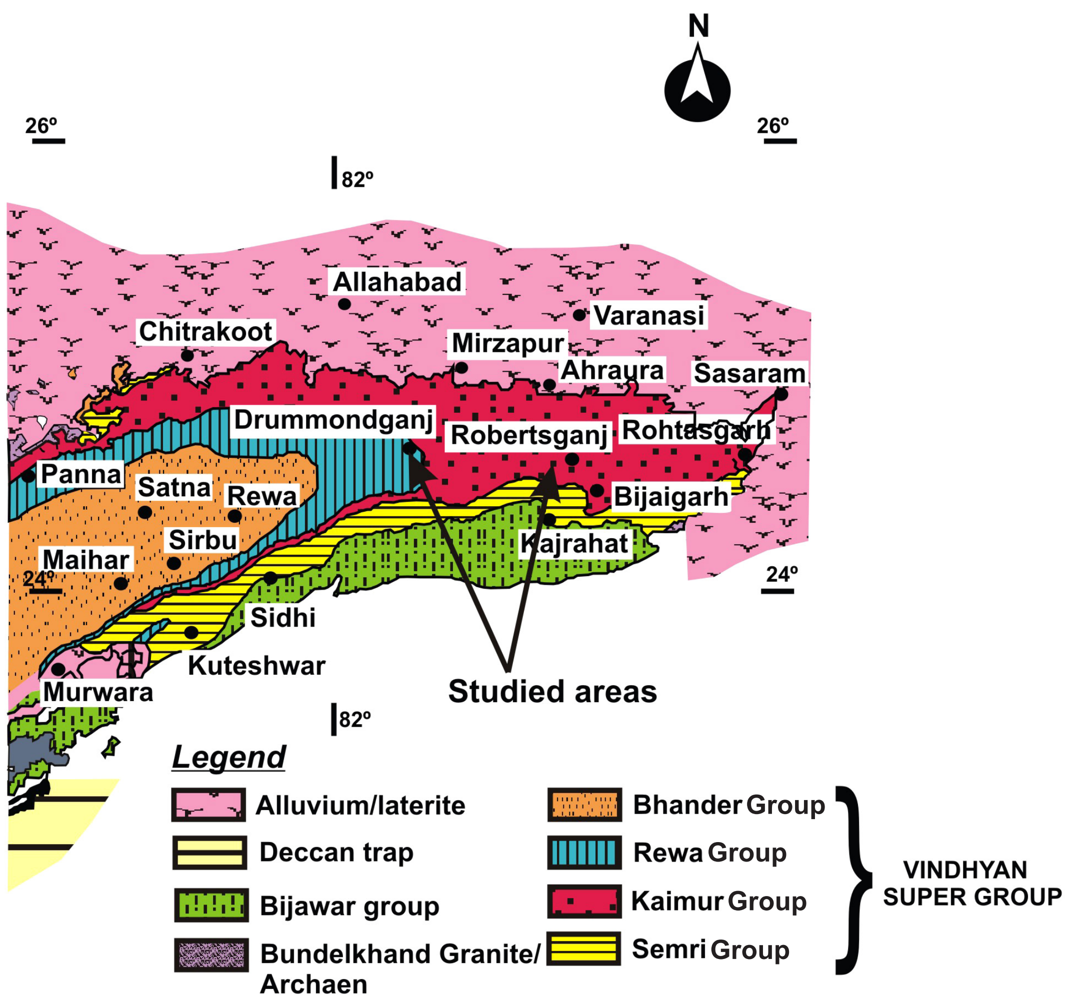

Fig. 1. Location and regional geological map of a part of the Vindhyan Basin (modified after Soni *et al*., 1987).

environmental analysis in conjunction with lithofacies analysis (Tanner, 1959; Shukla *et al*., 1999). For the petrography, fresh samples were collected on the basis of lithofacies variation from bottom, middle and top levels of sections. Thin sections of the samples were prepared and subjected to petrographic analysis under advanced Olympus microscope. During microscopic investigation, grain size, shape and grain to cement and grain to grain relationship were determined. The proportions of quartz, feldspar, rock fragments, mica, heavy minerals and cement/matrix were determined. About 300 grains per slide were counted by point counting method (Dickinson, 1985) and the relative proportions of quartz, feldspar and rock fragments were determined and plotted on QFL triangular diagram to determine the lithology and tectonic setting.

LITHOFACIES ANALYSIS

Three sections are studied in which the first hillock section (A) is about 25 m in thickness and second hillock (B) is 13 m and third hillock C is about 22 m in thickness (Figs. 1, 2). Following de Raaf *et al*. (1965) and Walker (1984), facies analysis in the present case is based on parameters such as grain-size, sorting, primary physical structures, palaeocurrent pattern and geometry of lithounits. On the basis of the well-preserved physical structures at least 4 major and 8 sub-lithofacies have been identified (Figs. 2 and 3). Facies association has helped to develop a conceptual depositional model for the Scarp Sandstone Formation. A brief description of the lithofacies (A to D) and their sub-facies is given below and summarized in the Fig. 3.

A. Large-Scale cross-bedded fine- to medium-grained sandstone lithofacies

This lithofacies is generally 1 m to 2.5 m thick and shows development of 4 subfacies which are associated in variable combination to form fining upwards cycles (Figs. 4, 5 and 7).

Large-Scale trough cross-bedded facies: This facies is characterized by large trough sets and ranges in thickness from less than 1.5 to 2 m. It is developed in iron pigmented red colored, medium-grained sandstones and characterized by thick cross-bed sets capped by thin laterally impersistent clayey siltstone layers of a few centimetres thick. These fine-grained units are structured internally by small-scale trough cross-sets. These facies are present above the planar cross-bedded facies with deep erosional contact and eroded by herringbone cross-bedding facies at its top. Mean azimuth of trough cross-beds varies between 220^o and 300^o (Figs. 2 and 5C).

Large-scale planar cross-bedding with mud-drapes: It is the dominant type of cross-bedded facies. It cross-cuts the lower small-scale cross-bedded facies and is eroded by trough/herringbone lithofacies. These facies are medium grained and characterized by thick cross-bed sets with low foreset inclination of 12° to 15°. The sets are 1-2 m thick and tens of meters in lateral extent. Their mean dip direction varies from 250^o to 360^o. The sets commonly occur as grouped sets or cosets. These sets have erosional upper and lower bounding surfaces. The topset, foreset and bottom set range in thickness from 50-70 cm. Internally, these cross beds are simple with few reactivation surfaces and laterally extensive having mud-drapes present on the foresets. Mud-drapes are present as very thin layer in range of millimeters, internally thinly laminated and devoid of any structures within them (Fig. 5A). Boersma and Terwindt (1981) observed that sandwaves, occurring in areas with a dominant tide, made unidirectional structures. So, foresets are inclined in the direction of dominant tide.

Herringbone cross-bedded facies: This facies is fine to medium grained and characterized by almost 180^o degree palaeocurrent reversal. This facies erodes planar/trough cross - bedded facies and is cross-cut by tidal bundled facies above it. They have dip direction ranging from 70^o-350^o for both the directions and occur in the thickness of 1.2-1.5 m. They are laterally tens of meters extensive and are persistent at the lower as well as at the upper stratigraphic levels (Fig. 5B). According to Boersma and Terwindt (1981), dunes are characteristic of areas in which ebb and flood were of a comparable strength and appeared to build bi-directional structures (Figs. 2, 3 and 5B).

Cross-bedding facies with tidal bundles: During the dominant tide a lateral succession of cross-strata, called a tidal bundle is generated (Boersma and Terwindt, 1981). Cross-bedding facies with tidal bundles cross-cuts the herringbone cross-bedded lithofacies and sharply succeeded by rippled siltstone lithofacies at the top. This facies is developed in medium-grained sandstones having thickness ranging from 2-2.5 m. In the hillock A, tidal bundles are present at the level of about 2.5 m and 12 m, at the level of 2.5 m and 5.5 m in the hillock B and at 2m and 20 m in hillock C. Tidal bundles with double mud-drapes and increasing thickness in down current direction are observed. Neap cycle tidal bundles are 25 - 40 cm thick and spring cycle bundles are 70 - 90 cm thick (Fig. 2, 4 and 6). Their wavelengths vary from 5-6 m in spring bundles and 1-2 m in neap bundles. Though bundles are not fully preserved, still 7-8 distinct bundles are visible in spring cycle and approximately 18 bundles in neap cycle. Internally, these bundles show low angle planar cross-beds and are enclosed between gently sloping erosive or non-erosive mud-draped surfaces which are rippled and crinkled. The bundles formed around neap tide are small, reflect fall in acceleration state and thickening of mud-drapes. These mud-drapes are either erosional or depositional. Spring cycle tidal bundles are larger, reflect more pronounced full vortex, thinning of mud-drapes and increased length and height of cross-bedded interval. The foresets of the some tidal bundles are sigmoidal in shape and become rippled at the down current end of the bedforms. The full vortex structure tends to be more pronounced around spring tide but disappear during neap tide. The dip direction of these tidal bundles ranges from 220^o-300^o (Figs. 4 and 6). Also, the internal structure of these bundles contains double mud-draped sandy foresets.

Interpretation: Trough cross-beds are formed by migration of 3D bedforms or dunes in shallow water condition (Harms *et al*., 1982; Breda and Preto, 2011). Trough cross-bedding (Fig. 4) is formed in fine-grained sandstone in a lensoid sandbody, which indicates deposition in the sub-tidal environment (Reineck and Singh, 1980; Mowbray and Visser, 1984). The planar cross-bedding (Fig. 5A) is formed by the migration of 2-D bedforms (Breda and Preto, 2011). The migration of one large-scale bedform over another bedform indicates high energy and large sediment influx (Allen, 1980 and Reineck and Singh, 1980). Mud drapes present within cross-sets indicate episodic migration of dunes that remained stable over multiple depositional events under the tidal setting (Willis *et al*., 1999). Herringbone cross-beddings (Figs. 5B) are highly asymmetrical bedforms, represent current reversal and support the strong evidence for tidal activity (Wilson, 2010). Also, Mowbray and Visser (1984) and Ojo and Akande (2003) supported the view that herringbone type reversals occur in such shallow marine environment where channel filling is done by tidal activities. The tidal bundles (Fig. 6) are formed as a result of fluctuation in current strength,

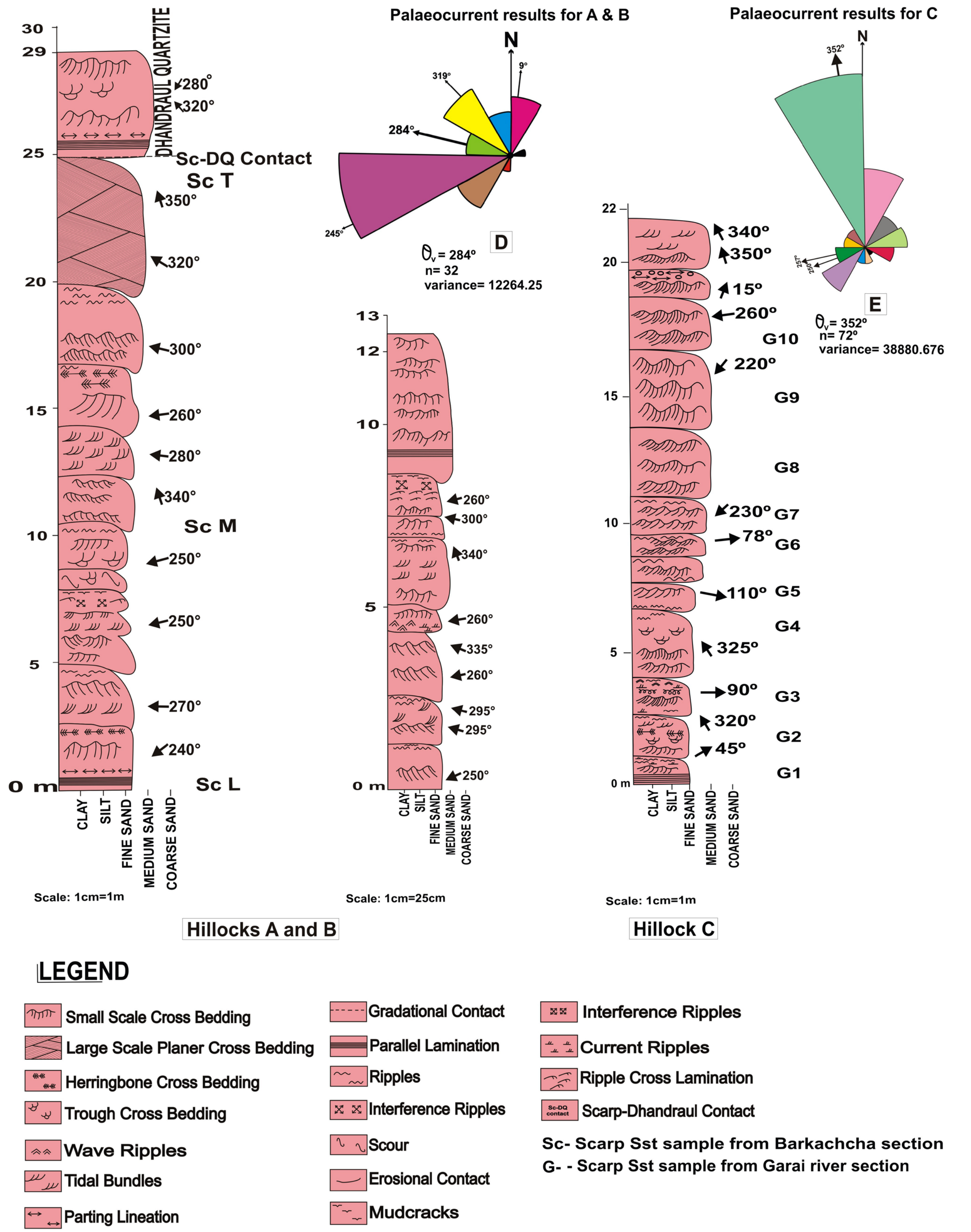

Fig. 2. Lithologs of the studied hillock sections representing distribution of primary sedimentary structures and various lithofacies from the Scarp Sandstone Hillocks. (A) Represents Hillock 'A' at Barkachha; (B) represents Hillock 'B', 500 m laterally away from the hillock A at Barkachha. (C) Litholog of the Garai river section; (D) & (E) represent rose plots for the Barkachha and Garai river sections respectively.

NAME OF THE LITHOFACIES	CHARACTERISTIC FEATURES	INTERPRETATION
Ripple cross-laminated siltstone lithofacies	They are present at the top of each shoaling cycle, sharply eroding tidal bundled facies and other cross-beds; migration of small-scale ripples in many directions; bifurcating crests;mud-cracks; interference and current wave ripples.	Indicating exposure at the top of each shoaling cycle; shallow water sedimentation features.
Fine to medium grained sandstone with tidal bundles	Co-sets visible; planar and trough cross -strata; bipolarity in foresets; current reversals; Migrating bedforms; tidal bundles reflecting increasing and decreasing strength of currents; double mud-drapes on foresets.	Depostion by tidal currents; currents reversals indicating changing direction of bedform migration; mud-drapes reflecting deposition from slack water.
Large scale planar, trough and herringbone cross-bedded silt-fine sandstone lithofacies	Foresets showing high variability in palaeocurrents and are represented throughout the section; herringbone cross-bedding is profusely developed.	Formed by migration of 2D- and 3D bedforms; note palaeocurrent variability.
Low angle horizontally laminated lithofacies with primary parting lineation	Horizontal lamination identified by grain-size; mineralogical; compositional and/or color changes dominated by fine-grained deposits; Parting lineation is visible in the form of low ridges on the upper-plane bed surface reflecting subtle grain-size changes.	Horizontal lineation indicate that deposition took place in the upper flow regime conditions orientation of parting lineation indicates line of water flow.

Fig. 3. Major lithofacies present in the Scarp Sandstone sections in the order of their occurrence from bottom to top with their characteristic features and interpretation.

direction and water depth (Boersma and Terwindt, 1981; Basilici *et al*., 2012). Mud-drapes mark a slack water period and lasts for 10-20 minutes (Boersma and Terwindt, 1981). The mud-drapes formed are as a result of cyclic instability in flow (Singh and Singh, 1992). The thickness variation in bundles is believed to result from neap-spring variations in maximum tidal current velocity and a number of other factors which cause sediment transport rates in the dominant current direction (and therefore bedform migration rates) to vary (Uhlir *et al*., 1988). During neap cycle, tidal bundles are arranged in thin bundles because the tidal range and current speed is minimum at that time (Mazumder and Arima, 2005) (Fig. 4), and during spring cycle, thick bundles of a tidal rhythm are present (Fig. 6). Sigmoidal cross-beds are typically reported from more open, sand dominated parts of estuaries (Shanley *et al*., 1992). Presence of

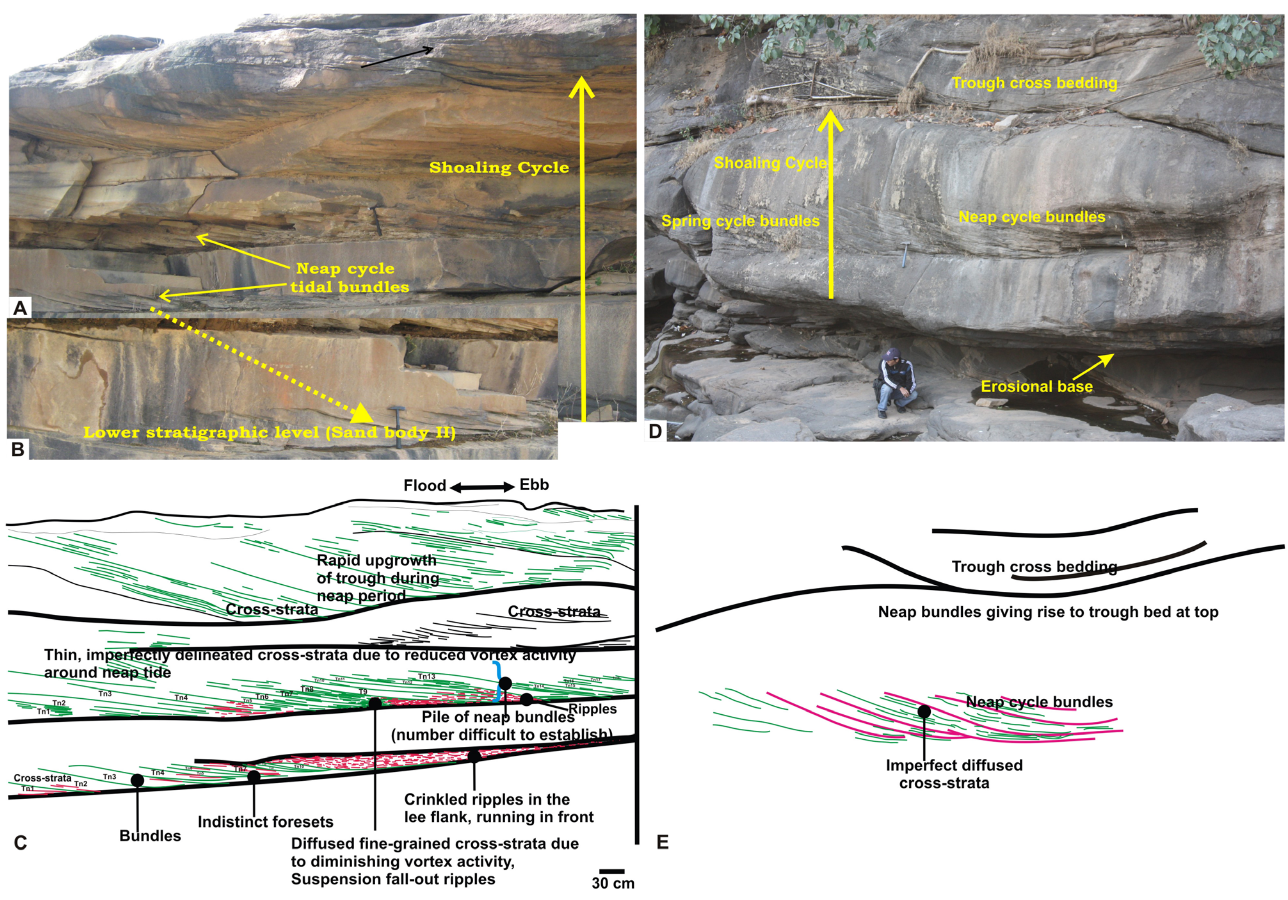

Fig. 4. (A-D) Photographs showing trough cross-bedded lithofacies, along with representation of neap cycle tidal bundles and shoaling cycles. Yellow arrow pointing the close-up view of neap bundles at the lower stratigraphic levels at (B); (C-E) Schematic sketch of (A-D) respectively showing the neap cycle bundles leading to the rapid formation of trough cross bedded unit after neap period, neap tidal bundles marked as Tn1, Tn2....Tn_n. Photographs (A-B-C) are from the Barkachcha section and (D-E) from the Garai river section.

double mud-drapes suggests that current conditions were highly fluctuating between major tidal flow events. The lower and upper mud-drapes between the sandy cross-bedding are formed as a result of slack-water period between the former and later tide (Visser, 1980; Singh and Singh, 1992). Mud-drapes are present between two successive bundles which represent the standstill phase flanked by dune migration of bedforms (Boersma and Terwindt, 1981) (Fig. 6B). According to Singh and Singh (1992), double mud-draped separation of individual bundles is a feature of sub-tidal deposits. They indicate complete current reversal where sediments are deposited by the leading and the secondary current (De Boer *et al*., 1989; Dalrymple, 1992, 2010; Ponten and Bjorklund, 2007) (Fig. 7B).

B. Low-angle horizontally laminated lithofacies with primary parting lineation

These facies are flat, plane bedding varying in thickness from 1.5 - 2 m. They are thinly laminated and parallel or dipping at very low angles. The bedding plane surfaces show presence of well-developed primary parting lineation. These facies have erosional relationship with the overlying small scale cross bedded facies. At the top of parallel bed parting lineation is present which is formed parallel to the flow direction, so that its orientation will indicate the trend of the palaeocurrent.

Interpretation: The plane laminated facies with parting lineation closely resembles a high energy beach environment (Reineck and Singh, 1980; Dalrymple *et al*., 1992; Bose and Chakraborty, 1994). This lithofacies show excellent development of parting lineation which belongs to Upper flow regime (Harms *et al*., 1982). Solitary cross-beds associated with horizontal laminations suggest latest events of deposition on beach face under the influence of strong tidal and longshore currents intermittently attacking the sloping beach (Shukla and Pant, 1996).

C. Small-scale cross-bedded silt-fine sandstone lithofacies

These facies are characterized by fine grained sandstone with highly variable palaeocurrent trends varying from 220^{o}-355^{o}. These facies are present above horizontal laminated facies with deep erosional contact and are eroded by large scale planar/trough cross bedded facies. They are dominant throughout the section having average thickness ranging from 1 – 2 m (Figs. 2 & 7A).

Interpretation: Palaeocurrent variability associated with adjacent bedforms within individual shoaling cycles suggest that tidal currents used the same course for several cycles, such is another characteristic indicating deposition near shallow valley margins (Shukla and Bachmann, 2007).

D. Rippled siltstone lithofacies

This facies is 1.5-2 m thick and are characterized by well developed shallow water sedimentation features like interference rippled siltstone, modified rippled siltstone, current rippled siltstone, wave rippled siltstone and mud cracked clayey siltstone facies. These facies grade or cross-cut the tidal bundled facies are present at the top of each cycle indicating exposure (Figs. 2 & 7).

Interpretation: Presence of modified ripples, interference ripples and modified current ripples are signatures of shallow water conditions and intermittent exposures under intertidal setting. Modified ripples and mud cracks point to intermittent subaerial exposure of saturated depositional interface (Shukla and Pant, 1996). The sedimentary characteristics and presence of

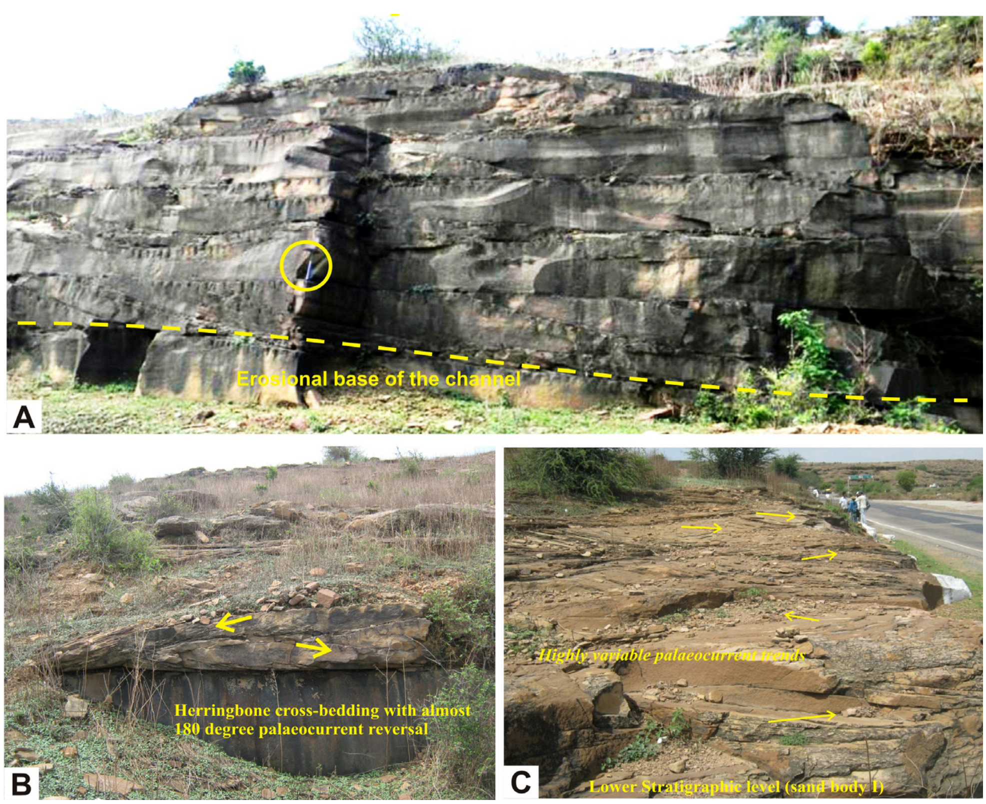

Fig. 5. (A) Large scale Planar cross-bedded lithofacies preserved in the channelized sandstone body. (B) Herringbone cross-bedded lithofacies showing almost 180° palaeocurrent reversals. (C) Large-scale trough cross-bedding with variable palaeocurrent trends. Yellow arrows are pointing to palaeocurrent directions.

both wave and current formed low to moderate energy primary physical features like graded bedding, ripple cross-lamination, flaser bedding and ripples of varied morphology and dimension are suggestive of intertidal sandflat (Reineck and Singh, 1975) origin, where bedload transport under tidal action dominated over slack water (suspension) depositions (Klein, 1970; Shukla and Pant, 1996).

LITHOFACIES ASSOCIATION

The visual observation shows that the lithofacies are repetitive in nature and form upward fining unit cycles (Fig. 2 & 3). The vertical association of lithofacies from bottom to top shows the occurrence of low angle, horizontally laminated lithofacies with parting lineation large scale planar/ trough cross bedded lithofacies herringbone cross bedded lithofacies cross-bedding with tidal bundles lithofacies Small-scale cross bedded silt-fine sandstone lithofacies which become rippled at the top leading to the formation of rippled siltstone lithofacies (Fig. 8). The whole of the Scarp Sandstone section in the study area is made up of upward fining cycles (Fig. 2) of the above nature.

PETROGRAPHY

The sandstone is channelized and thickly bedded light red and brown in colour with thinner siltstone interbeds. Quartz is the major mineral and constituting more than 80% of the detrital grains. Quartz grains are sub-rounded to rounded and sub-angular too. Quartz can be classified into monocrystalline and polycrystalline types mainly (Fig. 9). Monocrystalline quartz is most dominating among framework grain constituents and shows better rounding than polycrystalline grains. Other varieties of quartz present are stretched metamorphic quartz and volcanic quartz. The size of quartz grains varies from 0.2 mm to 1 mm which is found increasing from bottom to top of all sections. Grain contacts are mostly concavo-convex type but sutured grains also occur at a few places in the upper stratigraphic level samples (Fig. 9). Development of overgrowths in quartz grains seen but it is not very pronounced. Inclusions of mica flakes are present in the quartz grains. Muscovite and biotite are the main micaceous minerals which are mainly found scattered but sheared mica flakes are also noticeable at one or two places. Intensively fractured quartz grains occupy some places in patches and pseudomatrix found in the Barkachcha locality samples (Fig. 9). Most of the feldspars inferred are sodic (albite), microcline and orthoclase making nearly 5 to 6% of the detrital grains (Fig. 10). Feldspar is also found to be altered into clay. Rock Fragments of all sedimentary (chert), metamorphic (quartzite) and igneous origin are recognized in the sandstone varying between 14-20 % of the detrital grains (Fig. 9). Minerals of low grade metamorphism like hypersthene is most commonly present as heavy mineral whereas other minerals like olivine, zircon, and tourmaline also contribute at few places (Figs. 9 & 10). Representation of matrix is highly varied. Siliceous, argillaceous and rock fragment matrix is present in fairly good amount in sandstone and cementing material is siliceous. Iron matrix is also present at few places. QtFL plot (Fig. 11) after Dickinson and Suczec (1979) of detrital modes of samples taken

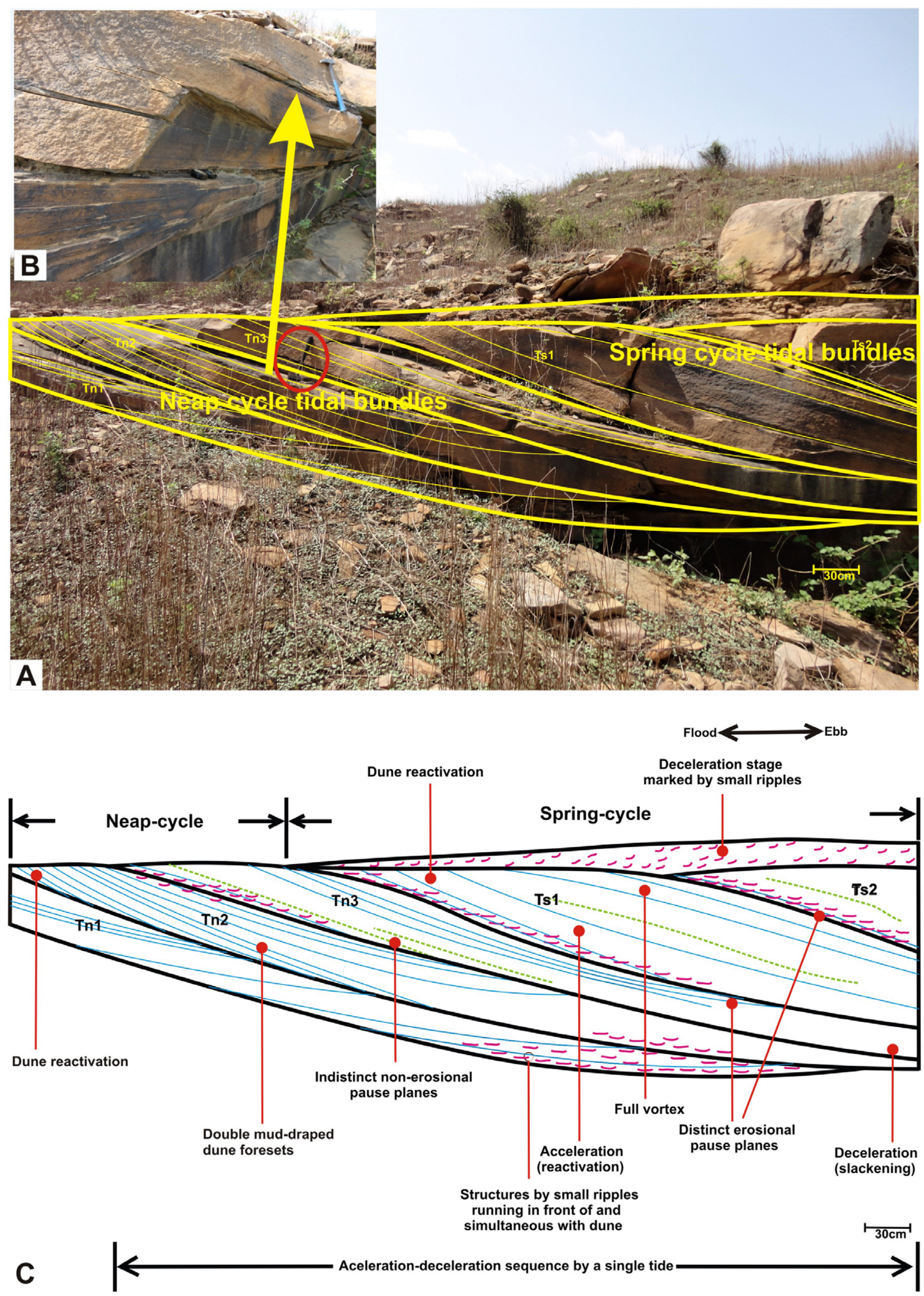

Fig. 6. (A)Tidal bundles with the various stages preserved, Yellow arrow pointing towards the close-up view of double mud-draped foresets at (B); (C) Schematic sketch of tidal bundles, bundles marked as Tn1, Tn2.....Tn_n as neap cycle bundles and Ts1, Ts2.....Ts_n as spring cycle bundles.

from lower middle and upper stratigraphic levels of the Scarp. Although the percentage of quartz does not vary much in all the three outcrops (80-90%), they show little increasing trend in quartz and lithic fragments (8-10%) percentage from lower to upper stratigraphic levels within the outcrop. Mineralogical and textural maturity is moderate which improves from bottom to top levels that indicates arenitic grade of sandstone. (Fig. 9).

Interpretation: Based on the detrital grain composition of the sandstones, several conclusions can be made regarding the likely provenance of the sediments (Figs. 9-11). The sandstone composition does not support any change in the source area over time. The sandstone is having domination of monocrystalline quartz is fine to medium grained, moderately to well sorted and grain shape is sub-angular to sub-rounded which is suggestive of moderate degree of transportation. The fine-grained monocrystalline grains are most likely the product of breakage and chipping of larger quartz grains derived from an igneous provenance. Polycrystalline and stretched quartz grains were most likely derived from a metamorphic source (Dickinson, 1970; Ghazi and Mountney, 2011). Low polycrystalline to total quartz (Qp/ Q) ratio indicates that the main source for the sediment was via the erosion of plutonic, granitic material (cf. Dickinson, 1970; Ghazi and Mountney, 2011). Pseudomatrix and fractured quartz grains are the result of increase of pressure on them which is due to burial and compaction which occurs during early stage of diagenesis (Worden and Burley, 2003) (Fig. 11). Inclusions in quartz support the metamorphic parent rock (Fig. 10). Volcanic quartz is identified with perfectly straight sides and rounded corners of the hexagonal quartz, straight extinction and no inclusion (Folk, 1980) which is indicative of volcanic source. Presence of feldspar is indicative of nearby source as feldspar is irresistible mineral and easily breaks down. Alteration of feldspar to clay indicates rapid erosion in the area. Feldspar content is very low which is suggestive of high degree of weathering in the region and also that source rock was feldspar containing. The presence of feldspar indicates that the source of sandstone is granitic and gneissic and supports the evidence of hot, arid climate during transportation (Ghazi and Mountney, 2011). Grain contacts are concavo-convex and also sutured which implies that the area was undergoing low degree of burial and compaction also (Worden and Burley, 2003) (Fig. 11). Detrital micas were most likely derived from low-grade metamorphic rocks like quartzite, schist, and gneiss, or from plutonic igneous rocks of granitic composition (Ghazi and Mountney, 2011). Sheared and stretched mica grains also support compaction. Heavy minerals such as hypersthene, olivine, tourmaline and zircon are present as accessory mineral which may be derived from volcanic or metamorphic rocks (Fig. 10). Inclusions in quartz are suggestive of metamorphic source. Samples contain sedimentary, metamorphic and volcanic rock fragments and some feldspathic grains cemented in siliceous cement. Authigenic growth over quartz arenites and the siliceous cement imply percolation of alkaline nature of fluids in to the pore spaces and porous grain texture before cementation. The textural and compositional characteristics of sandstone plotted on QFL triangular diagram suggest a nearby mixed provenance comprising of metamorphic, sedimentary and igneous origin (Dickinson, 1985) (Fig. 11). The samples are falling in the recycled orogen provenances. Presence of rock fragments indicates that the detrital grains have been derived from sedimentary, volcanic and metamorphic sources. Out of which the metamorphic sources dominate over the other two sources, it is more clear that the majority of the sediments from the Scarp Sandstone belong to metamorphic source. Also according to Chakrabarti *et al.* (2007) granitic source was not the major source for the deposition of Vindhyan sediments. The above petrographic results also favour that mixed igneous provenance sources were present in the Scarp Sandstone but they were not the major source. Instead, sediments were derived from a nearby mixed source terrain dominated by metamorphic rocks.

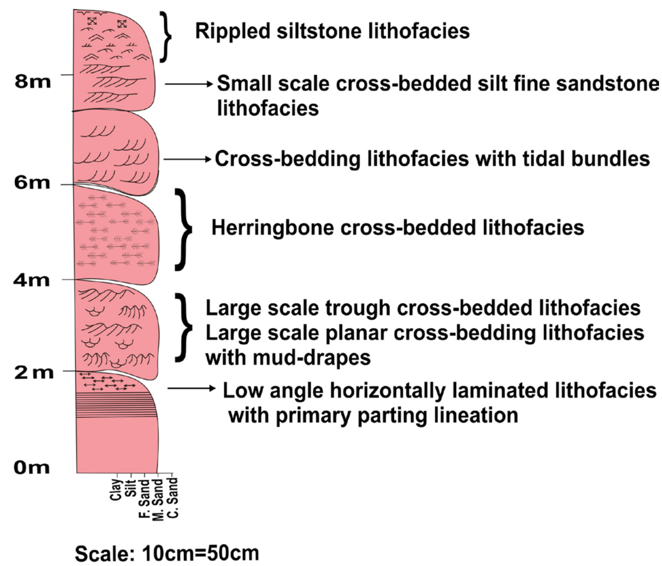

Fig. 8. Vertical association of lithofacies, in order of appearance from bottom to top.

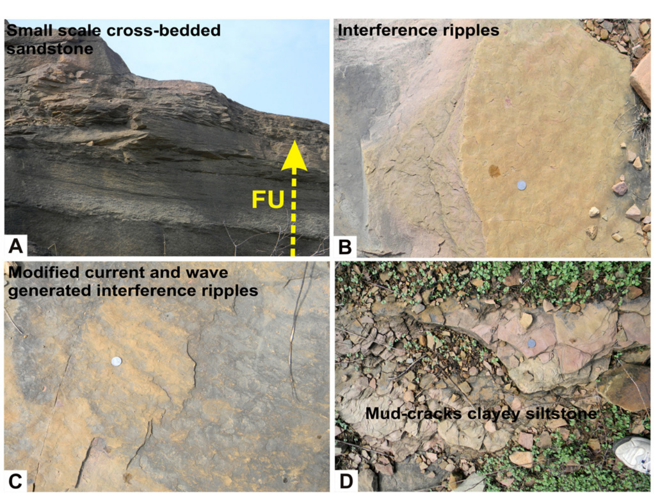

Fig. 7. Rippled siltstone lithofacies. (A) Yellow arrow pointing in the direction of upward fining cycle FU (shoaling cycle), small scale cross-bedded sand units at the top. (B) Interference ripples, (C) Modified current and wave generated interference ripples, and (D) Mudcracked clayey siltstone.

PALAEOCURRENT ANALYSIS

Palaeocurrent analysis involves the study of ancient sediment dispersal patterns and helps in determining provenance, palaeoslope, shore-line orientation and basin geometry if combined with parameters, e.g. facies distribution and channel axis orientation (Selley, 1968; Potter and Pettijohn, 1977; Pant and Shukla, 1999). Palaeocurrent directions are preferably collected from planar and trough cross-beddings. Palaeocurrent

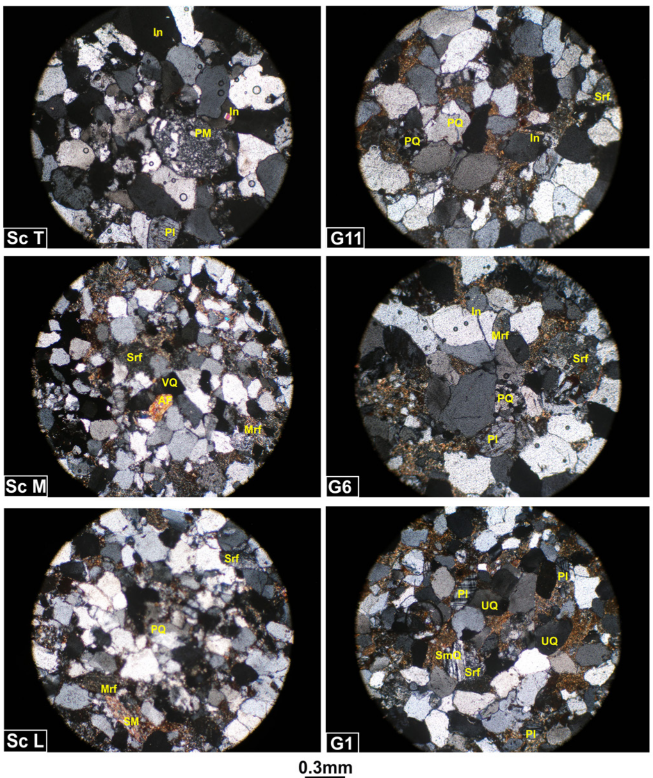

Fig. 9. Photomicrographs of thin sections (under 10x) of the Scarp Sandstone samples; G(1,6 & 11) represent thin sections from the lower, middle & upper stratigraphic levels of the Garai River section; Sc L (lower), Sc M (middle) and Sc T (top) are the Barkachcha section samples; Z= zircon, T= tourmaline, In= inclusion, Ms= muscovite, UQ= undulose quartz, VQ= volcanic quartz, AF= altered feldspar, Pl= plagioclase, PQ= pollycrystalline Quartz, SC= sutured Contacts, PM= pseudomatrix, SM= Stretched mica, Mrf= metamorphic rock fragment, srf= sedimentary rock fragment. SmQ= stretched metamorphic quartz.

patterns, however, if interpreted with respect to palaeoshoreline orientation, can yield important deduction regarding sediment dispersal and nature of tides and waves (Picard, 1967). Study of palaeocurrent of Scarp Sandstone gives the NW-SW directed polymodal palaeocurrent system, shows 240^{o} dispersion and mean current oriented to WWN at 284^{o} for Barkachcha section and 360° dispersion and mean current oriented to NNW 352° (Fig. 2D-E).

DISCUSSION

As indicated earlier by some workers, the depositional environment of the Scarp Sandstone and the Dhandraul Quartzite has long been a point of discussion and they are variously interpreted as marine shoal complex (Singh, 1973) and/or fluvial (Bhattacharya *et al*., 1986 and Bhattacharya and Morad, 1993) in origin. The channelized nature of the multi-storeyed sand bodies and their hundreds of metre wide lateral extent may imply deposition in estuarine setting during transgression (Shukla and Bachman, 2007) (Figs. 2, 4 and 5); and negates the possibility of fluvial/delta sedimentation. Estuarine conditions are characterized by major changes of current strength, direction and water depth during the short-period ebb-flood cycle as well as over the longer neap-spring-neap cycle, and that finds an accurate and logical response in the sedimentary structures in the top layer of an estuary fill (Boersma and Terwindt, 1981). Due to the changing current strength and fluctuations in water depth, lithofacies characters also change generating characteristic fining upwards lithofacies association in the Scarp Sandstone succession. The overall coarsening upward trend in the grain-size along with concurrent increase in textural and mineralogical maturity of the arenite grade sandstone implies shoreface translation/retreat towards the inner part of the estuary under progressive transgression (Figs. 2, 9 and 12). The outcrop consists of fining upward (FU) repetitive unit cycles filling the channelized sand bodies, characterized by herringbone cross-bedding, tidal bundles with double mud drapes, small to large scale planar and trough cross-bedding at the base, and features of exposure and shallow water sedimentation represented by wave ripples, interference ripples, ripple cross lamination and mud cracks near the top (Figs. 2, 3, 7 and 8). These features suggest deposition representing as shoaling bar cycles in sub-tidal to inter-tidal domain with intermittent exposure (Figs. 2 to 8). The size, shape and rate of migration of tidal bedforms, according to Klein (1970) are determined by the degree of dominance of one tide over the other (tidal asymmetry) (Boersma and Terwindt, 1981). Klein (1970) found the travel distance of bedforms per tide to increase with grain-size. Neap-Spring tide variation in bedform migration is also reported by Allen and Friend (1976). During Spring tides, bedforms migrate at great distances and migration distances are almost negligible during neap tides. Therefore, tidal bundles formed around neap-tide are small, but growing larger towards the spring tide (Figs. 4 and 6). Each tidal bundle is a resulting bedform preserved by the dominant tide. The deposition and preservation of thin and laterally extensive mud drapes on sand beds is due to large sand-wave asymmetry, and sudden increase of mud concentration, large time-velocity asymmetry and low strength of tidal currents, and high eccentricity of the tidal-current ellipse (Figs. 4 and 6).

The reversal of bedforms is another important occurrence (Fig. 6(A-C). Klein (1970) observed the bedforms to be asymmetrical and to move in the direction of the dominant tide only. In the areas of lower tidal range (mesotidal), structural bidirectionality appears to be more common (Reineck and Singh, 1973; Terwindt, 1971), although unidirectionality is also

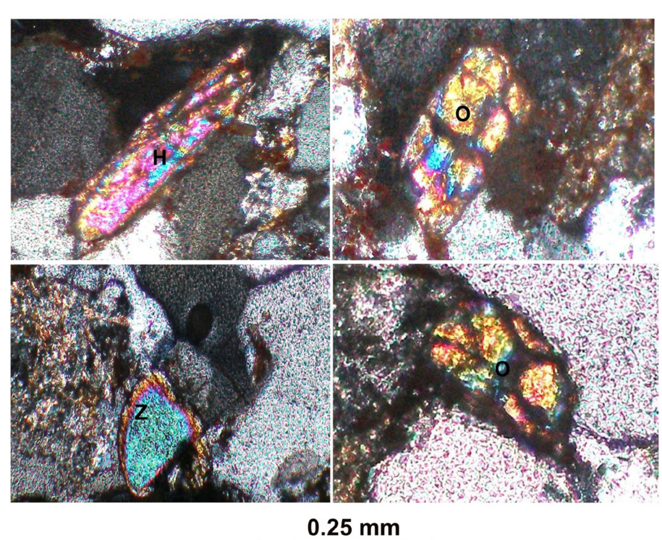

Fig. 10. Photomicrographs of some heavy minerals observed in Barkachcha and Garai river Scarp Sandstone thin sections; H= hypersthene, O= olivine, Z= zircon.

a major feature here (Allen and Friend, 1976). In the section, bidirectionality and reversals are quite common, along with unidirectionality at the lower as well as at the upper stratigraphic levels (Fig. 6A-C). Maximum thickness of tidal bundles is about 2-2.5 m (Fig. 6), which demarcates the tidal range. All these signatures support that deposition occurred in the mesotidal range. The palaeocurrent of foresets is dominantly towards NW direction and imply the dominance of ebb-currents (Fig. 2). This was also demonstrated by the internal structures in which bidirectional (herringbone) cross-stratification was a rare occurrence (Boersma and Terwindt, 1981). Current reversals, mud drapes, tidal bundles are the typical characteristics of inner shelf and nearshore tidal settings (Allen, 1982; Dalrymple, 1992). These tidal sequences consistently occurring in the whole outcrop, both laterally and vertically, so tidal origin is believed. According to Visser (1980), sub-tidal deposits have presence of double mud-layers along foresets of cross-stratification which consistently occurs at various levels in the Scarp Sandstone section. Nature of shoaling cycles (Figs. 2, 4 and 7) indicates deposition primarily above the wave base conditions within marine dominated parts of the estuary. However, 40-60 m wide channels showing stacked bar cycles may represent tidal channels/ inlets dissecting estuary mouth bar deposits (Figs. 3, 4 and 5). Such channels are quite common in mesotidal to macrotidal settings. Tides moving through these channels become more energetic due to confinement of flow and increased amplitude. In case of the Scarp Sandstone Formation of the study area, such channels are aligned in NW - SE direction indicating a NE - SW coastline trend (Fig. 2D-E). According to Kumar and Sharma (2010), the inferred palaeoshore line trend for the underlying Rewa and Bhander Groups of the Vindhyan Supergroup was E–W. However, according to Vredenburg (1906) and Auden (1933), the coastline of the Vindhyan Sea was located just north of the present-day outcrops of the Vindhyan sediments in Panna and the Chitrakut area (Figs. 1 and 2D-E). When NW and SW directed polymodal palaeocurrent pattern is interpreted with channel axis in the NW-SE direction with respect to inferred NE-SW shoreline trend of the Vindhyan Sea, it implies longshore sediment dispersal and domination of ebb-current over the entire tidal current system. The palaeocurrent pattern is polymodal (Fig. 2D-E) due to combination of longshore currents, tidal activity and wave action (Soegaard and Erikkson, 1985), depositing sediments in the sub-tidal channels, shoals and bars (Pant and Shukla, 1999). Petrography reveals that the sandstone is fine to medium grained, well sorted, sub-rounded to rounded, feldspathic with sedimentary, metamorphic and volcanic rock fragments, siliceous cement containing heavy minerals such as hypersthene, olivine, tourmaline, zircon, etc. On the basis of petrography, the sandstone is categorized as sub-litharenite (Figs. 9 and 10). The textural and compositional characteristics of the sandstone suggest a nearby mixed provenance of metamorphic, sedimentary and igneous origin (Fig. 11). All the above-mentioned characteristics, when pieced together, suggest that the Scarp Sandstone is a shoal complex and a product of shallow marine deposits where tidal processes were dominating. Taking all the observations under consideration, a depositional model is prepared following Dalrymple *et al.* (1992) (Fig. 12), in which the studied sections lie in the more marine and open part of the estuary where the tidal processes were prevalent.

CONCLUSIONS

The channelized nature of the multi-storeyed sand bodies and their hundreds of metre wide lateral extent imply deposition in estuarine setting during transgression. Presence of sedimentary features such as the herringbone-cross-beddings

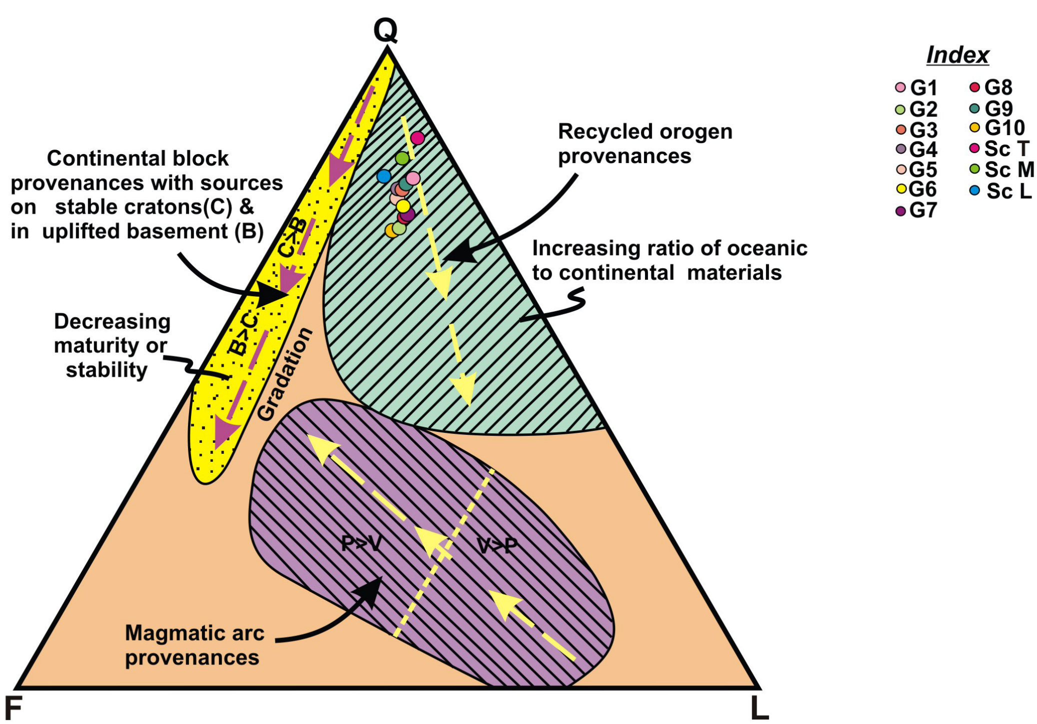

Fig. 11. Q-F-L, provenance discriminating diagrams (Dickinson, 1985) for Scarp Sandstone sections. G1,2,3....n stands for the sample from the lower level to upper level. Sc L,M,T = Scarp Sandstone samples from lowermost, middle and topmost bed of the Barkachha section.

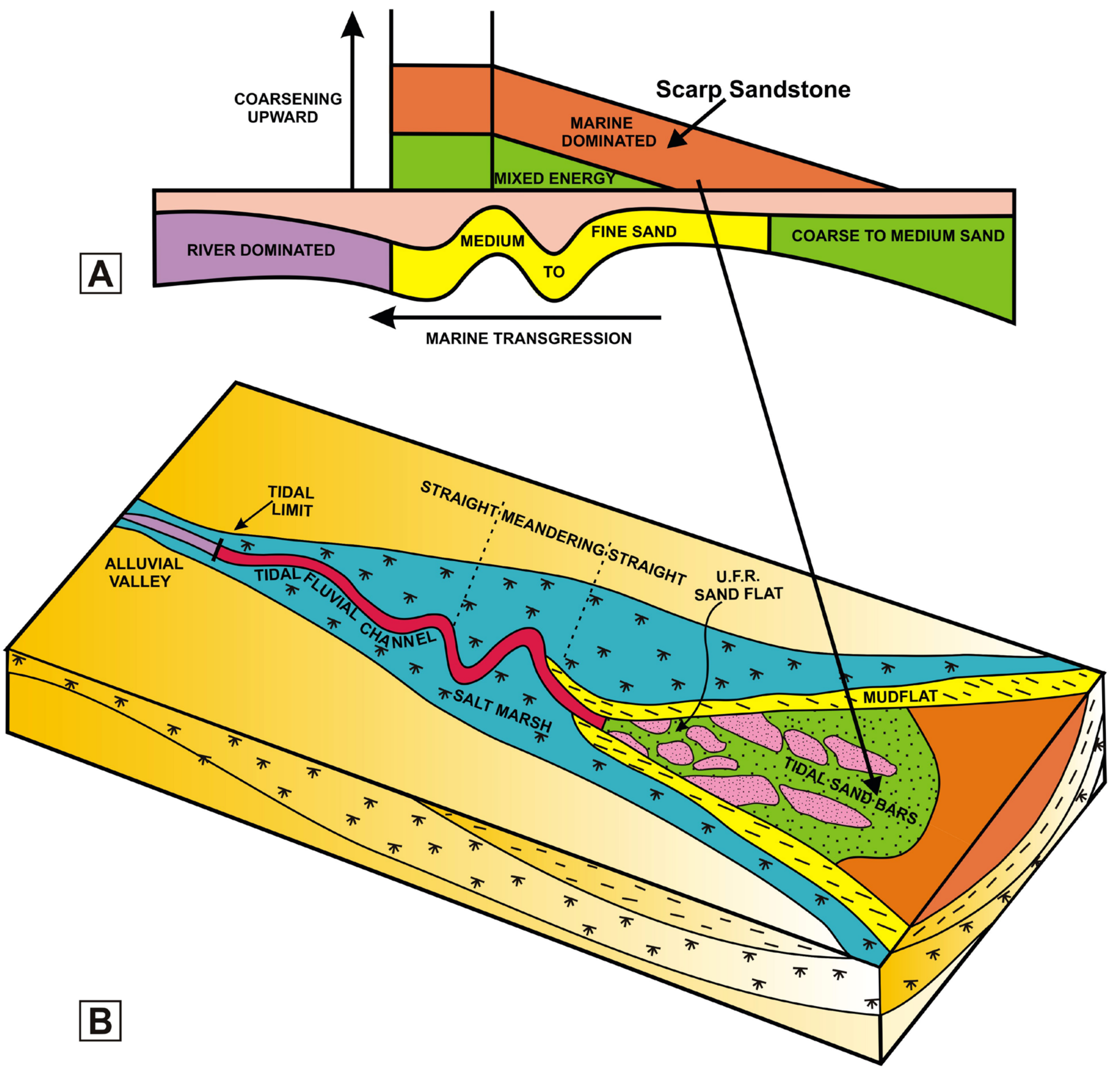

Fig. 12. (A) Depositional model suggested for the Scarp Sandstone; (B) Sedimentary facies within the tide–dominated estuary (after Dalrymple *et al*., 1992).

and current reversals throughout the outcrops strongly supports tidal activity over the entire system. Nature of the shoaling cycles indicates deposition primarily above the wave-base conditions within marine-dominated parts of the estuary. The palaeocurrent patterns indicate longshore sediment dispersal and domination of ebb-current over the tidal current system. Deposition of the Scarp Sandstone occurred in the conditions of tide-dominated estuary (Fig. 13).

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