Textural Attributes and Lithofacies Analysis of Quaternary Geomorphic Surfaces in Middle Ganga Plain, India

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Abstract

Geomorphic surfaces of the Ganga plain are depositional surfaces, and the succession of sediment deposited on their top is younger than the time of the formation of the relevant surface. The relative timing of their deposition is recognized based on their morphological interrelationship and order of superposition.

In the middle Ganga plain, three geomorphic surfaces are well-developed. The oldest geomorphic surface (T_2), formed by sheet flow processes during monsoon season, consists of silt, sandy silt, and silty sand. Sediments are poorly to very poorly sorted, very fine skewed to fine skewed, and kurtosis ranges from leptokurtic to platykurtic. The Ganga River is incised into the T_1 surface up to 4–8 m in the study area; T_1, also known as the river valley terrace, is incised into the T_2 surface exposing cliffs of 8 to 20 m heights. T_1 surface representing older sediments of active channels is characterized by rippled and cross-bedded silt, sand, and lensoid units of silty mud. Mean grain size ranges from very fine sand to medium silt; sediments are poorly to moderately sorted, Skewness ranges from very fine skewed to fine skewed, and kurtosis ranges from very leptokurtic, leptokurtic, and mesokurtic. The T_0 surface is the youngest geomorphic surface of the Ganga basin representing river channels and their associated flood plains. The Ganga River shows varied channel patterns, from meandering to braided and straight channels. Channels carry medium sand to very fine silt; sorting is very poorly to poorly sorted, Skewness is very fine skewed to fine skewed, and kurtosis ranges from leptokurtic, mesokurtic, and platykurtic.

1. Introduction

The Ganga plain's geomorphic surfaces are depositional surfaces with sediment deposited on top that is more recent. The relative timing of their deposition is recognized based on their morphological interrelationship and order of superposition. In the Ganga plain, six geomorphic (Fig. 1 (B)) surfaces have been identified; these are marginal plain upland surface (MP), Piedmont fan surface (PF), Upland terrace surface (T_2), valley terrace surface (T_1) Megafan surface (F), river and active flood plain surface (T_0) (Singh, 1996; Singh, 1999; Shukla et al., 2001; Shukla and Bora 2003)

MP is located south of the axial river Ganga. It comprises sediments derived from Peninsular craton (Singh, 1999; Shukla et al., 2001). T-2 is considered time equivalent to MP surface (Singh, 1999; Srivastava et al., 2003). The upland terrace surface of the Ganga basin is a flat surface with a gentle slope (5–10 cm/km). This surface is often designated as Older alluvium (Varanasi Older alluvium) or Banger (Singh, 1999; Srivastava et al., 2003). Megafan surface resting over the oldest T_2 surface is mainly sandy and represents sedimentation under higher sediment–water discharge conditions (Singh, 1999; Shukla et al., 2001). The surface developed adjacent to the Himalayan front all along its length from east to west (Singh, 1999; Srivastava et al., 2003). PF overlaps the megafan surface and is gravely in nature. T_1 surface developed within the broad river valleys, entrenched in T_2, MP, and MF surfaces (Singh, 1999; Shukla et al., 2001). T_1 surfaces are believed to be formed under high rainfall and sediment input compared to modern times (Singh, 1996). T_0 surfaces are the youngest geomorphic surface of the Ganga basin (Singh, 1999; Srivastava et al., 2003). The river shows varied channel patterns ranging from meandering to braided and straight reaches in different basin parts.

The grain size analyses are generally based on sediment size distribution, i.e., mean (Phi), sorting, Skewness, and kurtosis. The sediment's mean size indicates the water or current force that can cause the sediments to move. It suggests the transportation dynamic system's general proficiency (Singh et al., 2007; Flemming, 2007). The sorting of sediments depends on the sediments' size, strength, and variation in the energy condition of the depositing agent (Folk and Ward, 1957). Poorly sorting in sediments indicates variable current velocities and turbulence during deposition, while good sorting indicates steady currents (Amaral and Pryor, 1977). Skewness gives the degree of symmetry of the sediment distribution. Sediments that are favorably skewed (towards the negative phi values) are those that are weighted towards the coarse end-member. Members are considered to be negatively skewed (towards the positive phi values) at the fine end. The variable energy conditions of the sedimentary deposition settings cause variation in the sign of Skewness (Friedman, 1967). According to Friedman (1979), the river sediments are typically positively skewed. The river's one-way flow causes positive Skewness because it chops off the coarse end of the size frequency curve. (Valia and Cameron, 1977). Negatively skewed sediments are due to higher energy depositional environments and are subject to transportation for a long time or velocity variation (Sahu, 1964). Kurtosis is the measure of how peaked the grain size frequency curve is (Folk and Ward, 1957). Leptokurtic and platykurtic, respectively, are terms used to describe frequency curves that have higher peaks than typical distribution curves (Folk and Ward, 1957).

The Indo-Gangetic Plain has obtained considerable interest from many earth scientists for the last three decades. Several works have been done in the Ganga plain in context of Sedimentological, Geomorphological, Chronological, neo-tectonic and channel migration (Oldham, 1917; Singh, 1996, Agarwal et al., 2002; Srivastava et al., 2003; Singh, 2004; Sinha et al., 2005; Singh et al., 2009; Shukla et al., 2012; Shukla 2013; Prakash et al., 2016; Sinha et al., 2017; Varma et al., 2017; Ghosh et al., 2017). The works in the Ganga plain are helpful in linking these Quaternary sediments from an environmental perspective for predicting future changes and also in the circumstances with the evolution of Himalaya, which resulted from the continent-continent collision of the Indian plate to Eurasian plate (Pilgrim, 1919; Philip et al., 1991; Singh, 2004; Shukla 2013; Prakash et al., 2016; Sinha et al., 2017). Thus, studying the Ganga plain and its Quaternary sedimentological history has become significant. But till now, only limited and sporadic sedimentological studies are available. The Banger surface may have depositional terraces, according to Mukherji (1963), who also examined how the formation of these terraces was influenced by climate and sea level variations. Pathak (1966) distinguished the Bhabar Belt, Terai Belt, Central Alluvial Plain, and Marginal Alluvial Plain as the four geomorphic components of the Ganga Plain. The regional upland surface was Varanasi older alluvium, Banda older alluvium, and the Piedmont fan deposits Bhat alluvium by Joshi and Bhartiya (1991); Khan et al. (1988). The Ganga Plain has also been the reports the tectonic and neotectonic activity (Singh and Rastogi, 1973; Mohindra and Parkash, 1994; Misra et al.,1994; Singh, 1999; Agarwal et al., 2002; Singh et al., 2009; Prakash et al., 2016). According to Agarwal et al. (2002), the pattern of neotectonic activity varies from Himalayan Orogen (compressional regime) toward the craton margin (extensional regime). Because of the craton, the peripheral bulge developed deformational features like extensional normal faults. Sinha et al. (2006) recognized a connection between the growth of calcrete and monsoonal precipitation in the Ganga plain's interfluves region. The Ganga River's shift and its impact on the hydrogeological potential of the Varanasi region were investigated by Shukla and Raju in 2008. Shukla et al. (2012) studied a 750 m-long Ramnagar cliff part that was exposed on the Ganga River's right bank close to Varanasi. Kanhaiya et al. (2017) have reported different grain-size variations and facies types in the floodplain of the Ganga River between Kanpur and Tanda (Chandauli). Sinha et at. (2017) suggest that the Ganga basin geomorphic framework can help develop a sustainable river management program, habitat suitability, environmental flows, and flood risk. Lithofacies and Textural analysis of the geomorphic surfaces (T_2, T_1, and T_0) have mainly been ignored.

Geomorphic elements have been studied based on lithofacies and grain size characters in the central Ganga Plain between Allahabad and Buxar. The studied geomorphic elements are active channel (T_0 surfaces), river valley traces/ younger terrace (T_1 surfaces), and older terrace/ Upland terrace surface (T_2 surface). The Ganga River flows from Chunar to Saidpur, exposing 10 to 15 m high cliffs of T_2 and T_1 surfaces, providing an opportunity to characterize them sedimentologically. Sedimentological documentation of geomorphic units has also been done to understand the geological-geomorphological evolution of the area.

2. Geological setting

The study area forms the Ganga river valley (GRV) sector III of M. Singh et al. (2007). In this sector, the Ganga River flows to SE and then turns to NE, flowing against the general slope of the Ganga Plain. From Allahabad to Chunar, the river flows in the SE direction, and after that, the river takes an acute turn and flows towards NE from Chunar to Buxar. Distorted menders, huge point bars, Islands, and narrow flood plains are observed within this river's reach. From Mirzapur to Chunar, the river flows along the Ganga Plain's southern peripheral bulge (Vindhyan Super Group). Sediment samples were collected from the older terrace (T_2), younger terrace (T_1), and present-day stream channel (T_0) along the Ganga River bank between Allahabad and Buxar. Location of the studied sections of T_2, T_1, and T_0 geomorphic elements in Fig. 1(C).

3. Methods

Sediment samples were taken in areas of exposed cliffs near the active channel. Polyethylene bags were used to collect the samples. Before the textural examination, all collected sediment samples were dried in a hot air oven at 50°C. To remove organic matter, 15% H_2O_2 was applied to the samples. To remove the extra moisture in the samples, the samples were heated up to 70^{o}C until the sparkle disappeared. For grain size analysis, the treated samples have been used. Total 203 {90 (T_2), 56 (T_1), 57(T_0)} samples are collected and analyzed for grain size. Particle size distributions were measured with a Malvern Laser

Particle Size Analyzer Mastersizer 2000 with a stirring speed of 2500 rpm and a measurement time of 25 seconds. All samples were ultrasonicated for 10 seconds to break up any aggregation of particles. Each sample was run three times to check the analysis's consistency. The Mean of each set of results was taken to textural analysis for each sample. Grain size analyses were conducted in the Department of Geology, Banaras Hindu University, Varanasi.

Grain-size data obtained from Malvern Mastersizer 2000 were used to determine grain-size parameters using GRADISTAT software (Blott and Pye, 2001). The present work uses the logarithmic Folk & Ward method (based on a log-normal distribution with ϕ size) and calculated mean grain size (Mz), standard deviation (SD), Skewness (SK), kurtosis (KG).

Bivariate plots of Mean versus sorting have been constructed. These plots are useful in understanding the geological implication of the textural parameters concerning the energy of transporting and depositing medium and the deposition conditions (Folk & Ward, 1957; Stewart, 1958; Tanner, 1991).

Sedimentary lithofacies were identified using sedimentological observation in the field and substantiated using sand-silt-clay ratios following subdivisions in the ternary diagram proposed by Blott and Pye (2012). Similar approaches to lithofacies classification have been used in the earlier workers (Friedman, 1967; Miall, 1996; Friend et al., 1986; Martinius, 2000).

4. Sediment facies of T2, T1, and T0

Three geomorphic surfaces, namely T_2, T_1, and T_0 are prominently developed within the study area.

4.1. T-2 Surface

The most prominent surface occurring south of the axial river Ganga is the Doab or interfluve surface. It characterizes highland areas of the older alluvium making the Upland Terrace Surface known as the T_2 surface. T_2 surface in Varanasi is also known as Varanasi Older Alluvium or Bhangar (Singh et al. 1999). On the surface, Upland interfluves exhibit various river channels, abandoned channel belts, and micro-geomorphologic features such as ponds and lakes. The river channels are mostly incised on this surface. T_2 surface is away from the reach of recurring floods by overtopping the river channels. Four sections of T_2 surfaces, namely the Shartri bridge section (Allahabad), Ram-Gaya Ghat section (Mirzapur), Nar Ghat section (Mirzapur), and Narbatpur section (Buxar), have been studied for lithofacies and grain size analyses.

4.1.1. Grain size parameters and sedimentary facies (based on Blott and Pye (2012) classification)

All the samples from all the studied sections were plotted on the Blott and Pye (2012) diagram to deduce grain-sized based facies constitution of the T-2 surface as a whole. The distribution of the sediments in the ternary diagram of Sand–The silt–Clay plot after Blott and Pye (2012) (Fig. 2) indicates that T-2 sediments fall well within the Slightly sandy-slightly clayey-silt, Slightly clay-sandy-silt, Very slightly clay-silty-sand, Very slightly sandy-slightly clayey-Silt (Fig. 3). The mean grain size of the T-2 surfaces lies between very coarse to medium silt (Table-1 and Fig. 4). Sorting of T-2 surface sediments varies from very poorly to poorly sorted. The Skewness of the T-2 surface sediments ranges from very fine skewed to fine skewed. Kurtosis of T-2 surface sediments varies from leptokurtic to platykurtic (Table-1 and Fig. 4).

4.1.1.1. Very slightly clay- silty- sand

Very slightly clay-silty-sand occurs only in the Jushi (Allahabad) section. These facies contains 49.58–53.73% sand, silt 42.71–45.84%, and clay3.55-4.56%. Very slightly clay-silty-sand facies locally constitute 5.2% of the entire T-2 surface. These facies are poorly sorted with very fine to fine Skewness and leptokurtic grain-size distribution.

4.1.1.2. Slightly clay-sandy-silt

Slightly clay-sandy-silt facies constitutes 31.57% of the sedimentary succession in the T-2 surface. These facies occurs in Jushi, Ramgya Ghat, Nar Ghat, and Buxar. This facies contains 21.2–39.8% sand, silt 53.1–69.3%, and clay 5.31–9.5%. Sediments are very poorly to poorly sorted with very fine skewed and mesokurtic to very leptokurtic grain-size distribution.

4.1.1.3. Slightly sandy-slightly clayey- silt

This facies contains 21.2–39.8% sand, silt 53.1–69.3%, and clay 5.31–9.5%. Slightly sandy-slightly clayey-silt facies constitute 58.03% of the spectrum. These samples are very poorly to poorly sorted with fine skewed and platykurtic to mesokurtic grain-size distribution.

4.1.1.4. Very slightly sandy- slightly clay- Silt

Very slightly sandy- slightly clay- Silt facies form 5.2% of the succession in the T-2 surface deposit. This facies contains 3.72–4.78% sand, silt 84.16–87.22%, and clay 7.02-11.0%. Samples are poorly sorted, fine skewed, and leptokurtic grain-size distribution.

4.1.2. Lithofacies

Field-based characters, grain size parameters, and the probable deposition environment of identified lithofacies are summarized in a tabular form in Table 2.

4.2. T-1 Geomorphic Surface

The T-1 geomorphic surface is developed within the Ganga River valley, which is entrenched into the T-2 surface. T-1 surface is believed to have undergone the conditions of high rainfall and sediment input compared to modern times (Singh et al. 1999). In the present study, two sections of the T-1 surface investigated are the HRI section (Allahabad) and Hanuman Ghat (Ramnagar Varanasi).

4.2.1. Grain size parameters and sedimentary facies (based on Blott and Pye (2012) classification) of T-1 surface

All the samples from all the studied sections were plotted on the Blott and Pye (2012) diagram to deduce grain-sized based facies constitution of the T-1 surface as a whole. The distribution of the sediments in the ternary diagram of Sand–Silt–Clay after Blott and Pye (2012) is shown in Fig. 2. In the ternary diagram, T-1 sediments fall well within the Very slightly clayey-silty-sand, Silty clayey-sandy-silt, Slightly sandy-slightly clayey-silt, Very slightly clayey-silty-sand, Slightly silty-sand (Fig. 2 and Fig. 3). So grain size based lithofacies are highly varied in the T-1 surface.T-1surface varies from very fine sand to medium silt (Table-1, Fig. 4(B)). T-1 surface sediments vary from poorly to moderately sorted (Table-1, Fig. 4(B)). The Skewness of the T-0 surface sediments ranges from very fine skewed to fine skewed. Kurtosis of Sediments of T-1 surface ranges from very leptokurtic to mesokurtic (Table-1, Fig. 4(B)).

4.2.1.1. Very slightly clayey- silty-sand

Very slightly clayey- silty-sand facies constitutes 21.24% of the sedimentary succession in the T-1 surface. This facies occurs in HRI (Allahabad) and Hanuman Ghat (Varanasi) sections. This facies contains 49.9–55.6% sand, silt 41.4–45.6%, and clay 3.00-4.5%. Sediments are poorly sorted with very fine skewed and very leptokurtic to leptokurtic grain-size distribution.

4.2.1.2. Silty clayey- sandy-silt

Silty clayey- sandy-silt facies form 21.24% of the succession in the T-1 surface deposit. This facies contains 27.00-38.5% sand, silt 49.8–65.3%, and clay 6.11–7.7%. Samples are very poorly sorted, fine skewed, and leptokurtic grain-size distribution.

4.2.1.3. Slightly sandy- slightly clayey- silt

Slightly sandy- slightly clayey-silt facies constitutes 42.85% of the sedimentary succession in the T-1 surface. This facies occurs in HRI (Allahabad) and Hanuman Ghat (Varanasi). This facies contains 9.4–20% sand, silt 70.3–78.2%, and clay 7.2–13.2%. Sediments are poorly sorted with fine skewed and mesokurtic to leptokurtic grain-size distribution.

4.2.1.4. Slightly silty-sand

Slightly silty-sand facies occurs only in the HRI (Allahabad) section. These facies contains 79.19–80.63% sand, silt 19.25–19.62%, and clay 00-1.5%. Slightly silty-sand facies locally constitutes 7.14% of the entire facies recorded in the T-1 surface. These facies are moderately sorted with symmetrically fine Skewness and mesokurtic to leptokurtic grain-size distribution.

4.2.1.5. Very slightly clayey-silty-sand

Very slightly clayey-silty-sand facies locally constitutes 7.14% of the entire facies recorded in the T-1 surface. Slightly clayey-silty-sand facies occur in the HRI (Allahabad) section. These facies contains 77.12–80.64% sand, silt 16.38–19.83%, and clay 2.97–3.03%. These facies sediments are poorly sorted with fine Skewness and very leptokurtic grain-size distribution.

4.2.2. Lithofacies of T-1 surface

T-1 surface is 4–8 m above the present river channel. Remote sensing images show meander scars on the T-1 surface. Field-based characters, grain size parameters, and the probable deposition environment of identified lithofacies are summarized in a tabular form in Table 3.

Table.1. Sedimentary facies (based on Blott and Pye (2012) classification) and textural parameters of the T-2, T-1, and T-0 surface along the Ganga River, middle Ganga plain, India.

Sedimentary facies	Mean (phi)	Sorting (phi)	Skewness	Kurtosis	Sand %	Silt %	Clay%
T-2 Surface							
Very Slightly clay-silty-sand	4.38-5.42	1.74-1.85	0.38-0.4	1.16-1.28	49.58-53.73	42.71-45.84	3.55-4.56
Slightly clay-sandy-silt	5.56-4.93	1.82-2.48	0.32-0.46	0.97-1.37	21.2-39.8	53.1-69.3	5.31-9.5
Slightly sandy-slightly clayey-silt	5.59-6.73	1.84-2.12	0.17-0.38	0.79-1.26	6.3-17.1	75.12-82.23	7.9-13.1
Very slightly sandy-slightly clayey-silt	5.34-6.38	1.69-1.80	0.27-0.28	1.11-1.22	3.72-4.78	84.16-87.22	7.02-11.05
T-1 Surface							
Very Slightly clay-silty-sand	3.8-4.21	1.54-1.71	0.12-0.33	1.22-1.57	49.9-55.6	41.4-45.6	3.00-4.5
Slightly clay-sandy-silt	4.67-5.38	2.01-2.17	0.25-0.34	1.02-1.33	27.00-38.5	49.8-65.3	6.11-7.7
Slightly sandy-slightly clayey-silt	5.45-6.51	1.85-2.06	0.14-0.38	0.94-1.22	9.4-20	70.3-78.2	7.2-13.2
Slightly silty- sand	2.27-3.30	0.76-0.94	0.08-0.13	1.08-1.18	79.19-80.63	19.25-19.62	00-1.5
Very slightly clayey-slightly silty- sand	2.15-3.21	1.71-1.93	0.31-0.34	1.74-1.84	77.12-80.64	16.38-19.83	2.97-3.03
T-0 Surface							
Very Slightly clay-silty-sand	3.76-4.56	1.16-2.44	0.33-0.37	1.06-1.58	50.2-64.7	32.7-42.3	2.6-7.5
Slightly clay-sandy-silt	4.69-5.37	1.97-2.19	0.28-0.36	1.12-1.20	23.4-42.3	51.2-68.5	6-8.1
Very slightly clayey-slightly silty- sand	2.88-4.83	1.02-1.94	0.30-0.53	1.24-1.74	76.7-89.3	8.4-19.5	1.7-3.8
Very Slightly silty- sand	0.97-1.09	1.09-1.14	0.26-0.28	1.10-1.12	97.59-97.92	2.07-2.40	0
Slightly clayey–silty-sand	3.62-4.63	1.89-2.00	0.27-0.38	1.13-1.24	40.40-43.55	50.16-55.31	5.25-6.28
Clayey silt	7.25-8.26	1.27-1.37	0.19-0.30	0.67-78	00	65.26-70.33	29.66-35.73

Table.2. Summary of the lithofacies analysis of T-2 surface.

Lithofacies	Characteristic	Depositional environment
Rippled silt	1-1.5 m thick, Ripple-parallel laminated, Minute calcrete nodules. Grain size distribution shows, Mean, 5.88 phi; Skewness, 0.31; Sorting, 1.91; Kurtosis, 0.99.	Small channel (Carling, 1996; Singh et al., 1999)
Silt	0.8-4.2 m thick, sheet like, burrowing activity, calcrete nodules. Grain size distribution shows, Mean, 5.84-6.36 phi; Skewness, 0.17-0.28; Sorting, 1.79-2.01; Kurtosis, 1.11- 1.28.	Dominant process of sedimentation is the sheet flow during monsoon rains (Kumar et al., 1995; Singh et al., 1999).
Bedded Calcrete	Make 0.15-0.60 thick bands of calcrete, interlayer with silty sediments, channelized. Grain size distribution shows, Mean, 5.77 phi; Skewness, 0.28; Sorting, 1.8; Kurtosis, 1.11.	Calcretized gully deposits (Machette, 1985; Singh et al., 1999)
Sandy silt	0.6-2.5 m thick, calcrete nodules, bioturbation, plant remains, basal contact is distinctly sharp, emphasizing the channelized character. Grain size distribution shows, Mean, 4.8-6.01phi; Skewness, 0.28-0.46; Sorting, 1.8 -2.09; Kurtosis, 1.06-1.37.	Deposits of small gullys (Singh et al., 1999; Nichols and Fisher, 2007)
Mottled silt	Occurs as 0.8-2.5 m thick sheet-like or lensoid units. Mottling is common, Containing abundant calcrete nodules. Grain size distribution shows, Mean, 5.79-6.18 phi; Skewness, 0.25-0.38; Sorting, 1.83-2.04; Kurtosis, 0.87-1.27.	It represents sheet flow deposits (Mack and James, 1994; Kumar et al., 1995)
Ferruginous nodules and calcrete bearing silt	3.5 m thick, calcrete and ferruginous nodules, absent of primary structure. Grain size distribution shows, Mean, 6.3 phi; Skewness, 0.29; Sorting, 2.05; Kurtosis, 0.88.	It represents sheet flow deposits (Kumar et al., 1995; Singh et al., 1999)

Table 3
Summary of the lithofacies analysis of T-1 surface.

Lithofacies	Characteristic	Depositional environment
Cross bedded sand	1m thick micaceous sand, animal and plant traces, calcrete nodules. Grain size distribution shows, Mean, 3.18 phi; Skewness, 0.32; Sorting, 1.74; Kurtosis, 1.93.	Sediment deposition in high energy sinuous channels under lower flow regime fluctuating energy condition (Allen, 1982; Ashley, 1990)
Laminated sand	0.8 to 1 m thick micaceous sand, animal and plant traces. Grain size distribution shows, Mean, 3.28; Skewness, 0.1; Sorting, 0.08–0.94; Kurtosis, 1.48.	Deposition in channels under lower flow regime (Kraus and Aslan, 1993; Shukal et al. 2012)
Silt	Common lithofacies developed in T-1 surfaces. 0.5-1 m thick, calcrete nodules ranges from mm to 12 cm in size, animal burrows and plant remains common. Grain size distribution shows, Mean, 4.67–6.51 phi; Skewness, 0.14–0.38; Sorting,1.87–2.17; Kurtosis, 0.97–2.05.	Abandoned channel fill deposits viewing vegetation and animal activity (Kraus and Gwinn,1997; Shukla et al. 2009)
Clayey silt	0.5–0.8 m thick, minute, sheet like, calcrete nodules, plant remains common. Grain size distribution shows, Mean, 4.21 phi ; Skewness, 0.33; Sorting, 1.71; Kurtosis,1.47.	Deposited in low lying over bank areas by suspension fall out (Farrel, 1987; Citterio and Gay, 2009)
Sandy silt	0.6–1.3 m thick, disseminated calcrete, root traces. Grain size distribution shows, Mean, 5.45–5.71; Skewness, 0.33; Sorting, 1.85–2.06; Kurtosis, 0.98–1.15.	Deposition in channels (point bars and flood bank) (Singh et al., 1999; Nichols and Fisher, 2007)
Silty sand	1–4.2 m thick, Light grey coloured sand, calcrete nodules, root traces, animal burrow. Grain size distribution shows, Mean, 3.83–4.04; Skewness, 0.12–0.26; Sorting, 1.22–1.57; Kurtosis: 1.54–1.69.	Deposition in channels (point bars and flood bank) (Singh et al., 1999; Nichols and Fisher, 2007)

Table.4. Summary of the lithofacies analysis of T-0 surface.

	Lithofacies	Characteristic	Depositional environment
Sand bar lithofacies	Rippled fine sand	1.5 -2 m thick, ripple-cross lamination, root traces, bioturbation. Grain size distribution shows, Mean, 2.5-2.6 phi; Skewness, 0.39-0.41; Sorting, 1.53-1.56; Kurtosis, 1.56-1.58.	Deposition in wide shallow ephemeral channels under lower flow regime condition (Rygel et al. 2004; Shukla et al 2006)
	Rippled and cross-bedded sand	0.5- 1 m thick, root traces. Grain size distribution shows, Mean, 4.5-4.8 phi; Skewness, 0.36-0.38; Sorting, 2.43-2.49; Kurtosis, 0.97-1.06.	Deposition in channels under fluctuating energy forming both 2D and 3D bedforms (Kraus and Aslan, 1993; Nichols and Fisher, 2007)
	Rippled and burrowed sand and silt	0.4 -4 m thick, laminated, root traces Grain size distribution shows, Mean,3.25-3.28; Skewness, 0.52-0.53; Sorting, 1.93-1.95; Kurtosis, 1.62-1.64.	Migration of bed form in the channel (Rygel et al. 2004; Shukla et al 2006)
Over-bank lithofacies	Silty clay	0.6-1.2 m thick, laminated, bioturbation Grain size distribution shows, Mean, 5.8; Skewness, 0.59; Sorting, 1.45; Kurtosis, 1.31.	Flood plain- crevasse deposits (Shukla et al 2004; Shukla et al. 2012)
	Mud	Thickness of the beds laterally varying between 10 and 30 cm, light grey to whitish grey, desiccation cracks. Grain size distribution shows, Mean, 8.25; Skewness, 0.29; Sorting, 1.26; Kurtosis, 0.77.	Low lying flood plain deposits (Kraus and Gwinn, 1997; Citterio and Gay, 2009)

4.3. T-0 Geomorphic Surface

The T-0 is the youngest geomorphic surface of the Ganga plain. The Ganga River shows varied channel patterns ranging from meandering to braided in different parts of the study area. In T-0 surface sand-bar deposits, channel and over-bank deposits have been studied.

4.3.1. Grain size parameters and sedimentary facies (based on Blott and Pye (2012**) classification) of T-0 surface**

The distribution of the sediments in ternary diagram of Sand–Silt–Clay after Blott and Pye (2012) in which T-0 sediments fall well within the Very slightly clayey-silty-sand, Slightly clayey-sandy-silt, Very slightly clayey-slightly silty-sand, Very slightly silty-sand, Slightly clayey-silty-sand, Clayey-silt (Fig. 2 and Fig. 3). T-0 surface varies from very fine sand to coarse silt (Table-1, Fig. 4(C-D)). T-0 surface sediments vary from very poorly to poorly sorted. The Skewness of the T-0 surface sediments ranges from very fine skewed to fine skewed. Kurtosis of Sediments of T-0 surface ranges from very leptokurtic to mesokurtic (Table-1, Fig. 4(C-D)).

4.3.1.1. Very slightly clayey- silty- sand

Very slightly clayey- silty-sand facies constitutes 15.38% of the overall facies spectrum of T-0 surface. Sediments are represented very poorly to poorly sorted, with very fine to fine skewed and mesokurtic to leptokurtic grain-size distribution. This facies contains 50.2–64.7% sand, silt 32.7–42.3%, and clay 2.6–7.5%.

4.3.1.2. Slightly clayey-sandy-silt

Slightly clayey-sandy-silt facies form 30.76% of the succession in the T-0 surface deposits. It comprises 23.4–42.3% sand, 51.2–68.5% silt, and 6-8.1% clay. Samples that are very poorly to poorly sorted with a very fine skewed and vary leptokurtic to leptokurtic grain size distribution.

4.3.1.3. Very slightly clayey-slightly silty-sand

Very slightly clayey-slightly silty-sand facies comprises 76.7–89.3% sand, 8.4–19.5% silt, and 1.7–3.8% clay. These facies constitutes 30.76% of the entire facies recorded in the sedimentary succession of the T-0 surface. Samples of this unit show poorly sorted, very fine skewed, and very leptokurtic to leptokurtic grain-size distribution.

4.3.1.4. Very slightly silty-sand

Very slightly silty-sand facies locally constitutes 7.69% of the sedimentary deposit in the T-0 surface. It comprises 97.59–97.92% sand, 2.07–2.40% silt, and 0% clay. This unit consists of poorly sorted, fine-skewed, and leptokurtic grain-size distribution.

4.3.1.5. Slightly clayey- silty- sand

These facies contains 40.40-43.55% sand, silt 50.16–55.31%, and clay 5.25–6.28%. Slightly clayey-silty-sand facies locally constitutes 7.69% of the entire facies recorded in the T-0 surface. These facies sediments are poorly sorted with very fine to fine Skewness and leptokurtic grain-size distribution.

4.3.1.6. Clayey- silt

Clayey-silt facies constitutes 7.69% of the sedimentary succession in the T-0 surface. This facies occurs in bypass bridge (Varanasi) sections. This facies contains 0% sand, silt 65.26–70.33%, and clay 29.66–35.73%. Sediments are poorly sorted with fine skewed and platykurtic grain-size distribution.

4.3.2. Lithofacies of T-0 surface

Based on field characters and grain-size parameters, lithofacies are summarized in tabular form in Table 4.

5. Bivariate plots

Bivariate plots show the relationship between textural parameters for the geomorphic surface sediments of the Ganga plane. Relationship between the textural parameters of the grain size used as environmental indicators by various workers (Mason and Folk, 1958; Sahu, 1964; Doeglas, 1968; Solohub and Klovan, 1970; Buller and McManus, 1972; Valia and Cameron, 1977; Goldbery, 1980; Kanhaiya, 2017). Sediments' mean size and sorting are controlled by the energy of the environment and the degree of sediment processing (Griffiths, 1967; Tanner, 1991; Long et al., 1996; Lario et al., 2000; Nag et al., 2016).

5.1. Stewart bivariate plot

Stewart (1958) proposed a bivariate plot of mean grain size and sorting showing different zone of the depositional environments such as beach, river, quiet water, and inner self. In the present study, sediments mean grain size (T-2, T-1, and T-0) was plotted against sorting values (T-2, T-1, and T-0) (Fig. 6(A)). It shows that most samples fall well within the quiet water condition.

5.2. Tanner bivariate plot

Textural parameters (Mean and Sorting) of Sediments (T-2, T-1, and T-0) plotted in the Tanner (1991) bivariate plot. It shows that all the sediments (T-2, T-1, and T-0) fall well within the fluvial and stream episode zone. Tanner (1991) plot further suggested that fluvial processes were responsible for sediment deposition (Fig. 6(B)).

6. Discussion

The deeply incised Ganga River into the T-2 surface, exposing 8–14 m high cliffs, indicates an incision by the river. The cliff sections expose laterally extensive sedimentary successions of the Upland terrace (T-1) surface and River valley terrace (T-1) surface. Four sections (Shashtri Bridge, Ram Gya Ghat, Nar Ghat, and Narbatpur section) are studied in different locations along the Ganga River between Allahabad and Buxar. The stratigraphic section comprises various lithofacies such as rippled silt, bedded calcrete, sandy silt, mottled silt, ferruginous nodules, and calcrete bearing silt. Mean grain size varies from very coarse to medium silt. Sediments are very fine skewed to fine skewed with leptokurtic to platykurtic grain size distribution (Fig. 4 (A)). These sedimentary deposits do not show any character of deposition by the river. The development of the T-2 surface in the study area may be the consequence of sedimentation in small channel and sheet flow processes, which indicates that these surfaces are not related to the fluvial processes of the Ganga River. This finding is in accordance with the view proposed by Singh et al., 1999; Srivastava et al., 2003a,b. The T-2 surfaces are dated and signify that interfluve (Doab) facies depositions have formed during 128 – 74 ka, and topmost sediments are deposited during 50 – 7 ka (Srivastava et al., 2003a,b).

The Ganga River shows a broad alluvial terrace (T-1 surface) incised in the T-2 surface in the study area, while the active channel of the Ganga River (T-0) is incised in the T-1 surface. The T-1 surface is 4–8 m above the present river channel.

HRI (Allahabad) and Hanuman Ghat section (Varanasi) of T-1 surfaces of the Ganga Pain were studied. The stratigraphic section comprises various lithofacies such as cross-bedded sand, laminated sand, silt, clayey silt, sandy silt, and silty sand. Mean grain size varies from very fine sand to medium silt. Sediments are very poorly to poorly sorted, fine to very fine skewed, and mesokurtic to leptokurtic grain-size distribution.

The present-day Ganga River in the Varanasi region is incised within the River valley Terrace (T-1-Surface), while the Upland Interfluve Surface (T-2 surface) is located much above the T-1-Surface, which Shukla and Raju, 2008 also report; Srivastava and Shukla, 2009. The Ganga River makes high cliffs at places where T-1-Surface has been eroded. The cliff height is essentially a result of up warping of the surface around 7 ka. Before coming to its present location, the Ganga River had a wide valley, shifting within its valley and changing its position many times between 40 ka to 7 ka. It appears that in the Varanasi, the river incision and cliff development is essentially related to the intra-basinal tectonics; though, this phase, in particular, is characterized by high precipitation and discharge (Prell and Kutzbach, 1987) and therefore, the incision might have initiated due to increased river discharge. Moreover, looking at the deformation in the Ramnagar, the role of climate and base-level as the cause of incision seems subordinate.

T-0 surfaces include the active channel of the Ganga River and its flood plains. The Ganga River shows varied channel patterns ranging from meandering to braided and straight channels. This narrow surface ranges from 1.5 km to 15 km wide within the studied stretch. Two fluvial landforms, sand bars, and levees, have been analyzed based on lithofacies and grain size variation. The sand bar comprises various lithofacies such as interstratified sand-silt mud, rippled sand, and cross-bedded bar sand. The mean grain size in sand bars varies from medium sand to silt. Kurtosis ranges from very leptokurtic to mesokurtic. Skewness varies from very fine skewed to fine skewed. Sorting runs from very poorly sorted to poorly sorted.

Two lithofacies, silty clay, and mud, have been identified in levees. Mean grain size varies from very fine sand to coarse silt with very poorly to poorly sorted sediments. Skewness ranges from very fine to fine skewed. Kurtosis ranges from very leptokurtic to leptokurtic.

7. Conclusion

The oldest geomorphic surface, the T-2 surface, formed by sheet flow processes during monsoon season, consists of silt, sandy silt, and silty sand. Sediments are poorly to very poorly sorted, very fine skewed to fine skewed, and kurtosis ranges from leptokurtic to platykurtic.

The Ganga River is incised into T-1 surface up to 4-8m in the study area. Rippled and cross-bedded silt, sand, and lensoid units of silty mud characterize T-1 representing older sediments of active channels. Mean grain size ranges from very fine sand to medium silt; sediments are poorly to moderately sorted; Skewness ranges from very fine skewed to fine skewed, and kurtosis ranges from very leptokurtic, leptokurtic, and mesokurtic.

T-0 is the youngest geomorphic surface of the Ganga basin. The Ganga River shows varied channel patterns ranging from meandering to braided and straight channels. Channels carry medium sand to very fine silt; sorting is very poorly to poorly sorted; Skewness is very fine skewed to fine skewed, and kurtosis ranges from leptokurtic, mesokurtic, and platykurtic.

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Figures

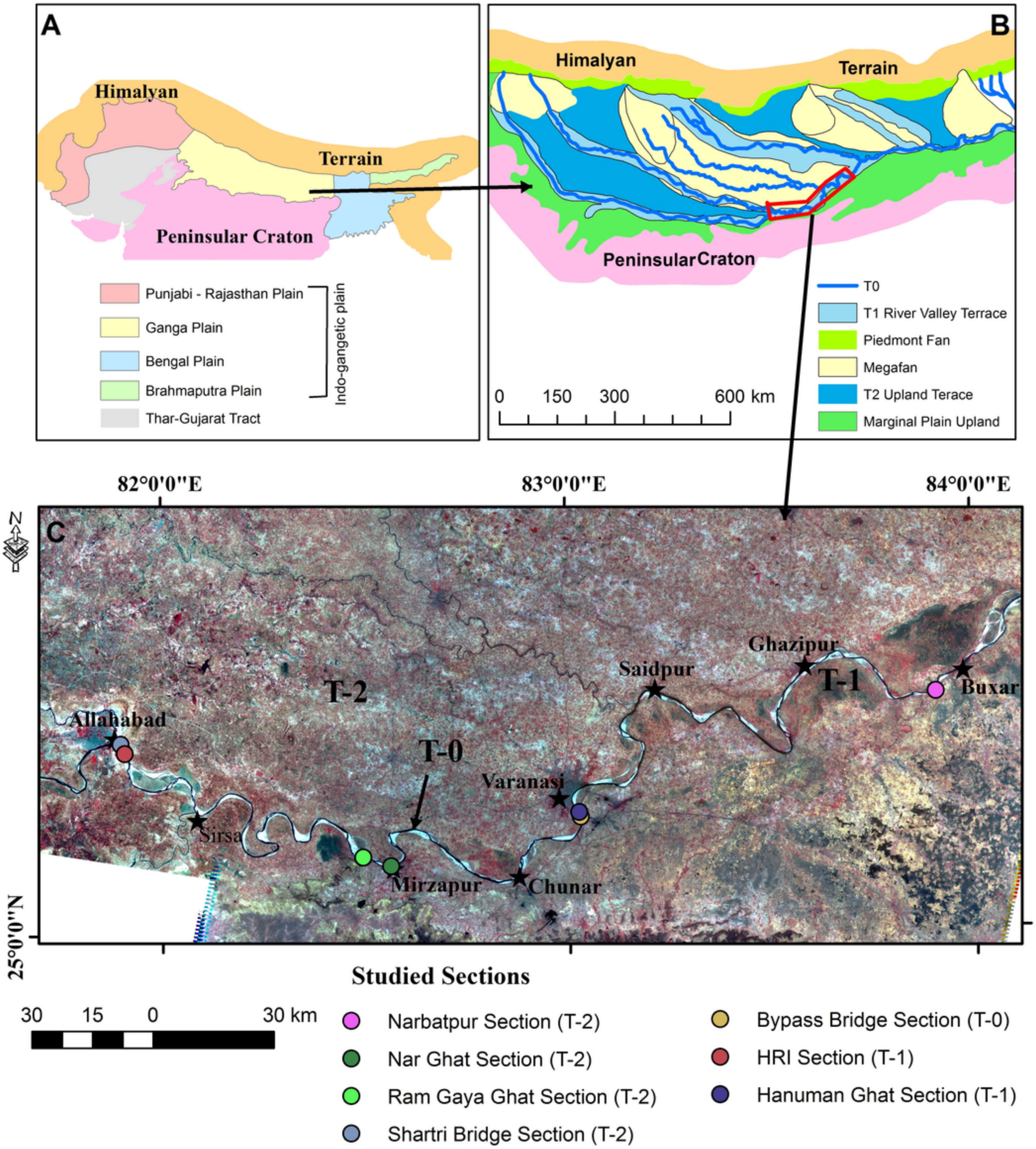

Figure 1

Location map of the study area (A) parts of Indo-Gangetic plain (B) Geomorphic map of the Ganga Plain showing regional geomorphic surfaces (Modified after Singh, 1996; Shukla et al. 2001). (C) Landsat image of the study area showing T-2, T-1, and T-0 surfaces exposed as cliff sections.

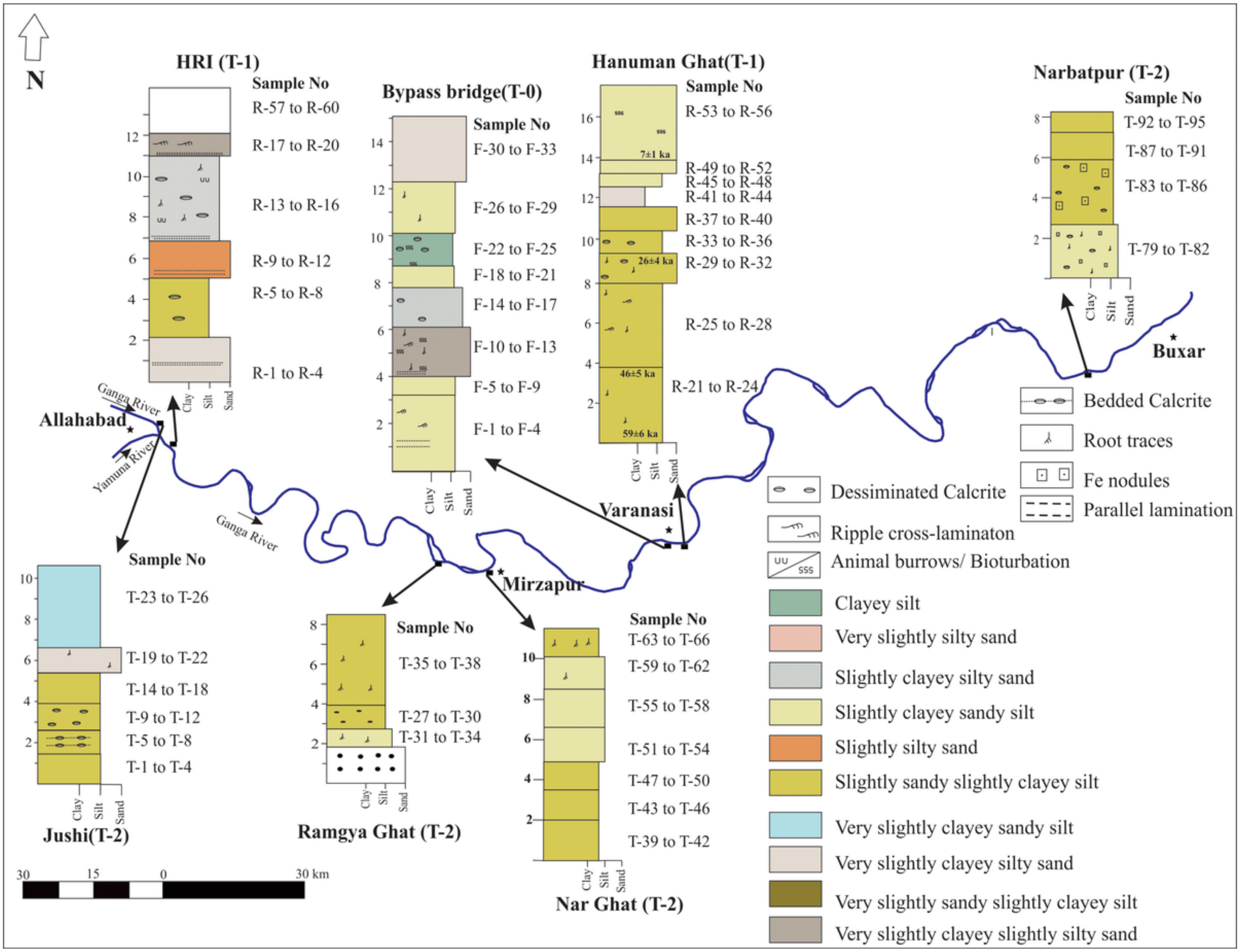

Figure 2

Particle size distribution of T-2, T-1, and T-0 sediments (Classification suggested by Blott and Pye, 2012).

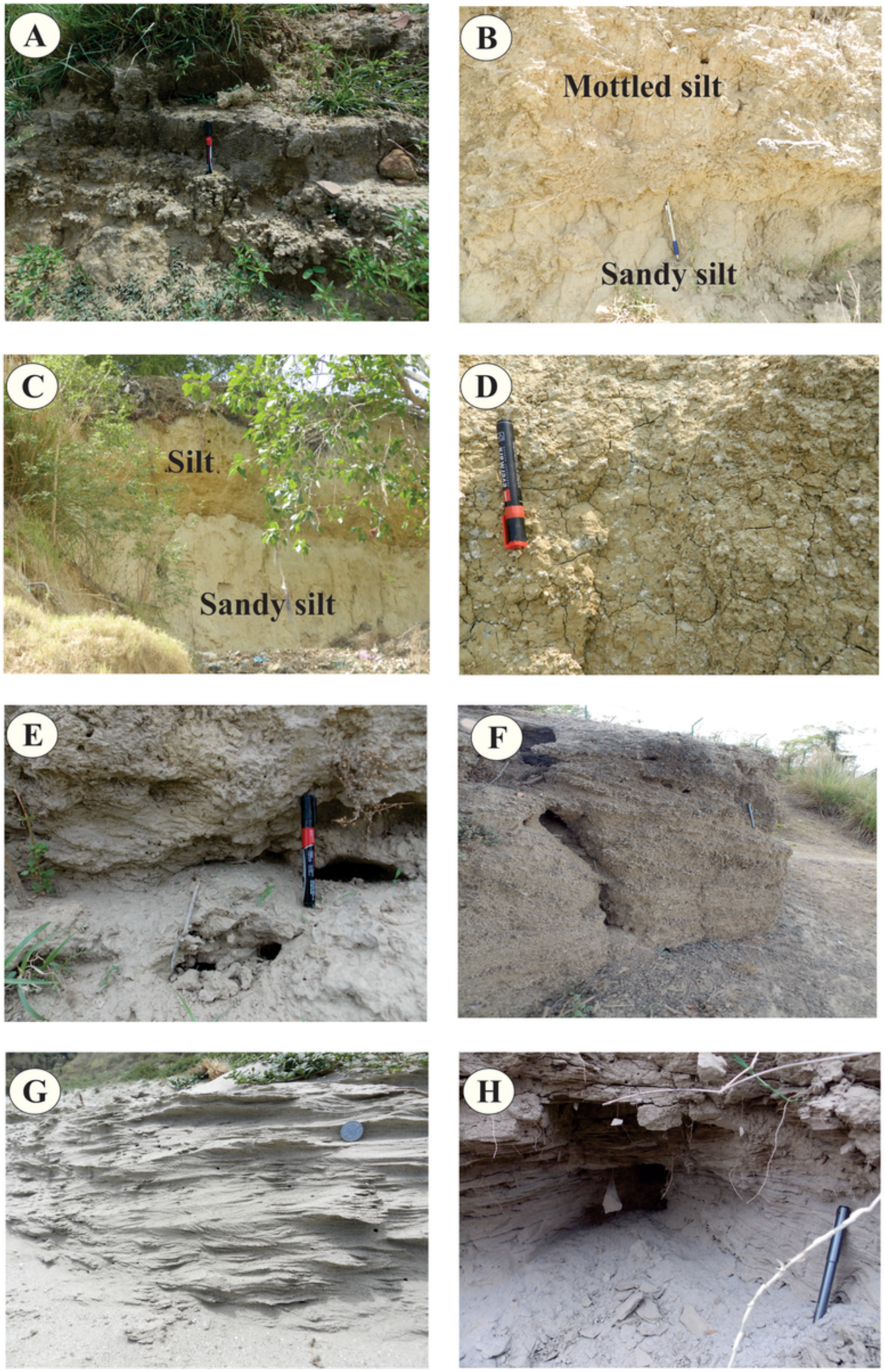

Figure 3

Lithological profiles of the studied geomorphic surfaces T-2, T-1, T-0 cliff sections showing the various sedimentary facies and sample numbers.

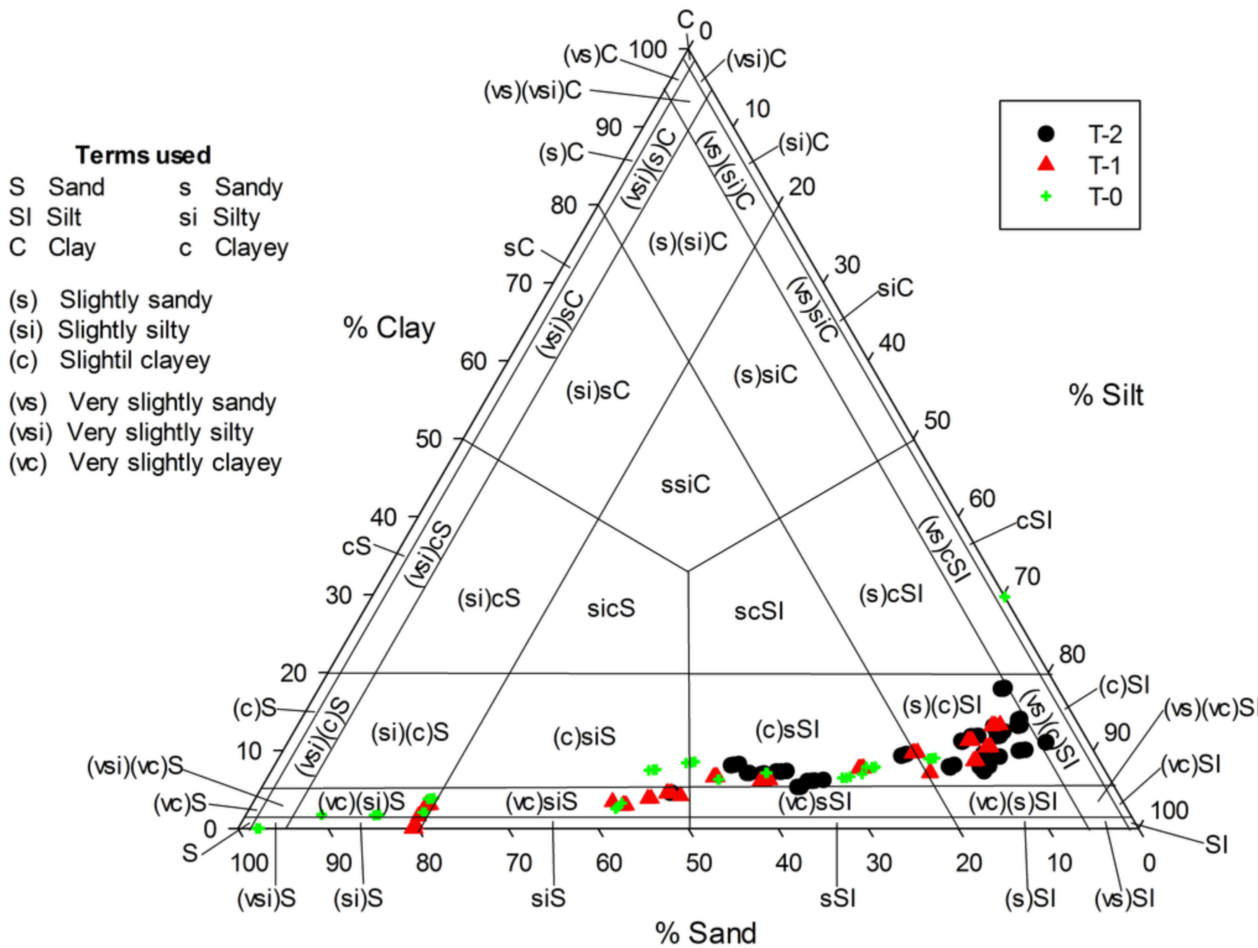

Figure 4

Bivariate plots (A) T-2 surface (B) T-1 surface (C) T-0 (sand bar) (D) T-0 surface (Levee).

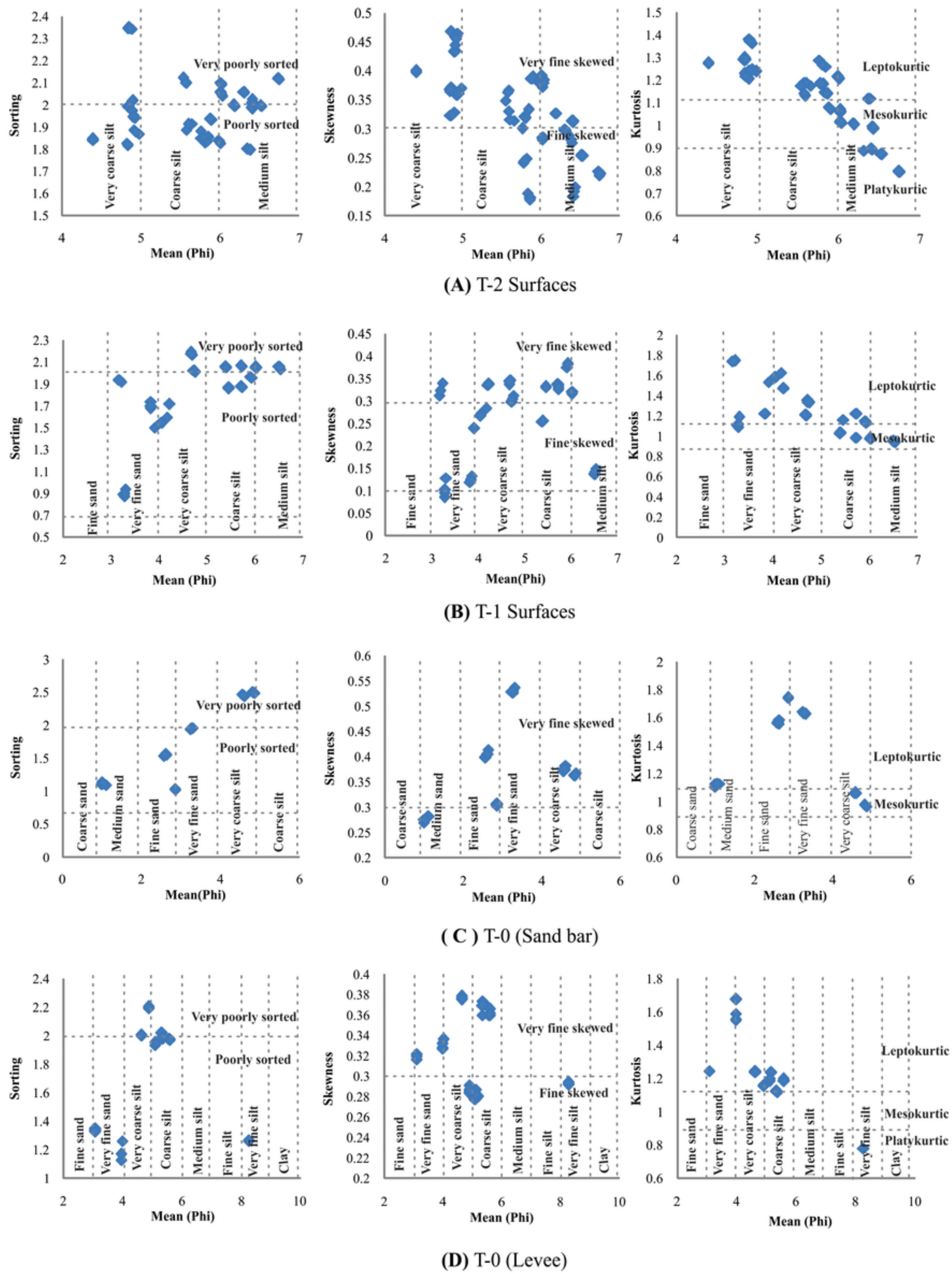

Figure 5

Photograph exhibiting different lithofacies in T-2, T-1, and T-0 surfaces. A-E are T-2 surfaces. F – T-1 surface and G-H are sand bar lithofacies (A) Calcrete bands in the cliff section at Jushi (B) contact between mottled silt and sandy silt at Ramgya ghat (C) sharp contact between sandy silt and silt at Nar ghat section (D) Ferruginous nodules and calcrete bearing silt at Narbatpur section (E)ripple silt at Jushi section (F) cross-bedded sand with calcrete nodules at HRI section (G) rippled fine sand and mud (H) rippled and burrowed sand and silt in sand bar deposit.

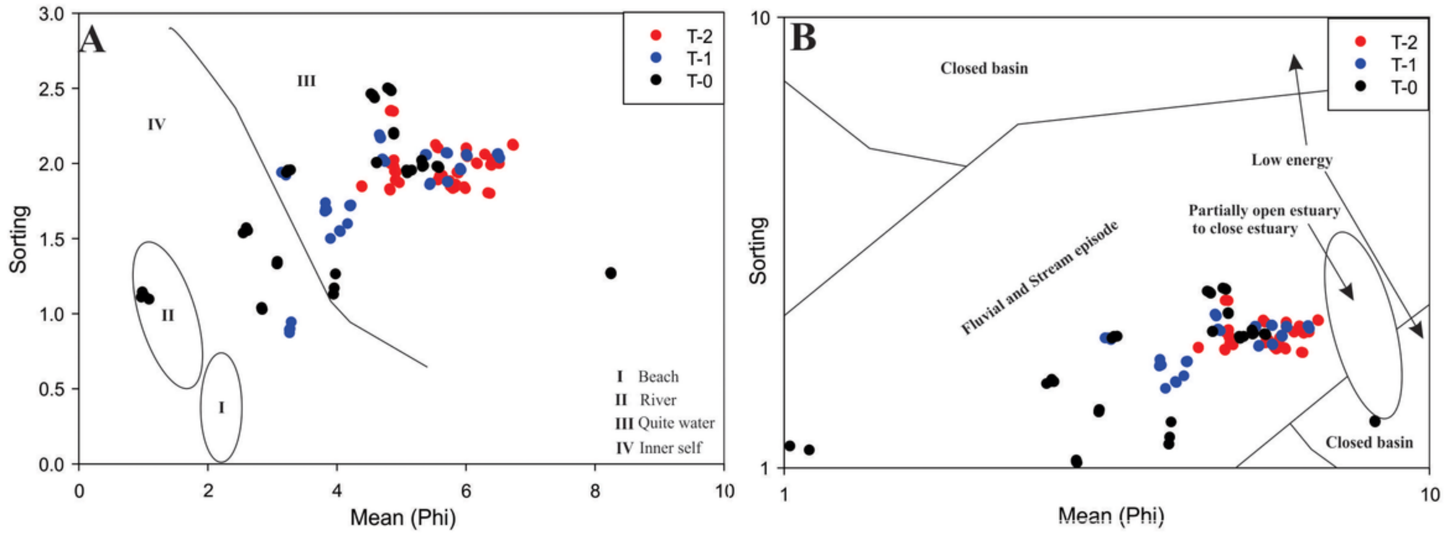

Figure 6

(A) Bivariate plots, mean size against sorting plot with subdivisions after Strewart (1958). (B) Bivariate plots, mean size against sorting plot with subdivisions after Tanner (1991).