Open Journal of Geology, 2012, 2, 80-90
http://dx.doi.org/10.4236/ojg.2012.22009 Published Online April 2012 (http://www.SciRP.org/journal/ojg)

Facies Development and Depositional Environment of the Patherwa Formation (Semri Group), Son Valley, India

Abul Hasnat Masood Ahmad[1], Ghulam Mohammad Bhat[2], Ruchi Agarwal[1]
[1]Department of Geology, Aligarh Muslim University, Aligarh, India
[2]Postgraduate Department of Geology, Jammu University, Jammu, India
Email: agrawal.geology@gmail.com

Received September 29, 2011; revised December 1, 2011; accepted February 16, 2012

ABSTRACT

The present study documents three facies associations recorded from the Patherwa Formation. These facies are related to tidally influenced fluvial channel (Facies association A), tidal channel (Facies association B) and tidal sand bar/tidal flat sandy facies (Facies association C). The spatio-temporal variation of these facies associations and palaeocurrent trends suggest tide dominated estuarine system. The estuaries were operational along a 60 km long NW-SE trending palaeo-shoreline. The Patherwa Formation grades up-section into facies packages of increasing tidal energy and terminate with the deposition within the upper flow regime estuarine settings.

Keywords: Vindhyan Basin; Sedimentary Facies; Palaeocurrents; Estuary; Tidal Flats; Upper Flow Regime

1. Introduction

The Vindhyan Supergroup represented by a thick pile of sediments belonging to the Semri, Kaimur, Rewa and Bhander Groups, is one of the largest Proterozoic sedimentary basins of India. It is spread over an estimated 100,000 km^2 area extending from Sasaram (Bihar) in the east to Chittorgarh (Rajasthan) in the west, see **Figure 1**. The Vindhyan basin is a peripheral foreland basin that developed in front of the arcurate fold belts of Aravalli, Delhi and Satpura with which it has a thrusted contact [1-3].

The Proterozoic Vindhyan Supergroup of India has attracted the attention of geologists since 1856 owing to the presence of diverse rock types [4]. These thick (4000 m) and unmetamorphosed sediments have been broadly divided into two lithostratigraphic units. The Lower Vindhyan or the Semri Group, and the Upper Vindhyan comprising of the Kaimur, Rewa and Bhander Groups each separated by conglomerate units [5]. The Semri Group is folded [6], whereas the Upper Vindhyans are known to be tectonically undisturbed. The Vindhyan Basin is bordered by the Aravalli-Delhi orogenic belt (2500 - 900 Ma) [7] in the west while the Satpura orogenic belt (1600 - 850 Ma) [8] occurs in the south and east. The Bundelkhand Granite Massif (3.3 - 2.5 Ga) [9] occurring at the centre of the basin divides the basin into two sub-basins, *i.e.*, the Son valley Vindhyans in the east and the Aravalli Vindhyans in the west. The sedimentary fill of Vindhyan Basin is commonly believed to be of Middle and Late Proterozoic age [10,11]. [12] classified Semri Group of Vindhyan Supergroup into eight Formations, see **Table 1**. The Semri Group depicts a cyclic sedimentation of rudacceous/arenaceous, argillaceous and carbonate facies, see **Table 1**. At least, three major cycles of sedimentation, each culminating in a tectono-magmatic activity, have been identified [12] in the Semri Group. [13] interpreted the depositional environment of the Vindhyan Basin to include high gradient environment. [6] suggests that the braid plain erg-transition appears to be a common phenomenon of the Proterozoic Era and its record should abound the terrestrial sandstones of that age. The Vindhyan sediments were deposited in the environments ranging from fluvial to deep marine conditions [6,14,15]. These rocks are deposited in an E-W elongated epeiric sea opening westward [16,17]. The studied Patherwa Formation forms the base of the Semri Formation in the Son Valley and has an angular unconformity/thrusted contact with the underlying Bundelkhand Granitoid Complex. The formation is composed of gritty to pebbly sandstones, medium grained sandstones and siltstones; conglomerates with cobbles, pebbles and clasts of quartz, chert, yellow and red jasper embedded in sandy matrix. The upper contact with the Arangi Shale Formation is conformable.

Rather limited facies and palaeocurrent investigations of the Patherwa Formation have been carries out; these include those of [12,13,17]. Well exposed sequences at Hardi, Obra, Kewta and Markundi were selected for the present work. The Lithostratigraphy of this succession

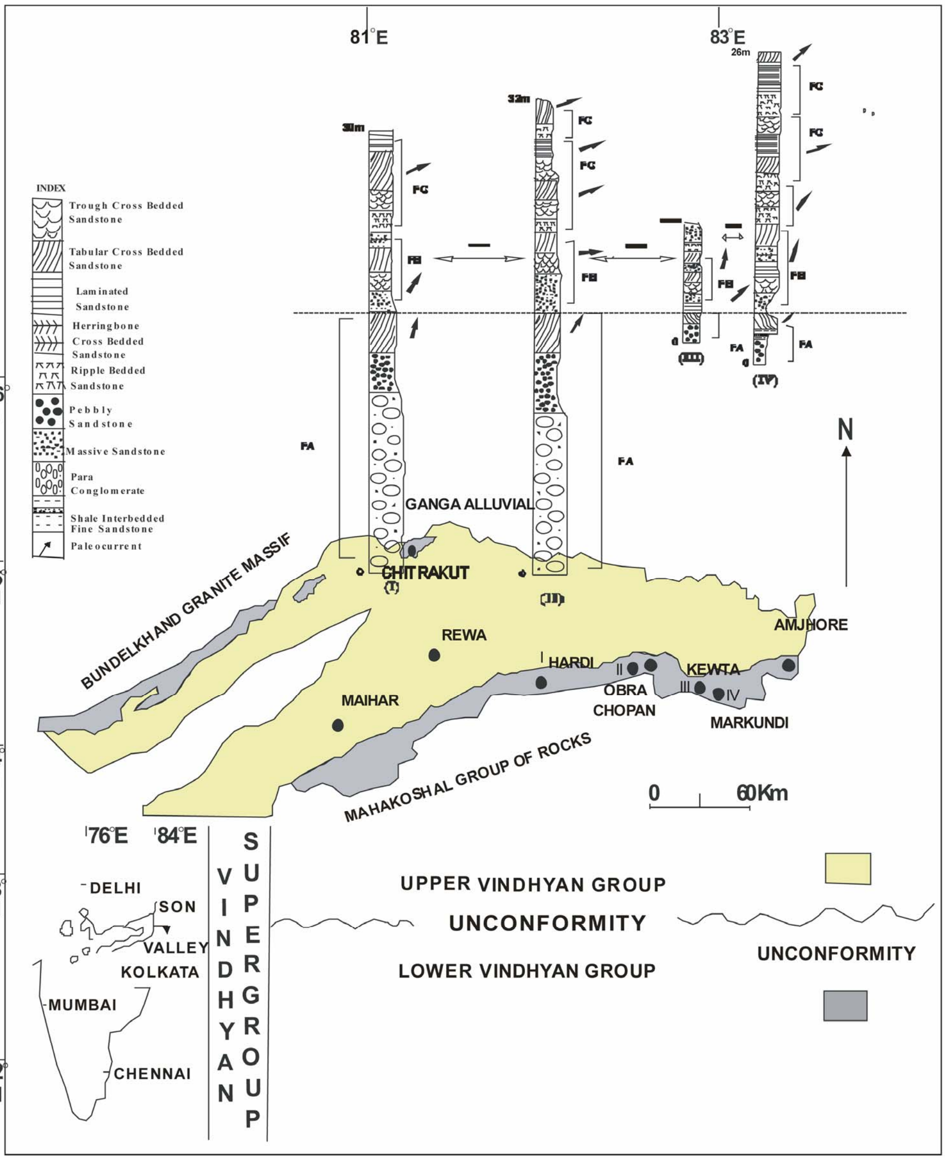

Figure 1. Geological map of the study area.

has been worked through a detailed investigation of these four measured sections, see **Figure 1**. In the following section, brief description of the lithounits of the formation is given: the basal part of the measured sections at Hardi and Obra comprises of conglomerates with pebbles and cobbles. In the Kewta and Markundi sections conglomeratic unit is not exposed, instead basal part of these sections is comprised of pebble bearing sandstones, which is also present in the other two sections and occurs over the basal conglomeratic unit. The lithofacies encountered in the measured sections are described in the following section on "Facies Analysis".

2. Facies Analysis

We measured and sampled the four selected sections bed by bed for facies- and palaeocurrent investigations. The routine methods of section measurement, lithofacies recording and collection of palaeocurrent data were followed. Documentation of the data sets is presented in the composite, see **Figure 1**. We recorded nine lithofacies from the four measured sections which are described in the following sub-sections.

2.1. Matrix-Supported Conglomerate Facies (Gm)

The matrix supported conglomerate is exposed near Obra Dam which extends up to Hardi Village section, see **Figure 2(a)**. This conglomerate facies is thickly bedded and form base of the succession. The conglomerate units are lenticular in shape and composed of rounded to sub-

Table 1. Stratigraphic succession with lithofacies assemblage of the Vindhyan Supergroup in the part of south U.P. (after Gupta and Jain, 1997).

CHOPAN AREA

Super Group	Group	Formation	Lithology
			DISCONFORMITY
VINDHYAN	SEMRI GROUP	Rohtas Limestone	Flaggy limestone with cherty parting. Black paper-thin shale, porcellanic shale with calcareous nodules. Blocky, massive, light grey, brown, fawn coloured stylolitic limestone interbeds.
		Basuhari Sandstone	Greenish grey, khaki green, olive green and porcellanic shales with siltstone interbeds. Glauconitic sandstone, silty sandstone, grreenish grey and khaki to brown quartz arenites.
		Bargawan Limestones	Fawn coloured limestone with quartz veins and black chert bands. Fawn to light grey coloured compact cherty limestone with stromatolites bands. Argillaceous flaggy limestone with siltstone interbeds.
		Kheinjua Shale	Olive to greenish grey khaki splintery shale with calcareous inter-beds and partings.
		Chopan Porcellanite	Light grey, greenish porcellanic shales, ash, tuff, anglomerate beds with arkosic sandstone.
		Kajrahat Limestone	Siliceous, cherty, dolomitic, limestone with stromatolites. Blocky and slabby limestone and dolarenite with argillite interbeds.
		Arangi Shale	Light grey, black, slabby limestone, stylolite bleached, purplish porcellanic shales and black carbonaceous shales.
		Patherwa Sandstone	Gritty to pebbly sandstones, medium grained sandstone and siltstone. Conglomerate with cobbles, pebbles and clasts of quatrz, quartzite, chert, yellow, and red jasper set in a sandy matrix.
			ANGULAR UNCONFORMITY/FAULTED CONTACT

rounded, moderately sorted to moderately well-sorted pebbles and cobbles. The basal part of the conglomerate unit lies on the granitic basement and is composed of more than 10 m thick massive conglomerate and is wedge shaped. The clasts are polymictic in composition comprising of vein quartz, pink, white and black quartzites, red Jasper and granite. The granule- and pebble clasts range in size from 3 to 5 mm and occasionally 10 to 15 mm. Pebbles and cobbles are scattered within the conglomerate facies. The conglomerate units have erosion contacts with intervening sandstone beds. This facies is also observed in the Hardi section and is equally well developed. However, this facies was not observed in other two sections at Kewta and Markundi, see **Figure 1**.

2.2. Pebbly Sandstone Facies (Spe)

This facies occurs in all the four measured sections at the same stratigraphic level. In the Kewta and Markundi sections this facies form the base of these sections. In other two sections it overlies Gm-facies. This facies is represented by coarse-grained sandstone containing pebbles. Maximum size of the pebbles is 4 cm. Pebbly sandstone beds pass upward into plane laminated sandstones. Base of the facies is erosive.

2.3. Interbedded Shale within Thinly Bedded Sandstone Facies (Fi-S)

This facies occurs over the pebbly sandstone facies in the Markundi section and comprises of fine-grained sandstones interbedded with thinly bedded reddish to whitish brown shale of variable thickness (0.4 to 1 m thick). The sandstone units of the facies exhibit plane to wavy lamination and small scale cross-bedding. Herringbone cross-lamina sets occur in the upper part of the facies. The facies shows gradational contact with the intervening shale beds.

2.4. Tabular Cross-Bedded Sandstone Facies (Sp)

This facies is composed of medium grained, moderate to moderately well sorted, quartzarenite to subarkose and reddish brown to pink sandstones. The sandstone beds show decrease in grain size up section. The cross-bedded units vary in thickness from 0.65 to 2 m, see **Figure 2(b)**. Cross-beds occur both in cosets and in single sets. Small scale, low angle tabular cross-bedded sandstones are also observed associated with this facies. The bounding surfaces of cross-beds are undulating. This facies occurs in all the measured sections at different stratigraphic levels. In the Obra and Markundi sections, it occurs at four levels and in the Hardi and Markundi sections it occurs at three levels. In all the sections this facies overlies the Spe-facies in the lower part of the sections. The palaeocurrent direction of this facies in its lower part is NE in Hardi, Obra and Kewta sections. The contact between this facies and the underlying facies is taken as datum

Figure 2. (a) Field photograph showing matrix supported conglomerate from bottom part of Obra secti on; (b) Tabular cross bedding from bottom part of Kewta section; (c) Trough cross bedding from bottom part of Markundi section; (d) Parallel lamination and tabular; (e) Symmetrical current marks from top part of Hardi section; (f) Wave ripples from middle part of Markundi Section; (g) Herringbone cross-bedding from middle part of Markundi section.

line for the entire basin because of its widespread distribution and more or less the same palaeocurrent direction.

2.5. Trough Cross-Bedded Sandstone Facies (St)

Both large and small-scale trough cross-bedding is observed in the studied sandstones, see **Figure 2(c)**. This facies is composed of erosive based, medium grained, moderate to moderately well sorted sandstone of 1.5 m thickness. This facies occurs in all the sections at different stratigraphic levels above the datum line. In the Hardi and Markundi sections it occurs at two levels, whilst it occurs at three levels in the Obra section and at one level in the Kewta section. The palaeocurrent directions of this facies vary at different stratigraphic levels with the same measured sections.

2.6. Parallel Laminated Sandstone Facies (Si)

This facies is composed of medium to fine grained, moderately sorted to moderately well sorted, quartzarenite and subarkose. The color of the sandstone is pink to reddish brown. Individual beds range in thickness from 1 to 5 m. The beds are mostly evenly laminated, see **Figure 2(d)**. Some beds have combination of horizontal lamination and low angle cross-beds. The bed contacts are sharp. The intra-sets with horizontal bedding are apparently massive, plane bedded to plane laminated. This facies occurs in the Markundi section at three stratigraphic levels. In the other three sections this facies occurs only at one level. This facies follows different facies up-section in different sections, see **Figure 1**.

2.7. Ripple Bedded Sandstone Facies (Sr)

Ripple bedded sandstones are common in Obra and Markundi sections and occur at two stratigraphic levels. In the Hardi and Kewta sections this facies occur at one level only. This facies consists of pink to reddish brown, medium to fine grained, moderate to moderately well-sorted and thinly bedded (30 to 75 cm) sandstones. The beds are mostly evenly laminated. The bed contacts are sharp. Both symmetrical and asymmetrical ripples are observed, see **Figures 2(e)** and **(f)**. Occasional occurrence of interference ripples is observed in Markundi section. Crests of the ripples are straight to sinuous, sometimes rounded and flat. The palaeo-shore orientation obtained from the ripple crest orientation is in the NW-SE direction.

2.8. Herring Bone Cross-Bedded Sandstone Facies (S-hb)

This facies is observed in the Hardi, Kewta and Markundi sections only at one stratigraphic level. Herringbone cross-bedding has been recorded in thick sandstone beds, see **Figure 2(g)**. The sandstone is medium grained, moderate to moderately well-sorted and mainly quartzarenite. Internally the facies is composed of thick and thin sandstone units which are occasionally laminated. Herringbone cross-beds are associated with tabular cross-bedding facies.

2.9. Massive Sandstone Facies (Sm)

This facies is observed in the Kewta section at two stratigraphic levels. In other three measured sections this facies occur at one stratigraphic level only. The facies is 1 to 2 m thick, coarse to fine grained, moderately sorted and red colored quartzarenite. This facies has sharp contact with the underlying and the overlying facies in all the sections.

3. Palaeocurrent Analyses

Azimuthal data of cross-bedded sandstone facies (St-, Sp- and (S-hb)-facies) were measured where cross-bedding surfaces are properly exposed or could be reliably reconstructed. The azimuthal data recorded at different stratigraphic levels in the four measured sections, were subjected to tectonic tilt correction because the average dip of the beds is about 20 degrees. The corrected data were plotted as rose diagrams which exhibit bidirectional/bimodal patterns, with modal axis and subsidiary modes generally towards NNE, NE and SW, see **Figures 1** and **3**. The crest orientation data was also recorded on the wave ripples (Sr-facies) from the four measured sections. Analysis of the data shows that the general trend of the palaeo-shoreline was in the NW-SE direction.

Calculation of vector means (Φ) and vector magnitude (L %) was done by vector summation method of [18]. The vector mean (Φv) for the four measured sections varies in the range of 2 to 263 and vector magnitude (L %) values fall in the range of 20 to 82. The bimodal to quadrimodal distribution with modes oriented approximately at 90 degrees reflect that the sediments were transported by the long-shore currents. The bimodal to quadrimodal distribution of cross-bedding azimuths up-section in the four measured sections indicate dispersal of sediments by multidirectional currents in the nearshore shallow marine environments [19,20]. In the Markundi section, quadrimodal distribution of palaeo-currents suggests complex current system involved in sediment dispersal. However, NW-SE oriented shoreline played the major role in sediments dispersal in the outer estuarine settings where sediments were dispersed by SE and NW long-shore currents. In the Kewta section polymodal distribution of palaeocurrent pattern indicates two main sediment transport directions: the NNE-NE onshore current direction was dominant dispersing agent while some sediment was also derived from SW direction. The rose

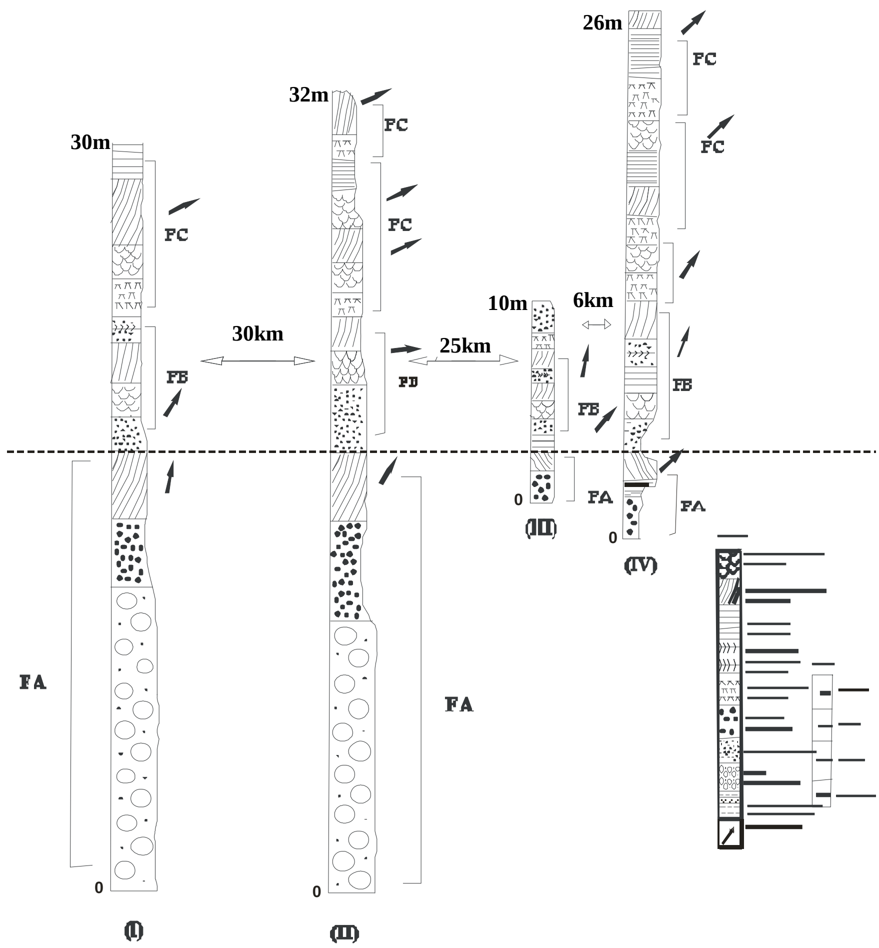

Figure 3. Showing the vertical and lateral variation of the study area.

diagram of Obra section indicates two directions of sediment dispersal: one along the NE onshore and the other in the NNW long-shore direction. The bimodal distribution of palaeocurrent pattern in Hardi section also shows dominance of onshore and long-shore currents for sediments dispersal.

4. Facies Association

Facies assemblage constitutes genetically related several lithofacies that occur in combination, and typically represent one depositional environment. The nine facies observed in the four measured sections are grouped in three facies associations which represent three genetically related depositional environments. They include:

1) Tidally influenced fluvial channel (Facies association A).

2) Tidal channel (Facies association B).

3) Tidal sand bar/tidal sandy flat (Facies association C).

Facies association A is dominant in the basal part of the studied sections, particularly in the Hardi and Obra sections, grades upwards into deposits that show stronger tidal influence producing typical fining upward facies packages. Facies association B is better developed in the Markundi section whereas facies association C is more abundant in the Obra section.

4.1. Tidally Influenced Fluvial Channel Facies (Facies Association-A)

Facies association-A represents a fining upward facies sequence comprising of Gm-, Spe- and Sp-facies in the Hardi and Obra sections. The maximum thickness of this facies association is 5.5 m. In the Kewta and Markundi sections Gm-facies is missing from the association. However, in the Kewta and Markundi sections Spe-facies form the base of this facies association which is overlain by Sp-facies in Kewta section. However, in the Markundi section Fi-S facies overlies the Spe-facies and is in turn overlain by Sp-facies. This facies assemblage comprises of thinning upward packages with a maximum thickness of 2.5 m. The basal contact of these packages is represented by the concave up erosion discontinuity surfaces.

Gm-facies is the most dominant followed by Sp-facies and Spe-facies. However, their relative thicknesses vary among the measured sections. The sandstone facies are poorly sorted, sub-rounded, coarse to medium grained and tabular cross-stratified sets. The set thicknesses vary from 0.3 m to <5 cm. The cross-bed sets decrease in thickness up-section and dip consistently at low angles (10˚ - 20˚). They dip consistently in the N/NE direction with few exceptions of S/SW dip. Generally the reactivation surfaces define the 10 cm thick foreset packages within the Sp-facies. The Gm-facies consists of poorly sorted conglomerates composed of laminated sandstone clasts. This facies is normal graded.

Interpretation

Facies association A is attributed to tidal influenced fluvial channels. The presence of deposits with concave up basal surfaces, though not exclusive, is suggestive of flow confinement within the channels [6]. Where this feature is not present, the fining and thinning upward facies successions are bounded by sharp, erosional bases attesting to deposition during a regime of decreasing flow energy, typical of channel fills [6,15,17]. Gm-facies records episodes of highest energy whilst St-facies was formed by migration of small to medium-scale, 2D or 3D bed-forms within channels.

Poor sorting coupled with very coarse sand to gravel-size sediments and the absence of bioturbation are the features which suggest tidal influence in the fluvial channel deposition. This feature distinguishes this facies association from the channel facies formed under dominant tidal influence. Bipolar cross-beds coupled with the reactivation surfaces are suggestive of some degree of tidal reworking. The dominance of the foresets dipping consistently at low angles is further evidence in support of tidal influence, as migration of 2D and 3D bed-forms in a tidal setting typically results in cross-sets that display low angle dipping foresets [21,22].

4.2. Tidal Channel Facies (Facies Association B)

This facies association comprises of Sm-, St-, Si-, (S-hb)- and Sp-facies. The facies association is well developed in the Markundi section whose thickness is 10 m. Si-facies of the association is missing in the Hardi section whereas Si- and (S-hb)-facies are missing from the Obra section. Sp-facies occur twice in the association in the Kewta section. Both St- and Sp-facies consist of moderately sorted, subangular to subrounded, coarse to very fine-grained sandstones. The cross-sets, up to 0.3 m thick, consistently display low angle foresets. Palaeocurrent patterns indicate main vectors towards the NNE, NE in the Hardi-, Obra-, and Kewta sections whilst in the Markundi section palaeocurrent direction is due NW. A typical feature of the St-facies is 5 - 10 cm thick packages of foresets defined by reactivation surfaces. St-facies locally grades laterally into fine to very fine-grained, laminated sandstone (Si-facies). This facies is, in general, composed of moderately sorted to moderately well-sorted, subrounded sandstones. Internally these sandstones show packages of alternating thick and thin tidal bundles ranging from 0.1 - 0.2 m thick. Thicker units of the facies show plane parallel stratification, cross-stratification. Fine-grained sandstones generally appear structure less. Locally cross-strata display opposite dipping foresets.

Interpretation

Like Facies association A, the Facies association B was also formed by confined flows within tidally influenced channels as indicated by the basal concave up erosion bounding surfaces and packages of tidal bundles. The organization of internal configuration, thinning and fining upward successions formed by the upward gradation from intraformational conglomerates (Gm-facies) to Si-, St-, and Sp-facies [23] attests to deposition during a waning flow regime typical of channels prone to lateral accretion [24]. Internal architecture of this facies association and sedimentary structures observed are similar to those found elsewhere in the association with many tidal channel deposits [25-29].

4.3. Upper Flow Regime Tidal Sand Flat/Sand Bar (Facies Association C)

The Facies association C comprises of Sr-, St-, Sp- and Si-facies and is well developed in the Hardi section where its thickness is 5 m. This facies association is widely spread in the study area and is recorded in all the measured sections. This facies association forms stacked packages (10 - 20 cm thick) of Sr-, St-, Sp-facies, St- and Si-facies, and Sr- and Sp-facies (Obra section); Sr- and St-facies, Sr-, Sp-, Si- and St-facies, Sr-, Si-, and Sp-facies (Markundi section). In the Kewta section this facies association is represented by Sr- and Sm-facies only. These packages are bounded at the base by either planar or erosion surfaces. Some of these packages occur in lenticular bodies of 0.4 m thick and 6 m long with fining and thickening upward trends. Analysis of the data collected on wave ripple crests in the Sr-facies suggests NW-SE orientation of the 60 km long palaeo-shoreline.

The internal structure of the Si-facies characterized by parting lineation shows planer laminated to very low angle dipping cross-stratification, whilst the Sp- and St-facies facies display characteristic tabular and trough cross-stratification. The Sr-facies shows climbing current ripples and symmetrical wave ripples on the planar surface. The sediments are well sorted, well rounded and fine to medium grained. Occasional pinch and swell lamellae are also observed within these facies packages. These undulating laminae display internal truncations which form broad scours or swales. Sr-facies occasionally displays tabular or highly undulating lower set boundary.

Interpretation

The Facies association C is inferred to represent tidal sand bar/sand flat deposits, based on the prevalence of tabular sandstones, internally displaying planar to very low angle dipping stratification. The abundance of parting lineation in the Si-facies indicates that the sediments were deposited in the upper flow regime condition [23, 30]. The rhythmic alternations of Si- with St- and Sp-facies (Markundi and Obra sections) indicates fluctuating upper to lower flow regime conditions within the tidal flats. Pinch and swell structures, symmetrical ripples and the scours and swales indicate frequent wave reworking [31]. The scours observed in this study are common in nearshore areas that have undergone periods of higher energy flow suggesting storm wave reworking [20,29, 32-34]. The similar facies architecture and evidences have been related to the upper flow regime of the tidal sand flats [20,28]. Number of ancient tidal sand bar examples similar to ours with upward-fining, lenticular facies packages have been reported elsewhere [21,24,35, 36]. Tidal bars are common features of upper flow regime within tidal sand flats in confined areas along the coasts dominated by high tidal velocities [21,28]. All the palaeocurrent recorded within this facies association is either perpendicular or oblique to the inferred NW-SE oriented palaeo-shoreline.

5. Discussions

The spatio-temporal facies variation, facies association, their stacking pattern and palaeocurrent data on directional features (trough- and tabular cross bedding) and wave ripple crests forms the basis of the proposed facies development and depositional model for Patherwa Formation, see **Figure 4**. The Facies association A documents evidences of confined fluvial channel facies and consistent unidirectional palaeocurrent record. The energy fluctuation of tidal currents results in highly unsteady flows producing frequent reactivation surfaces as observed in this association. The abundance of these surfaces separating foreset packages that are only few cm thick facilitates the differentiation of tidal influence from other disturbances in fluvial system [37,38]. The top unit (Sp-facies) of this facies association shows these evidences suggesting deposition in the inner estuarine settings transitional between fluvial and tidal sedimentation [21,34,39], see **Figure 4**. The clast size and thickness of the Gm- and Sp-facies decreases, and absence of Gm-facies from the Hardi section, from the west towards the Markundi section in the east suggesting differential potential of the fluvial channels contributing to the depocenters. The general palaeocurrent trend in this facies association (Sp-facies) is also consistent in the NNE to NE direction suggesting confined unidirectional estuarine flow regime. Tidal bundles are scarce or even absent from such settings due to the interference of fluvial influx [26,34,36,39].

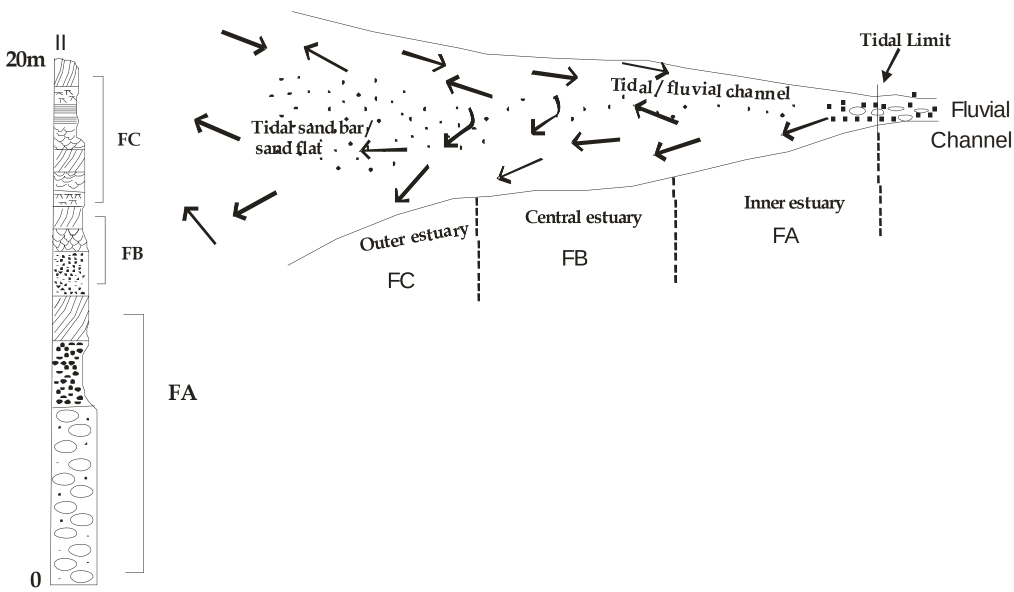

Figure 4. Schematic block diagram depicting the tidal dominated estuarine depositional model, symbols are reffered in Figure 1.

Up-section in the Facies association B evidence of tidal influence increases. The features attributed to or even diagnostic (e.g., tidal bundles) to tidal currents are more abundant. The upward increase in tidal influence is also associated with fining and thinning upward facies packages. These packages are related to meanders of straight-meandering-straight channel segments typically formed in central estuarine settings of the tide dominated estuaries [21,24,26,28,40]. Evidences of the tidal processes also include the abundance of cross-sets with reactivation surfaces, local presence of tidal bundles and reversed foresets ((S-hb)-facies). The palaeocurrent trends are comparatively more divergent (NNE-NE-N) seawards in this facies association.

Facies association C is attributed to the processes operative close to the shoreline as elongate sand bars associated with upper flow regime sand flats are typical of the seaward settings in the tide dominated estuaries [21]. The evidence of wave generated structures (*i.e.*, symmetrical, asymmetrical ripples and truncating surfaces, low angle dipping cross-lamination) in this facies association conforms to the outer estuarine settings [21]. Most of the tidal channel deposits interfinger with sand bar and upper flow regime sand flat deposits are more commonly recorded in tide dominated estuaries formed along meso-tidal to macro-tidal coasts [20,41,42]. However, in this case depositional settings are more consistent with the tide dominated outer estuarine settings. This is also supported by the palaeocurrent trends which are multimodal and more divergent seawards.

The lateral and vertical facies distribution, see **Figure 4** reflects tidal influenced estuarine settings for the Patgherwa Formation. The overall vertical gradation from tide influenced fluvial channel (Facies association A) to tidal channel (Facies association B) and tidal sand bar/ sand flat deposits (Facies association C) records upward increasing tidal influence.

6. Conclusion

Evidence of the genetic association of tidal-influenced fluvial channel, tidal channels and tidal sand bar/tidal sandy flat deposits is typical of tidal dominated estuarine system [21,27,29,34,36,43-45]. The presence of sedimentary structures attributed to tidal processes suggests that the Patherwa Formation was formed dominantly under the influence of tidal processes. In addition to facies association consisting of tidal influenced fluvial channel, tidal channel and tidal sand flat/sand bars, these characteristics support a tidal dominated estuarine settings.

7. Acknowledgements

The author gratefully thanks the Chairman, Department of Geology, Aligarh Muslim University, Aligarh for providing the necessary research facilities. One of the author (A. H. M.) is also thankful to council of Science and technology U.P. for financial help (CST/AAS/D-2203).

REFERENCES

[1] J. J. W. Rogers, "The Dharwar Craton and the Assembly of Peninsular India," *Journal of Geology*, Vol. 94, No. 2, 1986, pp. 129-143. doi:10.1086/629019

[2] B. P. Radhakrishna and S. M. Naqvi, "Precambrian Continental Crust of India and Its Evolution," *Journal of Geology*, Vol. 94, No. 2, 1986, pp. 145-166. doi:10.1086/629020

[3] H. Narain, "Geophysical Constrains on the Evolution of Purana Basins of India with Special Reference to Cuddapah, Godavari and Vindhyan Basins, Purana Basins of Peninsular India," *Memoir—Geological Society of India*, Vol. 6, 1987, pp. 5-32.

[4] T. Oldham, "Remarks on the Classification of the Rocks of Central India Resulting from the Investigation of the Geological Survey," *Journal of the Asiatic Society of Bengal*, Vol. 25, 1856, pp. 224-256.

[5] J. B. Auden, "Vindhyan Sedimentation in the Son Valley, Mirzapur District," *Geological Survey of India*, Vol. 62, Part 2, 1933, pp. 141-250.

[6] P. P. Chakraborty, "Sedimentary Records of Erg Developments over Braid Plain, Proterozoic Dhandraul Sandstone, Vindhyan Supergroup, Son Valley," *Memoir—Geological Society of India*, Vol. 36, 1996, pp. 77-99.

[7] A. B. Roy, "Stratigraphic and Tectonic Framework of the Aravalli Mountain Range," In: A. B. Roy, Ed., *Precambrian of the Aravalli Mountain*, India Memoir-Geological Survey of India, Rajasthan, 1988, pp. 3-31.

[8] R. K. Verma, "Geodynamic of Indian Peninsula and Indian Plate Margins," Oxford and IBH, New Delhi, 1991, pp. 1-357.

[9] M. E. A. Mondal, J. N. Goswami, M. P. Deomurari and K. K. Sharma, "Ionprobe 207Pb/206Pb Ages of Zircons from the Bundelkhand Massif, Northern India: Implications for Crustal Evolution of the Bundelkhand-Aravalli Protocontinent," *Precambrian Research*, Vol. 117, No. 1-2, 2002, pp. 85-100. doi:10.1016/S0301-9268(02)00078-5

[10] A. R. Crawford and W. Compston, "The Age of the Vindhyan System of Peninsular Indian," *Quarterly Journal of the Geological Society*, Vol. 125, 1969, pp. 351-371.

[11] B. P. Radhakrishna, "Purana Basins of Peninsular India (Middle to Late Proterozoic)," *Memoirs of the Geological Survey of India*, Vol. 66, 1987, pp. 1-518.

[12] S. Gupta, N. K. C. Jain, V. C. Srivastva and R. D. Mehrotra, "Depositional Environment and Tectonism during the Sedimentation of the Semri and Kaimur Groups of Rocks, Vindhyan Basin," *Journal of the Palaeontological Society of India*, Vol. 48, 2003, pp. 182-190.

[13] I. B. Singh, "Depositional Environment of the Vindhyan Sediments in Son Valley Area," *Recent Research Geology*, Vol. 1, 1973, pp. 146-152

[14] A. Bhattacharya and S. Morad, "Proterozoic Braided Ephemeral Fluvial Deposits: An Example from the Dhandraul Sandstone Formation of the Kaimur Group. Son Valley, Central India," *Sedimentary Geology*, Vol. 84, No. 1-4, 1993, pp. 101-114. doi:10.1016/0037-0738(93)90048-A

[15] P. K. Bose and P. P. Chakraborty, "Marine to Fluvial Transition: Proterozoic Upper Rewa Sandstone, Maihar, India," *Sedimentary Geology*, Vol. 89, No. 3-4, 1994, pp. 285-302. doi:10.1016/0037-0738(94)90098-1

[16] S. K. Chanda and A. Bhattacharya, "Vindhyan Sedimentation and Paleogeography: Post-Auden Development," In: K. S. Valdiya, S. B. Bhatia and V. K. Gaur, Eds., *Geology of Vindhyachal*, Hindustan Publishing Corporation, New Delhi, 1982, pp. 88-101.

[17] P. K. Bose, S. Sarkar, S. Chakraborty and S. Banerjee, "Overview of the Meso to Neoproterozoic Evolution of the Vindhyan Basin, Central India," *Sedimentary Geology*, Vol. 141, 2001, pp. 395-419. doi:10.1016/S0037-0738(01)00084-7

[18] M. R. C. Lindholm, "A Practical Approach to Sedimentology," Allen & Unwin, Crows Nest, 1987, pp. 43-58.

[19] R. C. Selley, "Paleocurrent and Sediment Transport in the Sirte Basins," *Special Publications of the International Association of Sedimentologists*, Vol. 8, 1967, pp. 395-410.

[20] G. Dev Klein, "Paleocurrent Analysis in Relation to Modern Marine Sediment Dispersal Patterns," *AAPG Bulletin—American Association of Petroleum Geologists*, Vol. 51, No. 3, 1967, pp. 182-190.

[21] R. W. Dalrymple, B. A. Zaitlin and R. Boyd, "Estuarine Facies Models: Conceptual Basis and Stratigraphic Implications," *Journal of Sedimentary Petrology*, Vol. 62, No. 6, 1992, pp. 1130-1146.

[22] B. A. Zaitlin, R. W. Dalrymple, R. Boyd and D. Leckie, "The Stratigraphic Organization of Incised Valley System, Implications to Hydrocarbon Exploration and Production with Examples from the Western Canada Sedimentary Basin," Canadian Society of Petroleum Geologists, Calgary, 1994.

[23] H. E. Reineck and I. B. Singh, "Depositional Sedimentary Environment," Springer-Verlag, New York, 1980.

[24] D. G. Smith, "Modern Point Bar Deposits Analogous to the Athabasca Oil Sands. Alberta, Canada," In: P. L. De Boer, A. Van Gelder and S. D. Nio Eds., *Tide Influenced Sedimentary Environments and Facies*, Reidel, Dordrecht, 1988, pp. 417-432.

[25] H. G. Reading and J. D. Collinson, "Clastic Coasts," In: H. G. Reading, Eds., *Sedimentary Environments*: *Processes. Facies and Stratigraphy*, Blackwell Science, Oxford, 1996, pp. 154-231.

[26] P. L. De Boer, A. P. Oost and M. J. Visser, "The Diurnal Inequality of the as a Parameter for Recognizing Tidal Influences," *Journal of Sedimentary Petrology*, Vol. 59, No. 6, 1989, pp. 912-921.

[27] D. A. Leckie and C. Singh, "Estuarine Deposits of the Albian Paddy Member (Peace River Formation) and Lowermost Shaftsbury Formation. Alberta, Canada," *Journal of Sedimentary Research*, Vol. 61, No. 5, 1991, pp. 825-849.

[28] S. D. Nio and S. H. Yang, "Diagnostic Attributes of Clastical Tidal Deposits, a Review," In: D. G. Smith, G. E. Reinson, B. A. Zaitlin and R. A. Rahmani Eds., *Clastical Tidal Sedimentology*, *Canadian Society of Petroleum Geologists*, Vol. 16, 1991, pp. 3-28.

[29] P. P. Bjorklund, "Stacked Fluvial and Tide dominated Estuarine Deposits in High Frequency (Fourth Order) Sequences of the Eocene Central Basin. Spitsbergen," *Sedimentology*, Vol. 52, No. 2, 2005, pp. 391-428. doi:10.1111/j.1365-3091.2005.00703.x

[30] K. Yagishita, J. Ashi, S. Ninomiya and A. Taira, "Two Types of Plane Beds under Upper Flow Regime in Flume Experiments, Evidences from Grain Fabric," *Sedimentary Geology*, Vol. 163, No. 3-4, 2004, pp. 229-236.

[31] J. F. M. De Raaf, J. R. Boersma and A. Ven Gelder, "Wave Generated Structure and Sequences from a Shallow Marine Succession/Lower Carboniferous, Country Cork, Ireland," *Sedimentology*, Vol. 24, No. 4, 1977, pp. 451-483. doi:10.1111/j.1365-3091.1977.tb00134.x

[32] J. Bourgeois, "A Transgressive Shelf Sequence Exhibiting Hummocky Stratification: Sebastian Sandstone (Upper Cretaceous) South Western Oregon," *Journal of Sedimentary Petrology*, Vol. 50, No. 3, 1980, pp. 681-702.

[33] R. J. Cheel and D. A. Leckie, "Hummocky Cross-Stratification," *Sedimentology Review*, Vol. 1, 1993, pp. 103-122. doi:10.1002/9781444304534.ch7

[34] K. Hori, Y. Saito, Q. Zhao, X. Cheng, P. Wang, C. Li and Y. Sato, "Sedimentary Facies of Tide-Dominated Paleochanging (Yangtze) Estuary during the Last Transgression," *Marine Geology*, Vol. 177, No. 3-4, 2001, pp. 331-351. doi:10.1016/S0025-3227(01)00165-7

[35] M. Raza and S. M. Casshyap, "Tectono-Sedimentary Model of Evolution of Middle Proterozoic Vindhyan Basin," In: Bhattacharya Ed., *Proceedings of Group Discussion on the Vindhyan*, *Journal of the Geological Society of India*, Vol. 58, 1994, pp. 278-289.

[36] A. D. Heap, S. Bryce and D. A. Ryan, "Facies Evolution of Holocene Estuaries and Deltas: A Large Sample Statistical Study from Australia," *Sedimentary Geology*, Vol. 168, No. 1-2, 2004, pp. 1-17. doi:10.1016/j.sedgeo.2004.01.016

[37] K. O. Ladipo, "Example of Tidal Current Periodicities from an Upper Cretaceous Sandstone Succession (Anambra Basin, S. E. Nigeria)," In: P. L. Boer, A. N. Gelder and A. D. Nio, Eds., *Tide Influenced Sedimentary Environment and Facies Sedimentology and Petroleum Geology*, Reidel, Dordrecht, 1988, pp. 333-358.

[38] J. Thorez, E. Geomaere and R. Dreesen, "Tide and Wave Influenced Depositional Environments in the Psamites Du Controz (Upper Famennian in Belgium)," In: P. L. De Boer, A. Van Gelder and S. D. Nio Eds., *Tide Influenced Sedimentary Environments and Facies*, Reidel, Dordrecht, 1988, pp. 389-415.

[39] J. A. G. Cooper, "The Role of Extreme Floods in Estuary-Coastal Behavior: Contrasts between Tides Dominated Micro-Tidal Estuaries," *Sedimentary Geology*, Vol. 150, No. 1-2, 2002, pp. 123-137. doi:10.1016/S0037-0738(01)00271-8

[40] M. M. Nichols and R. B. Biggs, "Estuaries," In: R. A. Davis, Eds., *Coastal Sedimentary Environments*, Springer-Verlag, New York, 1985, pp. 77-186.

[41] R. Houthuys and E. Gullentops, "Tidal Transverse Bars Building up a Longitudinal Sand Body (Middle Eocene Belgium)," In: P. L. Boer, A. N. Gelder and A. D. Nio, Eds., *Tide Influenced Sedimentary Environment and Facies Sedimentology and Petroleum Geology*, Reidel, Dordrecht, 1988, pp. 153-166.

[42] L. A. Buatois and M. G. Mangano, "Sedimentary Facies Depositional Evolution of the Upper Cambrian to Lower Ordovician Santa Rosita Formation in Northwest Argentina," *Journal of South American Earth Sciences*, Vol. 16, No. 5, 2003, pp. 343-363. doi:10.1016/S0895-9811(03)00097-X

[43] C. D. Woodroffe, J. Chappell, B. G. Thom and E. Wallensky, "Depositional Model of a Macrotidal Estuary and Floodplain, South Alligator River, Northern Australia," *Sedimentary Geology*, Vol. 36, No. 5, 1989, pp. 737-756.

[44] J. Chappell and C. D. Woodroffe, "Microtidal Estuaries," In: R. W. E. Carter and C. D. Woodroffe, Eds., *Coastal Evolution*: *Late Quaternary Shoreline Morphodynamics*, Cambridge University Press, Cambridge, 1994, pp. 187-218.

[45] M. E. Mulrennan and C. D. Woodroffe, "Holocene Development of the Mary River Plains, Northern Territory, Australia," *Sedimentary Geology*, Vol. 8, No. 5, 1998, pp. 565-579.

