Volume 17, Issue 4, 172529 (1-14)

Iranian Journal of Earth Science (IJES)

https://doi.org/10.57647/j.ijes.2025.16950

Sedimentary structures and facies analysis of the Ghaghara River, Ayodhya, Uttar Pradesh, India: A Case Study

Pawan Kumar Gautam[1,2,*], Dhirendra Kumar[3], Anoop Kumar Singh[1,2]

[1]*Department of Geology, University of Lucknow (LU), Lucknow, India.*
[2]*Department of Geology, School of Earth and Environmental Sciences, Babasaheb Bhimrao Ambedkar University, (A Central University), Lucknow, India.*
[3]*Department of Geology, School of Earth, Biological and Environmental Sciences, Central University of South Bihar (CUSB), Gaya, India.*

[*]**Corresponding author:** 89pawangautam@gmail.com

Original Research
Received:
2024-07-30
Revised:
2024-10-12
Accepted:
2024-10-20
Published online:
2025-06-24
Published in issue:
2025-10-30

Abstract:
The Ghaghara River originates from the Mapchachango glacier near Mansarovar lake and spreads over many parts of India and Nepal. It is the left bank and largest tributary of the Ganga River by volume. Its confluences with the Ganga River at Doriganj near Chhapra town in Bihar. Extensive studies have been carried out on flooding and lateral erosion, but no attention has been paid to sedimentary structures and facies along the Ghaghara River. The present study is focused on the facies analysis and sedimentary structures, which are exposed on a 196 cm high cliff section (Upland terrace surface T_2), along the Ghaghara River, Ayodhya Ghat, Uttar Pradesh. The facies are the paleosol unit (Facies I), silty unit (Facies II), and sandy unit (Facies III), which show high energy conditions and a high degree of transport rate while the mud unit (Facies IV), show low energy conditions and low degree of transport rate. The sedimentary structures have been identified such as the massive bedding in silty unit, planar cross-bedding and trough cross-bedding in sandy unit, and parallel laminations in mud unit at different depths of litholog. It also indicates that fluvial hazards occur during low-discharge periods due to sandy, silty, and muddy facies in the river valley deposits, which contribute to increased lateral erosion in the low discharge period and flooding occurs during the high-discharge periods.

Keywords: Ganga Plain; Ghaghara River; Facies analysis; Sedimentary structures; Natural hazards

1. Introduction

The Ganga Plain stands out as one of the world's largest and most dynamically changing terrestrial basins, is also recognized as one of the most densely inhabited regions globally due to its fertile soil, abundance of aquifers, smooth landscape, and favorable climate (Singh and Awasthi, 2011a; Singh et al., 2018; Gautam et al., 2022a; Gautam et al., 2022b). It extends from the Punjab Plain in the west to the Brahmaputra Valley in the east (Dewey and Bird, 1970; Dickinson, 1974; Singh, 1996). These fluvial sediments filled the Ganga foreland basin derived from the Himalayas and are transported by fluvial processes primarily by major permanent rivers such as the Indus and Ganga in the north and some sediments from the Peninsular craton in the south (Singh and Bajpai, 1989; Singh, 2004; Sinha et al., 2006; Singh and Tandon, 2007; Shukla and Raju, 2008; Singh, 1996; Gautam and Kumar, 2025). Characterized predominantly by Quaternary fluvial sediments (Singh, 1996; Singh and Singh, 2005). The fluvial deposits within the Ganga Plain represent one of the most substantial terrestrial sedimentary archives in South Asia. The distribution of channel deposits in fluvial environment studied by Colombera et al. (2019). These deposits play a crucial role in deciphering the impact of climate variations, tectonic activity, and eustatic changes on the evolution of the region (Gibling et al., 2005; Chandra et al., 2024). Contemporary pedo-

genic and sedimentary processes occurring in the Ganga Plains offer a modern analog for understanding Late Quaternary processes in the Himalayan foreland (Srivastava et al., 1994; Singh, 1996). The Ganga Plain holds the largest groundwater reserves in India, with the country's population heavily reliant on this resource for various developmental activities, including domestic, agricultural, and industrial uses (Groundwater Board, 2021). The average annual river discharge is 16650 cubic m/s (Jain et al., 2009). In some region of the world estimating groundwater recharge is essential for understanding water renewal and implementing sustainable water extraction practices (Lorenzi et al., 2024).
Facies are a distinctive rock unit that forms as a result of specific conditions of sedimentation, which in turn reflect particular processes or environments (Reading, 1996). Facies encompasses the combined lithologic and paleontological characteristics of a sedimentary rock (Moore, 1949; Teichert, 1958; Kiersnowski et al., 1995), while a facies model serves as a general overview of a specific sedimentary environment (Potter, 1959; Walker, 1976). Lithofacies analysis involves describing and classifying sediments, and then interpreting the sedimentary processes and depositional environments, usually through the application of a facies model (Anderton, 1985; Kontakiotis et al., 2020). Facies marker data, which includes information on lithology, sedimentary structures, paleontology, and mineral composition, can be used to infer the origin and formation environment of sedimentary rocks (Reading, 1978; Selley, 1982). Consequently, such data are crucial for paleogeographic reconstructions (Otari and Dabiri, 2015; Hou et al., 2019; Ogg, 2019; Kontakiotis et al., 2020; Elatrash et al., 2021; Khan et al., 2021). The sedimentary units and lithological facies have been identified from upland terrace surfaces from different parts of the Ganga Plain (Kumar et al., 1995; Singh et al., 1999; Srivastava et al., 2003a; Gibling et al., 2005; Singh and Singh, 2005; Singh, 2007; Singh and Awasthi, 2011a, 2011b; Yadav et al., 2023; Ali et al., 2023). The sedimentary records found within land formations provide crucial historical data for understanding past environmental conditions, including monsoon behavior and significant weather events (Singh et al., 2019).
The cliff sections exposed along the incised rivers of the Ganga Plain reveal the sedimentation history of the past 100 ka (Singh, 1996; Singh et al., 1997; Shukla et al., 2001; Srivastava et al., 2003b; Gibling et al., 2005; Sinha et al., 2007; Shukla, 2009; Srivastava et al., 2010; Pal et al., 2012; Roy et al., 2012; Shukla et al., 2012; Ghosh et al., 2019). In this study, stratigraphic succession displays a notable sequence of sedimentary structures such as silty unit (massive bedding), sandy unit (planar cross-bedding and trough cross-bedding) and mud unit (parallel lamination and massive homogenous layer).
The consistent paleo current directions observed in the planar cross-bedding suggest that the two-dimensional bedforms responsible for creating these beds moved in the same direction (Singh and Awasthi, 2011b). The rivers of the eastern Ganga Plain indeed play a significant role in the distribution of sediments in the region through the processes of channel avulsion and floods (Singh and Awasthi, 2011b; Sinha et al., 2014; Arjmandzadeh et al., 2020). The study area experiences flooding during the high discharge periods of the monsoon season and undergoes lateral erosion during the low discharge periods in the pre- and post-monsoon seasons (Singh and Awasthi, 2011b). Flooding and lateral erosion are identified as significant fluvial hazards in the Ghaghara River basin (Singh and Awasthi, 2011b).
Lateral erosion is an important geological process and is often classified as an independent natural hazard (Singh et al., 2010) caused by sandy facies, it plays a significant role in influencing the magnitude and impact of other natural hazards. Channel migration has been described in the Middle Ganga Basin (Philip et al., 1989) and along the Ghaghara River (Agarwal and Mishra, 1987). Lateral erosion is believed to be caused by flooding and is more severe on sandy soils compared to silty soils (Geyer et al., 2003). The river shows a braided channel pattern flowing within the valley (Gautam, 2023a). (Study of the lateral erosion along the Ghaghara River is study by (Gautam et al., 2024c).
Flooding has been identified as one of the most disastrous natural hazards, primarily affecting the Ganga Plain and the northeast region (Singh, 2007; Gautam et al., 2024b). Frequent flooding in eastern Uttar Pradesh is largely caused by the overflow of rivers like the Kuwana, Rapti, Chhoti Gandak, Ghaghara, and Great Gandak (Singh, 2007; Gautam et al., 2024a). Flooding and lateral erosion have been identified as significant fluvial hazards in the Ghaghara River region (Singh and Awasthi, 2011a). The geomorphology, sedimentology, and flood characteristics of the Ganga Plain rivers, including the Ganga (Singh, 2007), Ghaghara (Gautam et al., 2024c; Gautam et al., 2024b), and Sarda (Mitra et al., 2005), have been analyzed.
Flooding occurs during high-discharge periods, while lateral erosion operates during low-discharge periods (Singh and Awasthi, 2011b). This dynamic is further influenced by the direct and indirect impacts of climate change, which alter environmental conditions and affect river geomorphology (Gautam and Singh, 2022; Gautam et al., 2022a; Gautam and Singh, 2023; Gautam, 2023b, 2024). The impacts of climate change on depositional processes involve alterations to landscape geomorphology (Kumar et al., 2024). The current paper focuses on morpho-sedimentary and shallow surface facies analysis and their relation with the depositional environment and fluvial hazards.

2. Objectives

The objectives of the present study is

i. Detailed analysis of sediment characteristic in different lithological units along the Ghaghara River.

ii. Examine the sedimentary structures to interpret palaeo depositional environments.

iii. To develop a relation between sediment characteristics and lateral erosion, flooding risks.

iv. Recommendations for effective riverbank stabilization and flood risk management.

3. Study area

The study area is located in the Central Ganga Plain, Ayodhya, Uttar Pradesh (Fig. 1). A 196 cm high cliff section was analysed at 26°48′2″ N latitude and 82°13′28″ E longitude, on right bank of the Ghaghara River on upland terrace surface T_2 to prepare the litholog and also to collect the samples for facies analysis. The Ghaghara Plain is essentially composed of quaternary alluvium (Singh, 1996; Singh and Singh, 2005), which is mainly comprised of loose and unconsolidated sediments consisting of Sand, Silt, and Muddy-Sandy sequences (Gautam, 2023a). These sediments sequence deposited by various river systems developed under variable climatic conditions (Singh et al., 2009). Slope existing towards NW–SE direction (Kumar et al., 2018; Gautam et al., 2020; Gautam et al., 2023). The study area experiences a humid subtropical climate. The temperature ranges from 2 °C to 20 °C in winter and 30 °C to 47 °C during summer, respectively. The area receives maximum annual rainfall 80 to 160 cm (Jain and Sinha, 2003) during the monsoon season (June-September). Winds are mostly light and only a little stronger in the summer and monsoon seasons.

3.1 Geomorphic setting

The study area is situated at spans part of rivers as; Ghaghara, Sarju, and Tedhi interfluves regions. Satellite data show the general geomorphology of the area (Fig. 2 a). Cross-section along A-A' shows the channel incision and raised interfluve areas in which abandoned channels belts and alluvial ridges (Fig. 2 b). The Upland terrace surface (T_2) is the oldest geomorphic surface and is made up of the older alluvium. River valley terrace surface (T_1) consists of younger alluvium. This surface is prone to flooding during the high discharge period. The active floodplain surface (T_0) is the youngest geomorphic surface of the Ghaghara River basin (Singh, 1996; Srivastava et al., 2003a). Various researchers use subsurface data from the Ganga Plain to accurately understand the basement structure, as well as the dynamic characteristics of the sedimentary layers, including significant ridges and basins (Sastri et al., 1971; Rao, 1973; Raiverman and Raman, 1971; Lyon-Caen and Molnar, 1985; Singh, 1996).

3.2 Hydrological setting

The current study region is comprising the Ghaghara River and its tributaries, including the Sarju, Tedhi, Kuwana, Rapti, Chhoti Gandak, along with other water bodies such as minor channels, oxbow lakes, meander cutoffs, and ponds/lakes. The Ghaghara River experiences active flow during the monsoon season, leading to a steady increase in channel runoff. As a result, the river receives the majority of its water budget during this period. The average annual discharge is approximately 2993 m^3/s (Jain and Sinha, 2003).

4. Methodology

To identify the facies, sediment samples were taken from a prepared two-dimensional litholog of at 196 cm high cliff section from the upland terrace surface (T_2), which was exposed at Ayodhya Ghat, Uttar Pradesh. Stratigraphic columns are primarily used to display the sequence of lithologies and the true thickness of consistent sediment layers (Fig. 3). These columns are valuable for illustrating the repetition of beds, grading sequences, types of depositional environments, and for making stratigraphic correlations between different lithologic successions. Record the

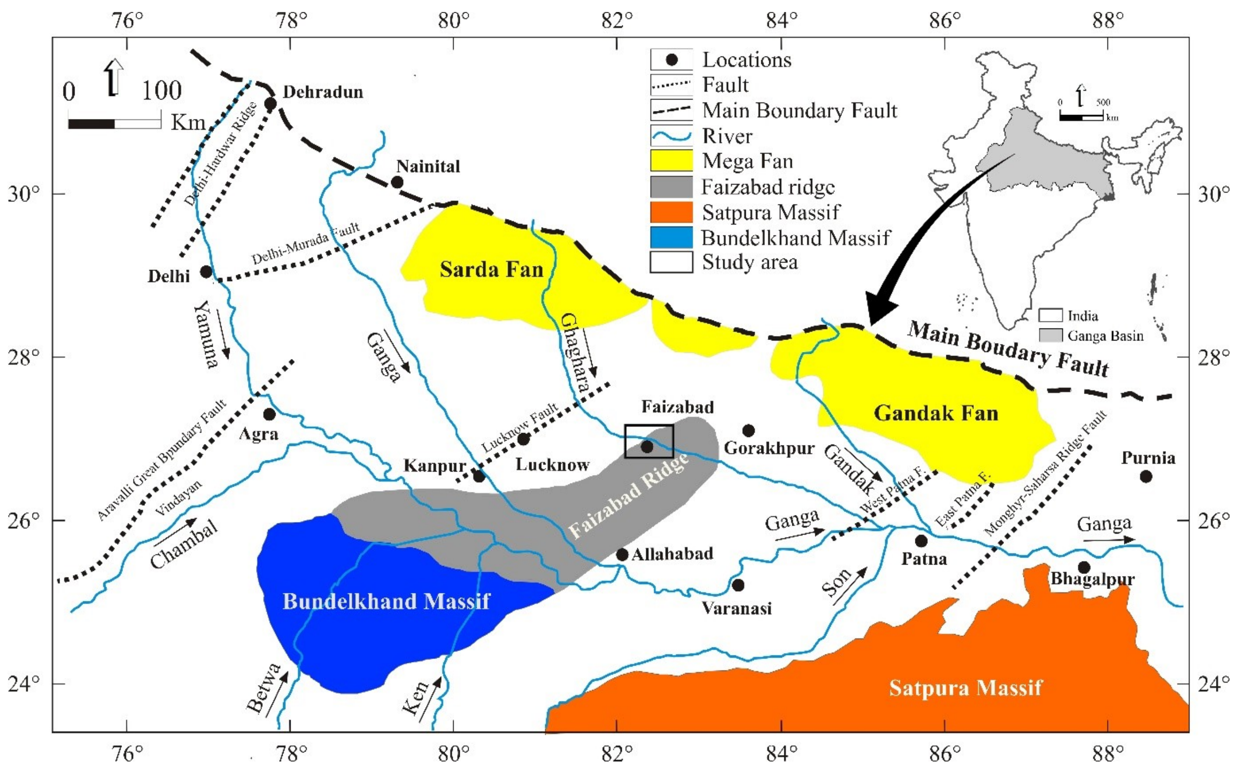

Figure 1. The map shows subsurface geology and tectonic framework of the upper and middle Ganga basin (after Singh (1996)).

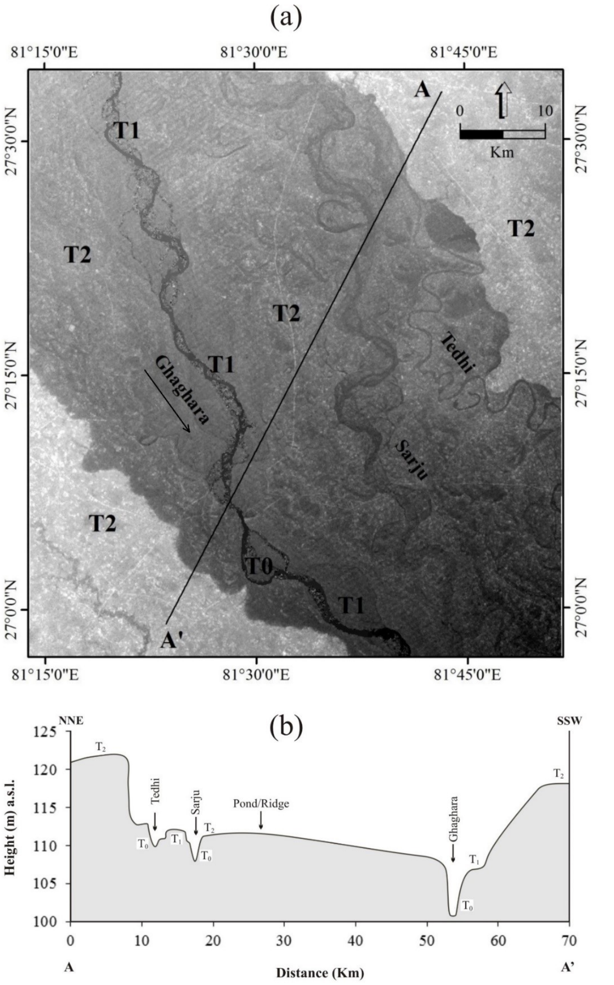

Figure 2. (a) Satellite data show the geomorphological features of the area, (b) Cross-section along A-A′ shows the channel incision and raised interfluve areas (Srivastava et al., 2003a).

thickness, color, texture, and composition of each layer has identify on the site. The paleosols were classified according to their color and grain-size composition.

4.1 Lithological units

The 196 cm high litholog (Fig. 3) was prepared in the field. It describes that the basal unit is 24 cm thick mud layer which is underlain by 9 cm thick fine sand unit. This fine sand unit (9 cm) is overlain by 16 cm thick mud layer, which is followed by an 18 cm thick cross bedded fine sand unit. The cross bedded fine sand unit is overlain by 10 cm thick mud layer and followed by a 3 cm sand and 10 cm thick mud unit. The top unit is mainly composed of 81 cm thick silt unit and it is overlain by 25 cm thick soil material with a mixture of plant/ root material. Various sedimentary structures such as massive bedding (in silty unit), planar cross-bedding (in sandy unit) and trough cross-bedding (in sandy unit) and parallel lamination (in mud layer) were identified in the litholog section (Fig. 3) at different depths. Moreover, individual litho-facies have been identified on the basis of sediment variation in colour, contacts with units, and sedimentary structures.

5. Results and discussion

The study is mainly divided into two parts: Facies analysis and Sedimentary structure (Table 1).

5.1 Facies analysis

The present facies analysis is based on sedimentological data collected from selected stratigraphic litholog on the Upland terrace surface of the Ghaghara River.

5.1.1 Facies I: Paleosol unit

The Paleosol facies are present at the top of the litholog between 0 to 25 cm. It includes two sub-units: Paleosol facies (Fp 1) and Paleosol facies (Fp 2). Paleosol facies (Fp 1) consist of a pedogenic layer containing organics-rich plant material, nodules, concretions, roots, burrows, and sandy silt (Fig. 3). It is overlain by massive siltstone (Fs l). This unit was formed in a suspension setting and evolved under high-energy conditions. Paleosol facies (Fp 2) are depicted at the top of the litholog. The uppermost part is 5 cm thick, brown, organically-rich plant material, massive pedogenic.

It is overlain by the Paleosol unit (Fp 1). The sedimentary structure developed in these facies is massive pedogenic and evolved in suspension settings. This unit was developed in high energy conditions and degree of transportation (Fig. 3). The Paleosol facies (Fp 2) is situated at the top of the lithology. Its uppermost part measures 5 cm in thickness and consists of brown, organics-rich plant material with a massive pedogenic structure. It is overlain by the Paleosol unit (Fp 1). The sedimentary structure is characterized by massive pedogenic features and evolved in a suspension setting. This unit was formed under high-energy conditions (Fig. 3).

In fluvial sequences, the development of a fully formed, mature paleosol indicates an extended interruption in the stratigraphic record, limited space for sediment accumulation, and the creation of surface gaps due to tectonic and climatic influences, particularly in regions where upstream factors exert significant control (McCarthy et al., 1998; McCarthy and Plint, 2003; Blum and Tornqvist, 2000; Plint et al., 2001; Demko et al., 2004; Rhee, 2006; Catuneanu et al., 2009).

5.1.2 Facies II: Silty unit

The silty facies, are present between 25 to 106 and are characterized by a yellowish-white, massive granular layer, dry material composed of well-sorted fine sand and silt. This layer exhibits either massive or faint lamination. This silt unit is positioned below a pedogenic unit (Fp 1) and above a sand unit (Fs 3). This layer developed under high-energy conditions, with fluctuating rates of transportation, ranging from high to low. Silt units indicate prolonged periods of relatively low to moderate energy within the depositional environments, characterized by fluctuating energy conditions (Singh et al., 2022) (Fig. 3).

5.1.3 Facies III: Sandy Unit

Sandy facies are present from the middle and lower part of the litholog and is composed of thick tabular units which are

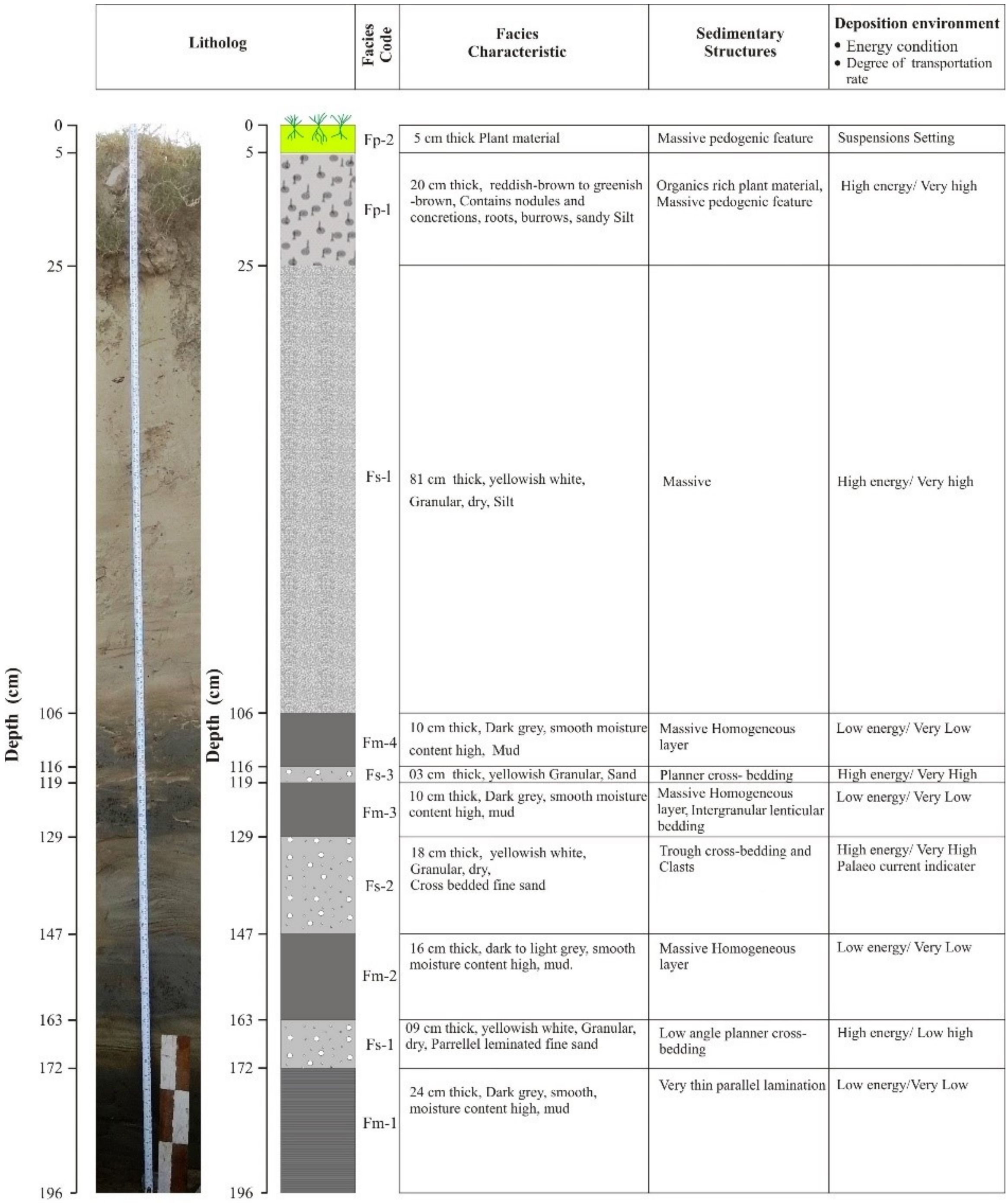

Figure 3. The Present figure reflect the litholog and associated litho units.

found alternately in the litholog. These facies are denoted as Fs l, Fs 2, and Fs 3 and it consists of 9 cm, 18 cm, and 3 cm, respectively. It consists of yellowish, granular, dry, and medium to fine-grain sand. The thickness of Sandy facies (Fs 1) consists of yellowish-white, granular, dry, fine sand and ranges from 163 to 172 cm. These facies are underlain by (Fm 2) and overlain by (Fm 1). These facies are prominent in the lower part commonly interbedded. The sandy unit is dominated by low-angle planar cross-bedding and overlain by very thin laminated mud (Fm 1). This sand unit (Fs 2) consists of a granular dry fine sand layer and ranges from 129 to 147 cm. These facies are underlain by (Fm 3) and overlain by homogeneous mud (Fm 2). It is mainly yellowish and comprises trough cross-bedding and mud clast, intergranular and lenticular bedding. The thickness of Sandy facies (Fs 3) ranges from 116 to 119 cm. These facies are underlain by (Fm 4) and overlain by (Fm 3).

This unit consists of granular, dry, fine sand. The sandy unit is dominated by planar cross-bedding. Energy conditions and the degree of transportation rate were very high (Fig. 3). This unit can be used as a palaeo current indica-

Table 1. Different facies association in the present study area.

<table>
<tr><th></th><th>FACIES I</th><th>FACIES II</th><th>FACIES III</th><th colspan="2">FACIES IV</th></tr>
<tr><td>Depth</td><td>Paleosol unit
(0-25 cm)</td><td>Silty unit
(25 to 106 cm)</td><td>Sandy unit
(116 to 172 cm)</td><td colspan="2">Mud unit
(106 to 196 cm)</td></tr>
<tr><td>Facies characteristic</td><td>Reddish-brown to greenish-brown</td><td>Yellowish, white granular and dry massive layer</td><td>Yellowish, granular, dry, and medium to fine-grain sand</td><td colspan="2">Mud is mainly d ark grey to light grey, smooth, with high moisture content</td></tr>
<tr><td rowspan="4">Sedimentary structure</td><td>Facies (FP 2)
(5 cm)
Massive pedogenic and evolved in suspension setting</td><td rowspan="4">Facies (FS 1)
(81 cm)
Massive or faint lamination</td><td>Facies (FS 1)
(9 cm)
Low-angle planar cross-bedding</td><td colspan="2">Facies (FM 1)
(24 cm)
Parallel lamination</td></tr>
<tr><td rowspan="3">Facies (FP 1)
(20 cm)
Nodules, concretions, roots, burrows, and sandy silt,
Massive pedogenic</td><td rowspan="2">Facies (FS 2)
(18 cm)
Cross-bedded fine sand, Trough cross-bedding</td><td>Facies (FM 2)
(16 cm)</td><td rowspan="3">Massive homogeneous layer and lenticular bedding</td></tr>
<tr><td>Facies (FM 3)
(10 cm)</td></tr>
<tr><td>Facies (FS 3)
(3 cm)
Planar cross-bedding</td><td>Facies (FM 4)
(10 cm)</td></tr>
<tr><td>Depositional environment</td><td>Energy conditions and degree of transportation rate were very high</td><td>Energy conditions and degree of transportation rate were very high</td><td>Energy conditions and degree of transportation rate were very high</td><td colspan="2">Energy conditions and degree of transportation rate were very low</td></tr>
</table>

tor (Singh and Awasthi, 2011b). The sand deposits exhibit cross-bedding, showcasing transient episodes of intense energy flux. These occurrences are characterized by short-lived, intermittent pulses of heightened energy, contributing to the dynamic sedimentary processes in fluvial environments (Walker and Cant, 1984).

5.1.4 Facies IV: Mud Unit

It is present in the lower part of the lithounit. These facies are denoted as Mud facies (Fm l), Mud facies (Fm 2), Mud facies (Fm 3) and Mud facies (Fm 4). It consists of 24, 16, 10 and 10 m, respectively, thick tabular units which are found alternately in the litholog. The mud is mainly dark grey to light grey, smooth, with high moisture content and contains a massive homogeneous layer to parallel lamination. This massive mud is deposited in fluvial overbank environments (Bridge, 1984; Singh et al., 2001). Energy conditions was low and the degree of transportation rate was very low (Fig. 3).

The Mud facies (Fm l) appear as massive, tabular and very thin parallel lamination with an overall absence of biogenic structures and soft-sediment deformation. The thickness of this facies ranges from 172 cm to 196 cm. These facies lie in the bottom of the litholog and it is underlain by (Fs 1). Thin sections of this lithofacies show no distinct porosity due to higher clay contents. The layer was developed in low energy conditions and the degree of transportation rate was very low (Fig. 4). The Facies (Fm 2) is characterized by very thin parallel laminated dark to light grey massive homogeneous mud layer. The thickness of these facies ranges from 147 to 163 cm. These facies are underlain by (Fs 2) and overlain by (Fs 1). The layer was developed during low energy conditions and the degree of transport rate was very low. Deposition of homogeneous mud is often associated with periods of low flow, where suspended sediment settles out of suspension due to reduced hydraulic energy.

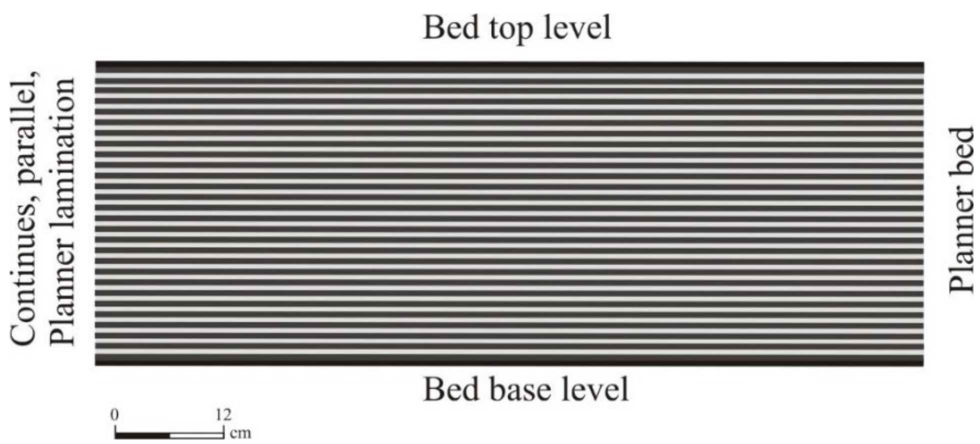

Figure 4. A planar bed, with planar internal lamination.

The Facies (Fm 3) is characterized by very thin parallel laminated dark to light grey massive homogeneous mud layer. The thickness of this facies ranges from 119 to 129 cm. These facies are underlain by (Fs 3) and overlain by (Fs 2). The layer was formed during low energy conditions and the degree of transport rate was very low.
The Facies (Fm 4) is characterized by very thin parallel laminated dark to light grey mud. The thickness of this facies ranges from 106 to 116 cm. These facies are underlain by massive siltstone (Fs l) and overlain by Sand unit (Fs 3). It is generally dark grey and massive homogeneous layer. It represents the lowest-energy conditions within the succession. It is interpreted to have been deposited mainly from suspension. The layer evolved in low energy conditions and the degree of transport rate was very low.

5.2 Sedimentary structures

The sedimentary structures are determined, namely: massive bedding, parallel lamination, lenticular bedding, trough cross-bedding and low-angle planar cross-bedding (Fig. 5 and 6).

5.2.1 Massive bedding

Massive bedding is a typical internal structure of beds (Fig. 3 and 5 a). It ranges from 147 to 163 cm, 119 to 129 cm, and 106 to 116 cm, followed by Fm-2, Fm-3, and Fm-4 in the Mud unit in exposed section (Fig. 5 b, c), respectively (Table 1). Massive bedding is often seen in fine-grained, low-energy diverse sedimentary environment deposits such as fluvial channels (Singh et al., 2022). It is most frequently seen in mud, where sedimentary structures cannot be delineated by textural variations.

5.2.2 Parallel lamination

Parallel lamination serves as a frequent internal structure within beds (Fig. 3 and 5 a). It ranges between 172 cm to 196 followed by Fm-1 in the Mud unit (Fig. 5a and d), t, respectively (Table 1). Laminated and peaty mudstone indicates the declining phase of river flooding and the formation of swamp deposits, suggesting sedimentation on the floodplain (Miall, 2000). A prevalent superficial structure is flat or horizontal bedding, aligning parallel to the major bedding surface.

5.2.3 Lenticular bedding

Lenticular bedding is a common internal structure of beds (Fig. 6 a). It ranges between 119 to 129 cm followed by Fm-3 in the Mud unit (Fig. 6 a and b), respectively (Table 1). This structure is associated with the Mud unit. Lenticular bedding is where mud dominates and the cross-laminated sand occurs in lenses (Fig. 7). They are common forms in relatively low-energy environments. The angular to the subangular shape of mud clasts suggests that the sediments are immature and have not been transported over long distances (Reineck and Singh, 1980).

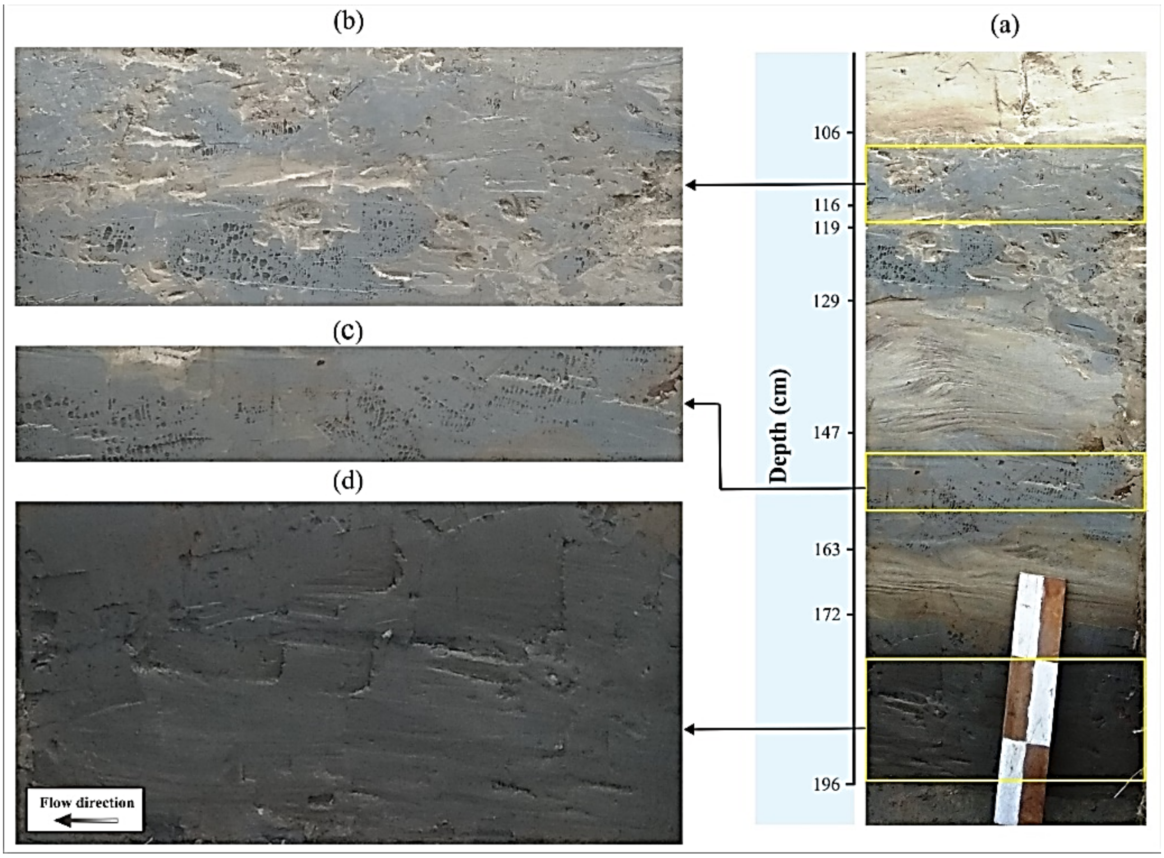

Figure 5. (a) Field photograph of the lithological succession (196 cm), (b) Laminated dark mud with clasts, intergranular sand, (c) Parallel laminated dark homogenous mud layer, (d) Parallel laminated dark homogenous mud layer.

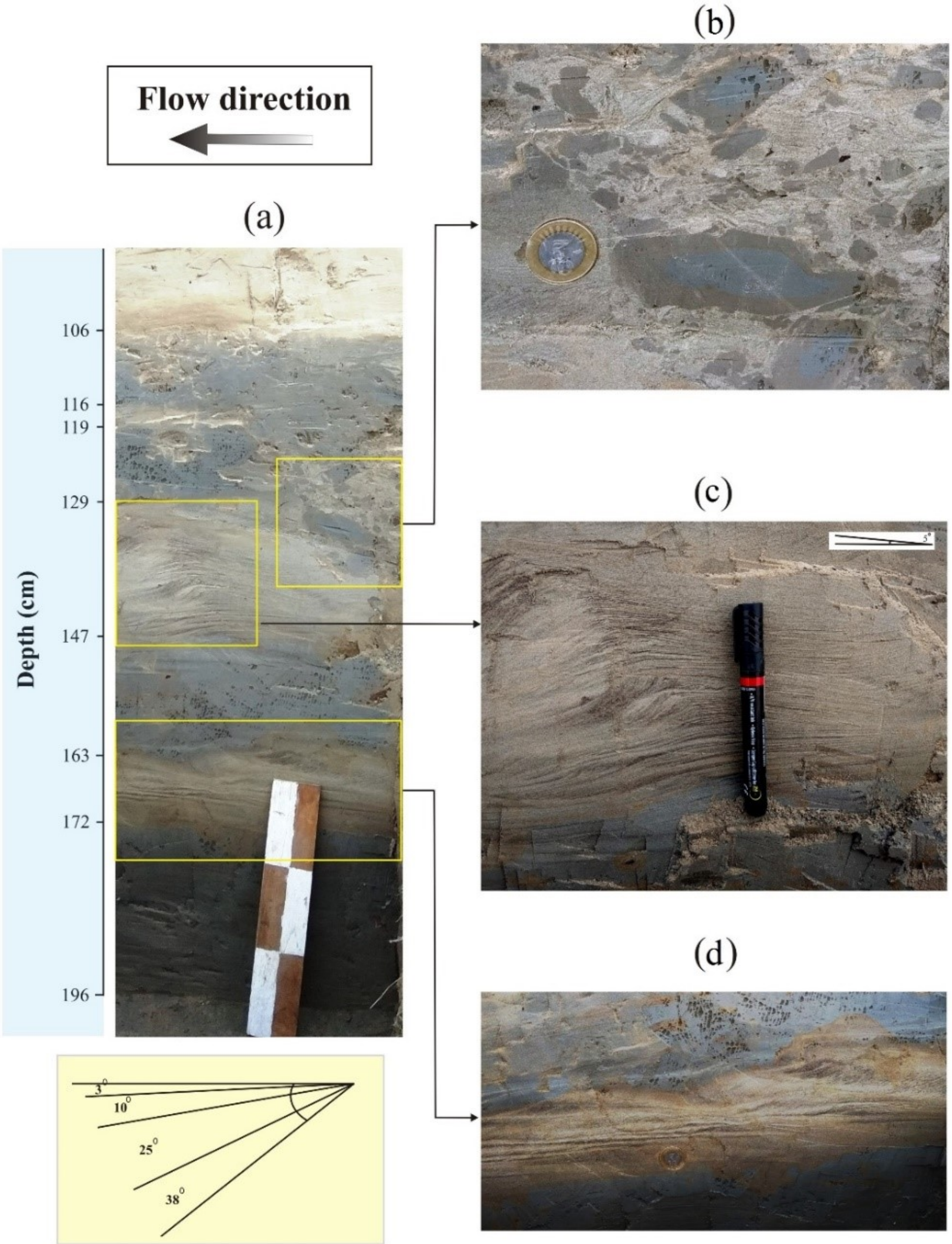

Figure 6. (a) Field photographs of the lithological succession (196 cm), (b) Clasts eye structure, intergranular and lenticular bedding, (c) Trough cross-bedding and (d) Low angle planer cross-bedding.

5.2.4 Trough cross-bedding

Trough cross-bedding is a common internal structure of beds (Singh and Singh, 2005). It is associate with Fs-2 facies and range from 129 to 147 cm (Fig. 6 a and 6 c), and Table 1). In trough cross-bedding, upward concave fore set lie within erosion scours, which are elongated parallel to current flow, closed up current and truncated down current by other troughs. Trough cross-beds develop in areas where there are higher flow intensities (Rubin, 1987), this erosion at the base of transverse bedforms' slip slopes is caused by higher flow velocities (Pettijohn et al., 1987). The trough cross-bedding consists of a scoop-shaped or cylindrical depression filled with curved foreset layers. These layers follow the contour of the trough, and both the trough axis and the crescent-shaped fill layers align parallel to the primary flow direction in the local area (Trexler and Cashman, 1990). The trough-shaped basal scour surfaces define

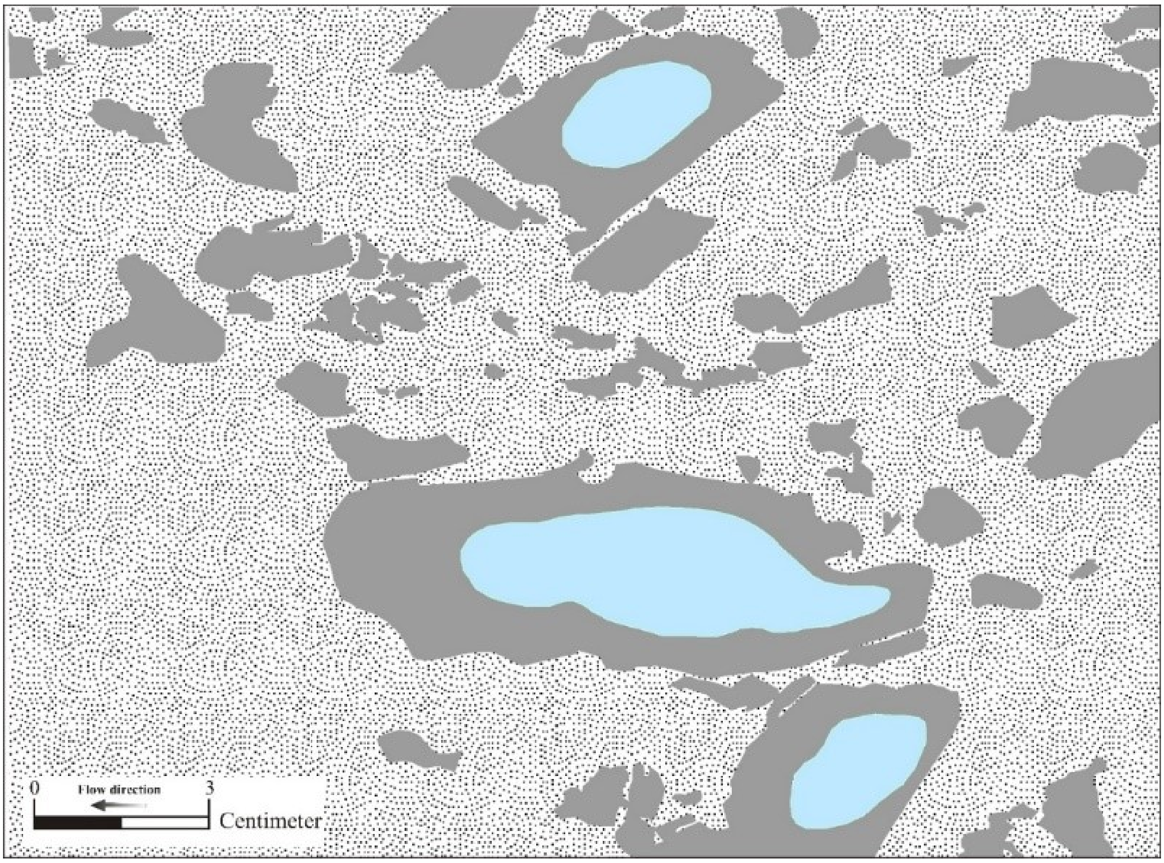

Figure 7. Clasts eye structure, intergranular and lenticular mud clasts associated within sand layer.

the boundaries of sedimentary units and typically exhibit a shallow dip ranging from 0° to 15° tends in the direction of sediment transport (Rider, 1996).

5.2.5 Low-angle planar cross-bedding

The low-angle planer cross-bedded facies are vertically surrounded by a mud layer and horizontally extend in very fine sand (9 cm) thick horizons (Fig. 6 a and 6 d). It ranges from 163 to 172 cm followed by Fs-1 facies (Table 1). This is a very common facies of channel bar deposits and the dip of the inclined laminae is usually 8-12° (Singh and Singh, 2005). Low-angle planar cross-bedding in the Ghaghara Plain is influenced by factors such as variations in sediment supply, seasonal changes in flow dynamics, and the geomorphological evolution of the river channel (Raj, 1994). Low-angle planar cross-bedding is a common internal structure of beds where the planar fore set is bounded above and below by sub-parallel sub-horizontal boundaries (Shukla, 2009). Fine to medium-grained sandstone showing planar cross-stratification and ripple cross lamination with erosive basal surface represent channel deposits (Miall, 2006).

6. Implications of the study

Different layers of sandy, silt, and mud facies in lithlog reflect that these uneven sediment deposits are responsible for lateral erosion along the Ghaghara River (Fig. 8). Due to the presence unconsolidated sediments, the river leads to bank instability and potential lateral erosion during low discharge periods in the pre- and post-monsoon seasons. Flooding is also likely to occur during high discharge periods due to the overflow of river water during the monsoon season.

The incidence of flooding is frequent in eastern Uttar Pradesh, which is broadly the result of spilling of rivers such as Kuwana, Rapti, Chhoti Gandak, Ghaghara, and Great Gandak (Singh, 2007). Stream bank erosion is believed to be caused by flooding, with erosion being more severe on sandy soils than on silty soils (Geyer et al., 2003). Singh et al. (2010) have conducted significant research on the lateral erosion of river channels in the mountain-fed rivers across various parts of the Ganga Plain. The region experiences flooding during periods of high-water flow in the monsoon season and is subject to lateral erosion during periods of low water flow in the pre- and post-monsoon seasons (Singh and Awasthi, 2011b). It is concluded that the rising frequency of disasters signifies unsustainable development. In most cases, humans are responsible for river-borne disasters. As population increases, people have begun to inhabit the river's danger zones. This renders lateral erosion a devastating hazard (Singh and Awasthi, 2011b; Roy et al., 2011).

7. Mitigation

The presence of sand, silt, and mud facies along riverbanks can make these areas susceptible to erosion during various flow conditions. Erosion of these sediments can lead to the widening of the river channel and the shifting of the river's course, contributing to lateral erosion. Effective riverbank stabilization measures and erosion control strategies are

Figure 8. Field photographs showing lateral erosion near (a) Lateral erosion towards left valley side at Manjha kala (Faizabad), (b) Sand and sediment deposition towards right valley side at Pitapur (Faizabad), (c) Lateral erosion near Veuda Manjha (Faizabad) towards right valley side.

often necessary in areas with these sediment types to mitigate the risk of lateral erosion and protect infrastructure and ecosystems along riverbanks. Managing lateral erosion in areas with sandy, silt, and mud facies often involves a combination of strategies, including bank stabilization techniques (e.g., riprap, vegetation planting), floodplain management, and channel restoration. These efforts aim to reduce the vulnerability of the riverbanks to erosion, protect infrastructure, and minimize the environmental impacts associated with lateral erosion. Understanding the geological and sedimentary characteristics of a river's banks is essential for effective erosion control and management.

8. Significance of the study

This study provides a detailed analysis of the lithological units and sedimentary structures along the Ghaghara River, revealing distinct facies including Paleosol, Silty, Sandy, and Mud units. The facies analysis indicates varying energy conditions and transport rates, which contribute to understanding the river's depositional history and sedimentary processes. Identifying sedimentary structures such as massive bedding, cross-bedding, and lamination enhances insights into historical environmental conditions and sediment dynamics. The research highlights the significant role of these sediments in influencing lateral erosion and flood risks, underscoring the need for effective erosion control and flood management strategies. Ultimately, this study supports the development of sustainable practices to mitigate riverbank instability and safeguard both infrastructure and ecosystems.

Future research should prioritize several key areas to enhance our understanding of sediment dynamics and riverbank stability. First, implementing long-term monitoring programs is essential for observing changes in sediment deposition and erosion over time. This approach will provide insights into the effects of seasonal and climatic variations on sedimentary processes. Additionally, investigating the impacts of climate change on sediment dynamics, river discharge, and flood frequencies is crucial for predicting and managing future risks effectively. Another important focus should be exploring the role of riparian vegetation in stabilizing riverbanks and mitigating erosion. Understanding how different types of vegetation contribute to erosion control can help in integrating effective strategies into river management practices. Developing advanced models to simulate sediment transport and deposition under various flow conditions is also necessary to improve predictive accuracy and enhance our ability to manage sediment-related challenges. Lastly, assessing the effects of human activities—such as land use changes, construction, and deforestation-on sediment dynamics and riverbank stability will provide valuable insights for promoting sustainable land management practices. Addressing these research areas will contribute significantly to better managing river systems and mitigating the risks associated with sedimentation and erosion.

9. Conclusion

- The current work incorporates the study of facies analysis and sedimentary structure of exposed outcrop (Clift section) on the Upland terrace surface (T_2) along the Ghaghara River in the Central Ganga Plain of India which shows a braided channel pattern flowing within the valley, and help to interpret the depositional environment.
- The facies are the Paleosol unit (Facies I), Silty unit (Facies II), and Sandy unit (Facies III), which show high energy conditions and high degree of transport rate while the Mud unit (Facies IV), shows low energy conditions and low degree of transport rate.
- In this study, sedimentary structures such as massive bedding (in silty unit), planar cross-bedding and trough cross-bedding (in sandy unit), and parallel lamination (in mud unit) were identified in the litholog section.
- The sandy, silt and mud facies have been identified as an erosion factor that causes lateral erosion along the river banks. These sediment types play a role in the erosional processes that affect riverbanks and can exacerbate the lateral shifting of river channels.
- Understanding and managing lateral erosion is crucial for mitigating the risks associated with these related hazards and protecting both human communities and the environment.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Agarwal C. S., Mishra A. K. (1987) Visual interpretation of F.C.C. satellite data for channel migration and water logging conditions along Ghaghara and Terhi rivers in part of district Gonda and Bahraich, UP. *Journal of the Indian Society of Remote Sensing* 15 (1): 19–28. DOI: https://doi.org/10.1007/BF03003665.

Ali G., Sajid M., Khan M. S. (2023) Soft sediment deformation structures in the sediment deposits of Ganga River and its oxbow lakes in parts of Indo-Gangetic Plain: implications for quake proxies and paleoseismicity tracking. *International Journal of Geosciences* 14 (1): 50–65. DOI: https://doi.org/10.4236/ijg.2023.141005.

Anderton R. (1985) Clastic facies models and facies analysis. *Journal of the Geological Society, London, Special Publications* 18 (1): 31–47. DOI: https://doi.org/10.1144/gsl.sp.1985.018.01.03.

Arjmandzadeh R., Teshnizi E. S., Ahmadi A. A., Mahdavi A., Tavsoli S., Dabiri R. (2020) The mineralogy, geochemistry and genesis of Aghol-Messi sedimentary copper-uranium deposit, Tabas block, Central Iran. *Researches in Earth Sciences* 11 (4): 47–70. DOI: https://doi.org/10.52547/esrj.11.4.47.

Blum M. D., Tornqvist T. E. (2000) Fluvial responses to climate and sea level change: a review and look forward. *Sedimentology* 47:2–48. DOI: https://doi.org/10.1046/j.1365-3091.2000.00008.x.

Bridge J. S. (1984) Large-scale facies sequences in alluvial overbank environments. *Journal of Sedimentary Petrology* 54:583–588. DOI: https://doi.org/10.1306/212f8477-2b24-11d7-8648000102c1865d.

Catuneanu O., Abreu V., Bhattacharya J. P., Blum M. D., Dalrymple R. W., Eriksson P. G., Fielding C. R., et al. (2009) Towards the standardization of sequence stratigraphy. *Earth Science Reviews* 92:1–33. DOI: https://doi.org/10.1016/j.earscirev.2008.10.003.

Chandra S., Gautam P. K., Singh A. P., al. et (2024) Site selection for suitability of dam construction using analytic hierarchy process (AHP): A review study on Rihand Dam, Uttar Pradesh, India. *Arabian Journal of Geosciences* 17:293. DOI: https://doi.org/10.1007/s12517-024-12097-x.

Colombera L., Mountney N. P., Medici G., West L. J. (2019) The geometry of fluvial channel bodies: Empirical characterization and implications for object-based models of the subsurface. *AAPG Bulletin* 103 (4): 905–929. DOI: https://doi.org/10.1306/10031817417.

Demko T. M., Currie B. S., Nicoll K. A. (2004) Regional paleoclimatic and stratigraphic implications of paleosols and fluvial/overbank architecture in the Morrison Formation (Upper Jurassic), Western Interior, USA. *Sedimentary Geology* 167:115–135. DOI: https://doi.org/10.1016/j.sedgeo.2004.01.003.

Dewey J. F., Bird J. M. (1970) Mountain belts and the new global tectonics. *Journal of Geophysical Research* 75 (14): 2625–2647. DOI: https://doi.org/10.1029/JB075i014p02625.

Dickinson W. R. (1974) Plate Tectonics and Sedimentation. *SEPM Special Publication* 22:1–27. DOI: https://doi.org/10.2110/pec.74.22.

Elatrash A. M., Abdelwahhab M. A., Wanas H. A., El-Naggar S. I., Elshayeb H. M. (2021) Multi-disciplinary approach to sedimentary facies analysis of Messinian Salinity Crisis tectono-sequences (South-Mansoura Area, Nile Delta): incised-valley fill geological model reconstruction and petroleum geology-reservoir element delineation. *Journal of Petroleum Exploration and Production* 11 (4): 1643–1666. DOI: https://doi.org/10.1007/s13202-021-01124-2.

Gautam P. K. (2024) Drainage analysis of the Karanja River basin, Karnataka, India using geo-informatics. *Applied Geomatics* 16:1025–1046. DOI: https://doi.org/10.1007/s12518-024-00584-5.

——— (2023a) Sedimentology of the lower part of Ghaghara River basin from Faizabad to Deoria. *Ph.D. Thesis, Geology Department, Lucknow University, Lucknow, India,* 1–161. http://hdl.handle.net/10603/518650

——— (2023b) The significance of morphometric analysis of Shimsha River, Karnataka, India to understand the hydrological and morphological characteristics. *River* 2 (4): 490–505. DOI: https://doi.org/10.1002/rvr2.66.

Gautam P. K., Chandra S., Henry P. K. (2024a) Estimation of flood inundation in river basins of Uttar Pradesh using Sentinel 1A-SAR data on Sentinel Application Platform (SNAP). *Arabian Journal of Geosciences* 17:107. DOI: https://doi.org/10.1007/s12517-024-11910-x.

Gautam P. K., Kumar D., Singh A. K., Singh D. S. (2023) Drainage network analysis and tectonics interference of the Reth River, Central Ganga Plain (India) using geospatial technology. *Geotectonics* 57 (3): 330–345. DOI: https://doi.org/10.1134/S0016852123030032.

Gautam P. K., Kumar N. (2025) Geo-hydrological analysis and watershed delineation of the Sarayan River, Ganga Plain, India: Integrating geospatial data for water resource management. *Arabian Journal of Geosciences* 18:111.
DOI: https://doi.org/10.1007/s12517-025-12255-9.

Gautam P. K., Singh A. K. (2023) Evaluation of active tectonic features of Nandakini River Basin, Lesser Himalaya, India by using morphometric indices: A GIS approach. *Advances in Environmental and Engineering Research* 4 (1): 1–14.
DOI: https://doi.org/10.21926/aeer.2301014.

Gautam P. K., Singh D. S. (2022) Flood hazard and risk assessment of Deoha River Basin, Central Ganga Plain, India: A GIS approach. *Disaster Advances* 15 (10): 42–51.
DOI: https://doi.org/10.25303/1510da042051.

Gautam P. K., Singh D. S., Kumar D., Singh A. K. (2020) A GIS-based approach in drainage morphometric analysis of Sai River Basin, Uttar Pradesh, India. *Journal of the Geological Society of India* 95:366–376. DOI: https://doi.org/10.1007/s12594-020-1445-9.

——— (2024b) Grain size and sediment load control on channel migration patterns of the Ghaghara River from Faizabad to Deoria, Ganga Plain, India. *Arabian Journal of Geosciences* 17:295.
DOI: https://doi.org/10.1007/s12517-024-12104-1.

Gautam P. K., Singh D. S., Kumar D., Singh A. K., Vishawakarma B. (2022a) Assessment of morphometric characteristics and decadal fluctuation of groundwater level of Kali River basin and its link with climate change, West Indo-Gangetic Plain, India using geographical information system. *Disaster Advances* 15 (5): 26–38.
DOI: https://doi.org/10.25303/1505da026038.

Gautam P. K., Singh D. S., Singh A. K. (2024c) Quantitative assessment of channel migration in the Ghaghara River, Ganga Plain, India. *Journal of the Geological Society of India* 100 (7): 919–935.
DOI: https://doi.org/10.17491/jgsi/2024/173935.

Gautam P. K., Singh D. S., Singh A. K., Kumar D. (2022b) Geomorphic analysis of Baghain River, Yamuna Basin, and its implication for drainage characteristic and tectonics using remote sensing and GIS techniques. *Journal of the Geological Society of India* 98:1573–1584. DOI: https://doi.org/10.1007/s12594-022-2214-8.

Geyer W., Brooks K., Neppl T. (2003) Streambank stability of two Kanas river systems during the 1993 flood in Kanas, USA. *Transactions of the Kansas Academy of Science* 106 (1/2): 48–53. DOI: https://doi.org/10.1660/0022-8443(2003)106[0048:SSOTKR]2.0.CO;2.

Ghosh R., Srivastava P., Shukla U. K., Sehgal R. K., Singh I. B. (2019) 100 kyr sedimentary record of Marginal Gangetic Plain: Implications for forebulge tactonics. *Palaeogeography, Palaeoclimatology, Palaeoecology* 520:78–95.
DOI: https://doi.org/10.1016/j.palaeo.2019.01.035.

Gibling M. R., Tandon S. K., Sinha R., Jain M. (2005) Discontinuity-bounded alluvial sequences of the southern Gangetic plains, India: aggradation and degradation in response to monsoonal strength. *Journal of Sedimentary Research* 75:369–385.
DOI: https://doi.org/10.2110/jsr.2005.029.

Groundwater Board U. P. (2021) Govt. of India. https://www.census2011.co.in

Hou M., Chen A., Ogg J., Ogg G., Huang K., Xing F., Chen H., et al. (2019) China paleogeography: Current status and future challenges. *Earth-Science Reviews* 189:177–193.
DOI: https://doi.org/10.1016/j.earscirev.2018.04.004.

Jain S. K., Sharma B. R., Zahid A., Jin M., Shreshtha J. L., Kumar V., Rai S. P., Hu J., Luo Y., Sharma D. (2009) A comparative analysis of the hydrogeology of the Indus-Gangetic and Yellow River basins. *In: Mukherji A., Villholth K. G., Sharma B. R., Wang J. (eds) Groundwater governance in the Indo-Gangetic and Yellow River basins: Realities and challenges. CRC Press,* 43–64.
DOI: https://doi.org/10.1201/9780203874479.

Jain V., Sinha R. (2003) River systems in the Gangetic plains and their comparison with the Siwaliks: A review. *Current Science* 84 (8): 1025–1033. https://www.jstor.org/stable/24107664

Khan J. M., Ghazi S., Mehmood M., Yazdi A., Naseem A. A., Serwar U., Zaheer A., Ullah H. (2021) Sedimentological and provenance analysis of the Cretaceous Moro Formation, Rakhi Gorge, Eastern Sulaiman Range, Pakistan. *Iranian Journal of Earth Sciences* 13 (4): 252–266. DOI: https://doi.org/10.30495/ijes.2021.1917721.1564.

Kiersnowski H., Paul J., Peryt T. M., Smith D. B. (1995) Facies, paleogeography and sedimentary history of the southern Permian Basin in Europe. *In: Scholle P. A., Peryt T., Ulmer-Scholle D. S. (eds) The Permian of Northern Pangea: Sedimentary Basins and Economic Resources. Springer, Heidelberg,* 119–136.
DOI: https://doi.org/10.1007/978-3-642-78590-0˙7.

Kontakiotis G., Karakitsios V., Maravelis A. G., Zarkogiannis S. D., Agiadi K., Antonarakou A., Pasadakis N., Zelilidis A. (2020) Integrated isotopic and organic geochemical constraints on the depositional controls and source rock quality of the Neogene Kalamaki sedimentary successions (Zakynthos Island, Ionian Sea). *Mediterranean Geoscience Reviews* 8 (9): 706.
DOI: https://doi.org/10.3390/jmse8090706.

Kumar D., Singh A. K., Gautam P. K., Vishawakarma B., Dubey C. A., Singh D. S. (2024) Response of global warming on glaciers of Garhwal Himalaya, India: A remote sensing and GIS approach. *In: Khare N. (ed) Polar Ice and Global Warming in Cryosphere Regions. Taylor and Francis (CRC Press)* 5:91–107.
DOI: https://doi.org/10.1201/9781003364115-5.

Kumar D., Singh D. S., Prajapati S. K., Khan I., Gautam P. K., Vishawakarma B. (2018) Morphometric parameters and neotectonics of Kalyani River Basin, Ganga Plain: A remote sensing and GIS approach. *Journal of the Geological Society of India* 91:679–686.
DOI: https://doi.org/10.1007/s12594-018-0923-9.

Kumar S., Singh I. B., Singh M., Singh D. S. (1995) Depositional pattern in upland surfaces of central Gangetic Plain near Lucknow. *Journal of the Geological Society of India* 46 (5): 545–555. https://www.geosocindia.org/index.php/jgsi/article/view/68057

Lorenzi V., Banzato F., Barberio M. D., Goeppert N., Goldscheider N., Gori F., Lacchini A., et al. (2024) Tracking flowpaths in a complex karst system through tracer test and hydrogeochemical monitoring: Implications for groundwater protection (Gran Sasso, Italy). *Heliyon* 10 (2) DOI: https://doi.org/10.1016/j.heliyon.2024.e24663.

Lyon-Caen H., Molnar P. (1985) Gravity anomalies and flexure of the Brazilian Shield beneath the Bolivian Andes. *Earth and Planetary Science Letters* 75:81–92.
DOI: https://doi.org/10.1016/0012-821X(85)90053-6.

McCarthy P. J., Martini I. P., Leckie D. A. (1998) Use of micromorphology for paleoenvironmental interpretation of complex alluvial paleosols: An example from the Mill Creek Formation (Albian), southwestern Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 143:87–110. DOI: https://doi.org/10.1016/S0031-0182(98)00080-7.

McCarthy P. J., Plint A. G. (2003) Spatial variability of paleosols across Cretaceous interfluves in the Dunvegan Formation, NE British Columbia, Canada: Palaeohydrological, paleogeomorphological and stratigraphic implications. *Sedimentology* 50:1187–1220.
DOI: https://doi.org/10.1111/j.1365-3091.2003.00600.x.

Miall A. D. (2000) Principles of sedimentary basin analysis. *Springer Verlag, Berlin Heidelberg,*
DOI: https://doi.org/10.1007/978-3-662-03999-1.

——— (2006) The geology of fluvial deposits: Sedimentary facies, basin analysis, and petroleum geology. *Springer Verlag, Berlin Heidelberg,* DOI: https://doi.org/10.1007/978-3-662-03237-4.

Mitra D., Tangri A. K., Singh I. B. (2005) Channel avulsions of Sarda River system, Ganga Plain. *International Journal of Remote Sensing* 26:929–936. DOI: https://doi.org/10.1080/0143116031000102458.

Moore R. C. (1949) Meaning of facies. *Geological Society of America Memoir* 39:1–34. DOI: https://doi.org/10.1130/MEM39-p1.

Ogg J. G. (2019) Integrated global stratigraphy and geologic timescales, with some future directions for stratigraphy in China. *Earth-Science Reviews* 189:6–20. DOI: https://doi.org/10.1016/j.earscirev.2018.01.001.

Otari M., Dabiri R. (2015) Geochemical and environmental assessment of heavy metals in soils and sediments of Forumad Chromite mine, NE of Iran. *Journal of Mining and Environment* 6 (2): 251–261. DOI: https://doi.org/10.22044/jme.2015.475.

Pal D. K., Bhattacharyya T., Sinha R., Srivastava P., Dasgupta A. S., Chandran P., Ray S. K., Nimje A. (2012) Clay minerals record from Late Quaternary drill cores of the Ganga Plains and their implications for provenance and climate change in the Himalayan Foreland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 356:27–37. DOI: https://doi.org/10.1016/j.palaeo.2011.05.009.

Pettijohn F. J., Potter P. E., Siever R. (1987) Sand and Sandstone. *2nd Edition, Springer-Verlag, New York,* 553. DOI: https://doi.org/10.1007/978-1-4612-1066-5.

Philip G., Gupta R. P., Bhattacharya A. (1989) Channel migration studies in the middle Ganga basin, India, using remote sensing data. *International Journal of Remote Sensing* 10:1141–1149. DOI: https://doi.org/10.1080/01431168908903953.

Plint A. G., McCarthy P. J., Faccini U. F. (2001) Nonmarine sequence stratigraphy: Updip expression of sequence boundaries and system tracts in a high-resolution framework. Cenomanian Dunvegan Formation, Alberta foreland basin, Canada. *American Association of Petroleum Geologists Bulletin* 85:1967–2001. DOI: https://doi.org/10.1306/8626D0C7-173B-11D7-8645000102C1865D.

Potter P. E. (1959) Facies model conference. *Science* 129:1292–1294. DOI: https://doi.org/10.1126/science.129.3358.1292.

Raiverman V., Raman K. S. (1971) Facies relations in the Subathu sediments, Simla Hills, N.W. Himalaya, India. *Geological Magazine* 108:329–341. DOI: https://doi.org/10.1017/S0016756800051402.

Raj R. (1994) River response to neotectonics and climate in the Ganga Plains. *In: Merh S. S., Sial A. N. (eds) Quaternary Environments and Geoarchaeology of India. Geological Survey of India Memoirs* 119:41–61.

Rao M. B. R. (1973) The sub-surface geology of the Indo-Gangetic Plains. *Journal of the Geological Society of India* 14:217–242. https://www.geosocindia.org/index.php/jgsi/article/view/61831

Reading H. G. (1978) Sedimentary Environments and Facies. *Blackwell Scientific Publications, Oxford,* 557.

——— (1996) Sedimentary Environments: Processes, Facies and Stratigraphy. *3rd Edition, Blackwell, Oxford,* 689.

Reineck H. E., Singh I. B. (1980) Depositional Sedimentary Environments: With Reference to Terrigenous Clastics. *Springer, Berlin,* DOI: https://doi.org/10.1007/978-3-642-81498-3.

Rhee C. W. (2006) Conceptual problems and recent progress in fluvial sequence stratigraphy. *Geosciences Journal* 10:433–443. DOI: https://doi.org/10.1007/BF02910437.

Rider M. H. (1996) The Geological Interpretation of Wireline Logs. *Whittles Publishing*

Roy N. G., Sinha R., Gibling M. R. (2011) Aggradation, incision and interfluve flooding in the Ganga Valley over the past 100,000 years: testing the influence of monsoonal precipitation. *Palaeogeography, Palaeoclimatology, Palaeoecology,* DOI: https://doi.org/10.1016/j.palaeo.2011.08.012.

——— (2012) Aggradation, incision and interfluve flooding in the Ganga Valley over the past 100,000 years: testing the influence of monsoonal precipitation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 356–357:38–53. DOI: https://doi.org/10.1016/j.palaeo.2011.08.012.

Rubin D. M. (1987) Cross-bedding, Bedforms and Palaeocurrents. *Concepts in Sedimentology and Palaeontology Special Publication, vol. 1. Society of Economic Palaeontologists and Mineralogists*

Sastri V. V., Bhandari L. L., Raju A. T. R., Dutta A. K. (1971) Tectonic framework and subsurface stratigraphy of the Ganga Basin. *Geological Society of India* 12:222–233. DOI: https://doi.org/10.17491/jgsi/1971/120302.

Selley R. C. (1982) An Introduction to Sedimentology. *2nd ed., Academic Press, London,* 417. DOI: https://doi.org/10.1017/S0016756800050834.

Shukla U. K. (2009) Sedimentation model of gravel-dominated alluvial piedmont fan, Ganga Plain, India. *International Journal of Earth Sciences (Geologische Rundschau)* 98:443–459. DOI: https://doi.org/10.1007/s00531-007-0261-4.

Shukla U. K., Raju N. J. (2008) Migration of the Ganga River and its implications on hydrogeological potential of Varanasi area, U.P., India. *Journal of Earth System Science* 117:489–498. DOI: https://doi.org/10.1007/s12040-008-0048-4.

Shukla U. K., Singh I. B., Sharma M., Sharma S. (2001) A model of alluvial megafan sedimentation: Ganga Megafan. *Sedimentary Geology* 144:243–262. DOI: https://doi.org/10.1016/S0037-0738(01)00060-4.

Shukla U. K., Srivastava P., Singh I. B. (2012) Migration of the Ganga River and development of cliffs in the Varanasi region, India during the late Quaternary: Role of active tactonics. *Geomorphology* 171:101–113. DOI: https://doi.org/10.1016/j.geomorph.2012.05.009.

Singh A. K., Kumar D., Dubey C. A., Gautam P. K., Vishawakarma B., Singh D. S. (2022) Glacial morpho-sedimentology and processes of landscape evolution in Gangotri Glacier Area, Garhwal Himalaya, India. *In: Khare N. (ed) Glaciers and Climate Change. Taylor and Francis (CRC Press),* DOI: https://doi.org/10.1201/9781003284413.

Singh A. K., Parkash B., Mohindra R., Thomas J. V., Singhvi A. K. (2001) Quaternary alluvial fan sedimentation in the Dehradun Valley piggyback basin, NW Himalaya: Tectonic and palaeoclimatic implications. *Basin Research* 13:449–471. DOI: https://doi.org/10.1046/j.0950-091x.2001.00160.x.

Singh D. S. (2007) Flood mitigation in the Ganga Plain. *In: Rai N., Singh A. K. (eds) Disaster Management in India. New Royal Book Company, India,* 167–179.

Singh D. S., Awasthi A. (2011a) Implication of drainage basin parameters of Chhoti Gandak River, Ganga Plain, India. *Journal of the Geological Society of India* 78:370–378. DOI: https://doi.org/10.1007/s12594-011-0102-8.

——— (2011b) Natural hazards in the Ghaghara River area, Ganga Plain, India. *Natural Hazards* 57:213–225. DOI: https://doi.org/10.1007/s11069-010-9605-7.

Singh D. S., Awasthi A., Bhardwaj V. (2009) Control of tectonics and climate on Chhoti Gandak River Basin, East Ganga Plain, India. *Himalayan Geology* 30 (2): 147–154. https://www.himgeology.com/volume_abstract.php?abstract=299

Singh D. S., Awasthi A., Nishat. (2010) Impact of climate change on the rivers of Ganga Plain. *International Journal of Rural Development and Management Studies* 4 (1): 1–8. https://www.geosocindia.org/index.php/jgsi/article/view/58361

Singh D. S., Dubey C. A., Kumar D., Vishawakarma B., Singh A. K., Tripathi A., Gautam P. K., Bali R., Agarwal K. K., Sharma R. (2019) Monsoon variability and major climatic events between 25 and 0.05 ka BP using sedimentary parameters in the Gangotri Glacier region, Garhwal Himalaya, India. *Quaternary International* 507:148–155. DOI: https://doi.org/10.1016/j.quaint.2019.02.018.

Singh D. S., Singh I. B. (2005) Facies architecture of the Gandak Megafan, Ganga Plain, India. *Special Publication of the Palaeontological Society of India* 2:125–140.

Singh D. S., Tiwari A. K., Gautam P. K. (2018) The Burhi Gandak: Most sinuous river. *In: Singh D. (ed) The Indian Rivers. Springer Hydrogeology, Springer, Singapore* 2:209–219. DOI: https://doi.org/10.1007/978-981-10-2984-4˙17.

Singh I. B. (1996) Geological evolution of Ganga Plain—an overview. *Journal of the Paleontological Society of India* 41:99–137. https://www.palaeontologicalsociety.in/vol41/v13.pdf

——— (2004) Late Quaternary history of the Ganga Plain. *Journal of the Geological Society of India* 64:431–454. https://www.geosocindia.org/index.php/jgsi/article/view/82863

Singh I. B., Bajpai V. N. (1989) Significance of syndepositional tectonics in facies development, Gangetic alluvium near Kanpur, Uttar Pradesh, India. *Journal of the Geological Society of India* 34:61–66. https://www.geosocindia.org/index.php/jgsi/article/view/66700

Singh I. B., Rajagopalan G., Agarwal K. K., Srivastava P., Sharma M., Sharma S. (1997) Evidence of Middle to Late Holocene neotectonic activity in the Ganga Plain. *Current Science* 73 (12): 1114–1117. https://www.jstor.org/stable/24101272

Singh I. B., Srivastava P., Sharma S., Sharma M., Singh S., Rajagopalan G., Shukla U. K. (1999) Upland interfluve (doab) deposition: Alternative model to muddy overbank deposits. *Facies* 40:197–210. DOI: https://doi.org/10.1007/BF02537474.

Singh V., Tandon S. K. (2007) Evidence and consequences of tilting of two alluvial fans in the Pinjaur Dun, Northwestern Himalayan foothills. *Quaternary International* 59 (1): 21–31. DOI: https://doi.org/10.1016/j.quaint.2006.08.017.

Sinha R., Bhattacharjee P. S., Sangode S. J., Gibling M. R., Tandon S. K., Jain M., Godfrey-Smith D. (2007) Valley and interfluve sediments in the Southern Ganga Plains, India: Exploring facies and magnetic signatures. *Sedimentary Geology* 201:386–411. DOI: https://doi.org/10.1016/j.sedgeo.2007.07.004.

Sinha R., Sripriyanka K., Jain V., Mukul M. (2014) Avulsion threshold and planform dynamics of the Kosi River in north Bihar (India) and Nepal: A GIS framework. *Geomorphology* 216:157–170. DOI: https://doi.org/10.1016/j.geomorph.2014.03.035.

Sinha R., Tandon S. K., Sanyal P., Gibling M. R., Stuben D., Berner Z., Ghazanfari P. (2006) Calcretes from a Late Quaternary interfluve in the Ganga Plains, India: Carbonate types and isotopic systems in a monsoonal setting. *Palaeogeography, Palaeoclimatology, Palaeoecology* 242 (3–4): 214–239. DOI: https://doi.org/10.1016/j.palaeo.2006.05.015.

Srivastava P., Parkash B., Sehgal J. L., Kumar S. (1994) Role of neotectonics and climate in development of the Holocene geomorphology and soils of the Gangetic Plains between the Ramganga and Rapti Rivers. *Sedimentary Geology* 94:129–151. DOI: https://doi.org/10.1016/0037-0738(94)90151-1.

Srivastava P., Rajak M. K., Sinha R., Pal D. K., Bhattacharyya T. (2010) A high-resolution micromorphological record of the Late Quaternary paleosols from Ganga–Yamuna interfluve: stratigraphic and paleoclimatic implications. *Quaternary International* 227 (2): 127–142. DOI: https://doi.org/10.1016/j.quaint.2010.02.019.

Srivastava P., Sharma M., Singhvi A. K. (2003a) Luminescence chronology of incision and channel pattern changes in the River Ganga, India. *Geomorphology* 51:259–268. DOI: https://doi.org/10.1016/S0169-555X(02)00223-4.

Srivastava P., Singh I. B., Sharma S., Shukla U. K., Singhvi A. K. (2003b) Late Pleistocene–Holocene hydrologic changes in the interfluve areas of the central Ganga Plain, India. *Geomorphology* 54:279–292. DOI: https://doi.org/10.1016/S0169-555X(02)00361-6.

Teichert C. (1958) Concept of facies. *Bulletin of the American Association of Petroleum Geologists* 42:2718–2744. DOI: https://doi.org/10.1306/0BDA5C0C-16BD-11D7-8645-000102C1865D.

Trexler J. H., Cashman P. H. (1990) Computer assisted palaeocurrent determination from trough cross-stratification. *Computers and Geosciences* 16:253–261. DOI: https://doi.org/10.1016/0098-3004(90)90133-E.

Walker R. G. (1976) Facies models 1. General introduction. *Geoscience Canada* 3 (1): 21–24. https://id.erudit.org/iderudit/geocan03_01art03

Walker R. G., Cant D. J. (1984) Sandy fluvial systems. *In: Walker R. G. (ed) Facies Models, 2nd edn. Geological Association of Canada, Newfoundland,* 71–90. https://journals.lib.unb.ca/index.php/GC/article/view/1141

Yadav S. K., Kanhaiya S., Singh S., Quasim M. A., Singh S. K., Kumar P. (2023) Facies architecture and textural attributes of the Late Quaternary cliff embankment sections of the Sai River, Central Ganga Plain, India. *Geosystems and Geoenvironment* 2 (4) DOI: https://doi.org/10.1016/j.geogeo.2023.100216.